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THE IMPACT OF REGULAR DIVING ON THE CONDITION OF THE MIDDLE EAR

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Abstract
Objectives: It is generally held that exposure to both high-pressure and long-lasting contact with water makes diving a potentially hazardous sports activity as far as the ears are concerned. There is a number of research investigating the condition of the middle ear in a short period following diving; however, the knowledge regarding the long-term effects of regularly repeated diving remains limited. **Material and Methods:** The aim of this study is to evaluate the function of the middle ear after a diving season in a group of 31 adults diving regularly (1–17 years) by means of the following methods: 1) interview, 2) otoscopy, 3) pure tone audiometry, 4) classic tympanometry, and 5) wideband tympanometry. **Results:** Periodic problems with pressure equalization in the middle ear were observed in 12 individuals (38.7%). In all the analyzed cases, the authors found a normal condition of the external auditory canal and the tympanic membrane in otoscopy, normal hearing in pure tone audiometry, curve type A, and normal gradient in both classic and wideband tympanometry. **Conclusions:** Safe diving (according to safety precautions) does not have any long-term negative effects on the condition of the middle ear. However, these observations should be verified in a larger group of divers. Int J Occup Med Environ Health. 2021;34(6)

Key words:
tympanometry, middle ear, high pressure, wideband tympanometry, scuba diving, acoustic impedance tests

INTRODUCTION

Scuba diving is one of the most frequently practiced sports in the world nowadays [1,2]. According to the Professional Association of Diving Instructors (PADI), more than 25 million diving certificates have been issued by that organization since 1967. What is more, 900 000 people start to dive every year. Presently, men account for >63% of all divers, although the percentage of women is progressively increasing [3]. In fact, diving constitutes a high-risk sport activity due to a number of factors, such as the risks associated with a distinct environment, breathing gases under pressure, as well as significant pressure changes in the surrounding water. The aforementioned changes are considerably greater than in everyday life, and even professional pilots or Himalayan climbers are not exposed to such sudden pressure changes. In fact, ear infections account for 55.1–72% of all otolaryngological disorders observed in divers [4,5]. Therefore, all diving organizations apply the following safe diving principles:

– the deepest immersion should be made first,
– the depth limits for a dive without decompression should not be exceeded,

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– the resurfacing speed should not exceed 9 m/s,
– at a depth of 6 m a security stop should be made for >3 min, and an ascent from the last 10 m should be very slow,
– it is prohibited to inhibit breathing during an ascent [6,7].

Nowadays, diving computers help divers to follow these safety recommendations.

Changes of water hydrostatic pressure correlate with the depth of diving. In freshwater, the pressure increases by 1 ata/10 m of depth. In practice, at a 10-meter depth, the diver is under twice as high pressure as on the land. During a descent, the increasing pressure of water affects the tympanic membrane; therefore, it is significant to increase air pressure in the tympanic cavity to avoid a middle ear injury. This can be achieved by means of supplying the air from the nasopharynx via the Eustachian tube, since the condition of these structures is crucial for safe diving [2,8]. Consequently, diving is strictly prohibited during any upper respiratory tract infections, or a limited function of the Eustachian tube [9,10]. In such situations, the sensation of pressure in one's ears occurs at a depth of 0.25–0.3 m, whereas pain occurs at a 2-meter depth.

A healthy Eustachian tube can be open at a depth of 0.2–0.4 m (pressure of 1.02–1.04 ata). At a 0.8-meter depth, the function of the Eustachian tube can be limited [9,11], and at 1.2 m (pressure of 1.12 ata), it can be completely blocked (the critical point), thus preventing the air supply to the tympanic cavity [9,12,13]. Therefore, it is crucial to supply the air actively by performing Valsalva or Toynbee maneuvers immediately, as well as by limiting the descent speed. In the case of problems with pressure equalization in the middle ear, there is a risk of the middle ear barotrauma and even a rupture of the tympanic membrane may occur [2,6,9,10,14]. Furthermore, rupture may lead to cold water stimulation of the labyrinth, vertigo, a decline of spatial orientation and, finally, even death.

A diver course and training in Poland typically begins in swimming pools in winter where divers train at a depth of 2–5 m. Within this range, the depth of pressure change is relatively high: 20–50% of the normal atmospheric pressure. Moreover, divers often perform pressure equalization maneuvers during training, particularly in the case of critical pressure values for opening the Eustachian tube.

Various research studies have reported the condition of the middle ear in a short period following diving [15–17]. Evens et al. [15] described numerous problems concerning the external, middle and internal ear among divers, such as otitis externa, osteoma of external auditory canal, barotrauma of the middle ear, and compressed air sickness. In the study by Özyurt [16], the dysfunctions of the middle ear were found much more frequently among beginners than among experienced divers [16], whereas Green et al. [17] presented a short-term influence of diving on the ears. However, the knowledge regarding long-term effects of diving is still limited, although Sames et al. [18] found no significant changes in the audiological system of professional divers within 10–25 years of diving.

The aim of this study is to evaluate the function of the middle ear in the group of adults diving regularly in cold freshwater following a diving season.

MATERIAL AND METHODS

The study group was enrolled by contacting local diving clubs. The group consisted of 31 regularly diving healthy volunteers (21 men and 10 women), aged 20–65 years (M = 39 years). The number of diving sessions ranged 9–98/year, the depth of diving ranged 18–50 m (M = 23 m), the pressure during diving was 2.8–6 ata (M = 3.3 ata), and the diving experience ranged 1–17 years. The variation in age, diver experience, the number of dives and a maximum dive depth (resulting from the PADI certification) is typical for a diving school/club. The cyclical diving training includes students of both genders, of different ages, with different experience and certifications.

Examinations were conducted more than 4 weeks after a diving season in Poland (in October and November) in order to avoid the possible short-time diving effects. The results were compared to a reference group consisting of individuals with a normal hearing (10 men, 29 women), aged 22–65 years (mean age: 30), who had never dived or been exposed to other high-pressure conditions. Due to the fact that the groups consisted of volunteers, it was not possible to create 2 identical groups. On the basis of the interview, a third group of 12 divers was established (6 men, 6 women). They reported episodic problems with the middle ear pressure (MEP) equalization during a descent. The obtained test results were analyzed for the entire group of divers, as well as separately for the group reporting problems with pressure equalization and the group of divers who had never experienced such issues.

All tests were performed in a quiet room where the background noise level was <20 dB_{SPL}. The background noise level was measured with B&K 2250 Sound Level Analyzer (Bruel and Kjaer, Naerum, Denmark), calibrated according to the IEC 61672 standard.

The following procedures were performed:

– an interview: the patient questionnaire targeted relevant data related to diving (diving experience, the number of dives in the year prior to the study, the date of the last dive, and maximum depth), pressure equalization problems, hearing problems, and a history of ear, nose and throat disease;
– otoscopic examination (a Delfino video-otoscope [Inventis, Padova, Italy]): the evaluation of the condition of the external auditory canal and the tympanic membrane (Teed's classification);
– pure tone audiometry (a Madsen Itera II [GN Otometrics A/S, Taastrup, Denmark] clinical audiometer);
– the audiometer (including electroacoustic transducers) was previously calibrated according to PN-EN 60645-1:2017-12, and the threshold values were determined using a Madsen Itera II diagnostic audiometer (GN Otometrics A/S, Taastrup, Denmark) equipped with TDH39 air-conduction headphones; the test was performed for the frequency range of 500–4000 Hz using the ascending two-thirds method for both ears;
– classic tympanometry (a Madsen Zodiac 901 clinical tympanometer [GN Otometrics A/S, Taastrup, Denmark]): the pressure ranging 200–(–400) daPa; with a pure tone frequency of 226 Hz;
– classic tympanometry (a Titan wideband tympanometer [Interacoustics A/S, Middelfart, Denmark]): the pressure ranging 200–(–300) daPa; with a pure tone frequency of 226 Hz;
– wideband tympanometry WBT (a Titan wideband tympanometer [Interacoustics A/S, Middelfart, Denmark]): the pressure ranging 200–(–300) daPa; frequency of 226–8000 Hz click; 3D modules were used for both, absorbance and 3D tympanometry.

Each test was performed once.

Tympanometric parameters, such as ear canal volume (ECV), middle MEP, static compliance (SC), gradient, and resonance frequency (RF) were analyzed. More specifically, ECV is estimated based on the measured volume as a function of pressure, and is an estimate of the volume of air medial to the probe, which includes the volume between the probe tip and the tympanic membrane. The normal value of this parameter for adults is 0.9–2 ml [19]. As regards MEP, it is defined as the difference between the pressure at which the peak occurs and the atmospheric pressure. Normative values for this parameter range –103–4.2 daPa [19]. Static compliance is the height of the peak on a tympanogram, its standard values ranging 0.2–1.5 ml. Gradient constitutes an objective measure which describes the steepness of the slope of the tympanogram near the peak, and its normative values range 32.8–125 daPa [19]. Finally, RF is the lowest frequency at which the spring and mass elements of the outer and middle ear structures contribute equally to the admittance. The RF of the middle ear conduction system varies from person to person and physiologically amounts to 630–1120 Hz [20].

Tympanometry constitutes a basic test of the middle ear condition [21–23]; however, Teed's otoscopic classification is regarded as a more sensitive tool in a short time after an ascent [2,16,17,24]. Teed's classification is effective in the evaluation of alterations due to the middle ear barotrauma. The condition of the ear is rated on a scale of 0–4 grades [2,24]:

- grade 0 – normal otoscopy,
- grade 1 – retraction c hyperemia of the malleus and incus,
- grade 2 – retraction c hyperemia of the entire membrane,
- grade 3 – fluid or blood in the middle ear,
- grade 4 – perforation of the tympanic membrane.

The wideband tympanometry technique gives much more information concerning the condition of the middle ear than classic tympanometry [21]. The aforementioned research studies prove that this method is effective in the diagnosis of various middle ear conditions, such as hypopressure, exudative otitis media, flaccidity or stiffness of the tympanic membrane, disruption of ossicular chain, or semicircular canal fistula [25,26]. However, in literature there is no research using this technique in divers, or in other individuals practicing water sports.

The wide frequency range of the measurement renders it more independent from the external interference, making the test more accurate in assessing the middle ear pathology in adults compared with the classical tympanometry [20,27,28].

This method also allows for the measurement of absorbance without changes in pressure exerted on the tympanic membrane, making it extremely useful in examining tympanic membrane perforation, postoperative evaluation, after insertion of a transtympanic drain, and in the diagnosis of otosclerosis [29].

Ethics

The tests were conducted at the Department of Hearing Healthcare Profession at the Poznan University of Medical Sciences. This study was approved by the Bioethics Committee of the Poznan University of Medical Sciences, Poznań, Poland (No. 272/17).

Statistics

The results of the classic tympanometry and wideband tympanometry were statistically analyzed in order to find any correlation with the diving experience. For this purpose, Statistica v. 12 software was employed. First, the distribution of the results was assessed using the Kolmogorov-Smirnov test with the Lilliefors correction for small groups, as well as by the Shapiro-Wilk test. Subsequently, the nonparametric Spearman's correlation between the diving experience (the time of practicing scuba diving) and the tympanometry results was evaluated. By means of the Mann-Whitney U test, the classic and wideband tympanometry results in the group of divers were compared with the results obtained in the reference group. The significance threshold was estimated as $\alpha = 0.05$.

RESULTS

In the analyzed group of individuals who dive regularly, the following results were found:

- interview: episodic problems with pressure equalization in the middle ear during a descent, which resulted in a break in diving (according to the safe diving principles), were observed in 12 individuals (38.7%);
- otoscopy: a normal condition of the external auditory canal and the tympanic membrane (degree 0 according to Teed's classification, and a lack of any other changes) were observed in all cases;
- pure tone audiometry: mean hearing thresholds for air conduction were calculated as the arithmetic mean of 4 basic frequencies: 500, 1000, 2000, and 4000 Hz for each ear separately; the individuals tested presented

Table 1. Comparison of the results for the group of divers and the reference group – the tests were conducted at the Department of Hearing Healthcare Profession, the Poznan University of Medical Sciences, November 2018

Variable	Participants (N = 70)						normative data [ref.]
	control group (N = 39)	divers (N = 31)	p	reporting problems (N = 12)	without problems (N = 19)	p	
Ear canal volume [ml] (Me±SD)							0.9–2.0 [19]
Titan	1.5±0.3	1.9±0.24	**<0.01**	1.8±0.3	1.8±0.3	0.39	
Titan (wideband tympanometry)	1.5±0.3	1.9±0.2	**<0.01**	1.8±0.3	1.8±0.3	0.39	
Zodiac	1.1±0.3	1.2±0.4	0.07	1.3±0.5	1.2±0.3	**0.03**	
Middle ear pressure [daPa] (Me±SD)							–103–4.2 [19]
Titan	–6.0±9.0	–6.5±17.6	0.70	–1.0±9.9	–6.5±16.5	0.14	
Titan (wideband tympanometry)	–2.0±11.9	–2.0±18.8	0.707	0.0±7.6	–0.5±26.4	0.30	
Zodiac	–5.0±11.6	–5.0±16.9	0.41	0.0±8.1	–5.0±16.1	**<0.01**	
Static compliance [ml] (Me±SD)							0.2–1.5 [19]
Titan	0.5±0.4	0.8±0.3	**<0.01**	0.7±0.4	0.7±0.3	0.44	
Zodiac	0.7±0.4	0.9±0.3	**0.02**	0.8±0.4	0.7±0.3	0.245	
Gradient [daPa] (Me±SD)							32.8–125.0 [19]
Titan	88.0±21.3	79.0±22.8	0.08	88.0±27.6	88.5±31.8	0.79	
Zodiac	82.5±22.1	72.5±25.8	**0.01**	75.5±21.1	75.0±23.3	0.96	
Resonance frequency [Hz] (Me±SD)							630–1120 [20]
Titan (wideband tympanometry)	774±178	627±120	**<0.01**	634±170	661±131	0.73	

Bolded are statistically significant differences.
Titan – classic tympanometry, the pressure ranging 200 –(–300) daPa; with pure tone frequency of 226 Hz; Titan – wideband tympanometry, the pressure ranging 200 –(–300) daPa, with frequency of 226–8000 Hz click; Zodiac – classic tympanometry, the pressure ranging 200 –(–400) daPa, with pure tone frequency of 226 Hz.

normal hearing, not exceeding 20 dB_{HL} according to the 1997 WHO standard;
- classic impedance audiometry: curve type A and normal gradient were observed in all individuals;
- wideband tympanometry: normal results were observed in all individuals.

In order to find out if there was any relation between frequent exposure to high pressure during diving and tympanometric parameters, which could suggest an increased risk of eventually developing middle ear problems, the results of both the group of divers and the reference group were compared. The Mann-Whitney U test demonstrated statistically significant differences between the group of divers and the reference group for parameters such as ECV (measured with a Titan tympanometer), as well as SC and gradient (measured with a Zodiak tympanometer) (Table 1). However, all the analyzed parameters were within the normal range according to Hunter and Sanford [19], even though a statistically significant difference between the groups was found. The significant difference may indicate some impact of regular diving on the middle ear, so it would be recommended to monitor

Table 2. Correlation between the diving experience and tympanometric parameters – the tests were conducted at the Department of Hearing Healthcare Profession, the Poznan University of Medical Sciences, November 2018

Variable	Participants (N = 31)					
	reporting problems (N = 12)		without problems (N = 19)		total	
	Spearman's correlation coefficient	p	Spearman's correlation coefficient	p	Spearman's correlation coefficient	p
Middle ear pressure [daPa]						
Titan	0.15	0.49	0.27	0.10	0.26	**0.04**
Titan (wideband tympanometry)	0.38	0.06	0.24	0.15	0.31	**0.02**
Zodiac	0.14	0.52	0.15	0.36	0.24	0.06
Static compliance [ml]						
Titan	0.26	0.22	–0.13	0.43	0.02	0.88
Zodiac	0.15	0.48	–0.18	0.29	–0.03	0.79
Gradient [daPa]						
Titan	–0.13	0.55	0.39	**0.02**	0.20	0.11
Zodiac	–0.08	0.71	0.23	0.16	0.16	0.22

Explanations as in Table 1.

the middle ear condition in divers on a regular basis in order to avoid any further issues.

The analysis was also performed for 2 groups of divers: individuals who reported problems with pressure equalization and divers who had never experienced any such problems during an ascent. The results of the tympanometric examination for both groups were compared using the Mann-Whitney U test (Table 1). The analysis indicated a statistically significant difference between MEP and ECV measured with a Zodiac tympanometer for both groups. In contrast, no significant differences were found for MEP and ECV measured using a Titan tympanometer.

Furthermore, a correlation between the diving experience and parameters such as MEP, SC and gradient were also analyzed (Table 2). Spearman's correlation showed a weak correlation between the diving experience and the MEP measured with a Titan tympanometer. No statistically significant correlation for the results obtained by means of a Zodiac tympanometer was detected; however, the p-value was very close to the threshold.

The correlation was also analyzed for the following 2 subgroups: divers who reported problems with pressure equalization and divers who had never had any such problems (Table 2). The results showed a weak correlation between the diving experience and gradient for the group of divers who had never experienced problems with pressure equalization.

Moreover, absorbance spectra for both the diving group and the reference group were also compared (Figure 1). No distinct differences between these results was observed. Even if slight differences occurred for some frequencies, these were within the standard deviation.

DISCUSSION

The authors present the results concerning the influence of regular diving on the condition of the middle ear. In the otoscopic examinations and impedance audiometry, no significant difference was observed between the group of divers and the reference group. Statistical analysis showed that multiple high pressure exposures did not affect the middle ear in divers as compared to the reference group, and all the obtained results were within the range of the normative data. In fact, Evens et al. [15] showed that education and training may prevent audiological problems. Özyurt [16] confirmed that statement and showed that inexperienced divers suffered more often from middle ear injuries. Therefore, since the group involved in this study consisted only of the trained divers associated in diving schools, the authors did not record any outer and middle ear dysfunctions. Ramos et al. [2] and Green et al. [17] conducted research with professional divers and observed a regeneration ability of the middle ear if the safety precautions were observed (breaks between the successive diving sessions). The tests outlined in this article were conducted after a diving season, hence the authors avoided the potential short-time diving effects.

The reference group participating in this research consisted of 10 men and 29 women, and the gender composition was different than in the study group: 21 men and 10 woman. Mazlan et al. [30] found some gender-related differences in the tympanometric parameters; however, the differences were not big enough to be clinically significant.

Research conducted by Sames et al. [18], Klingmann et al. [5] and Goplen et al. [31], investigated the long-term effects on the auditory system and showed that changes in hearing were not related to diving exposure, which is consistent with the findings obtained by the authors of this article.

Jansen et al. [32] and Ramos et al. [2] conducted studies on a group of recreational divers. In their studies, they investigated the short-term effects of diving [2,32]. In both studies, before the start of a series of dives, the divers presented correct otoscopic images and had type A tympanograms. This is consistent with the observations made by the authors of this article. The research focused on the short-term effects of diving. In both studies, a decrease

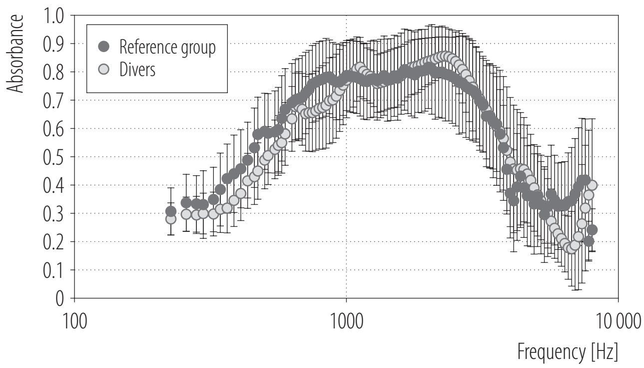

Figure 1. Absorbance at ambient pressure in relation to frequency for the group of divers and the reference group – the tests were conducted at the Department of Hearing Healthcare Profession, the Poznan University of Medical Sciences, November 2018

in MEP was observed as the number of dives increased. Ramos et al. [2] showed that pressure returned to normal 11 h after a descent. In isolated cases, a type C tympanogram and the MEP equalization problems were recorded immediately after an ascent. Jansen et al. [32] recorded an increase in the eardrum compliance following the first descent, although subsequent immersions no longer affected this parameter. Higher values of the eardrum compliance were recorded in the group of more experienced divers. In the performed long-term studies, no correlation was observed between experience and membrane susceptibility.

According to the study by Cyran et al. [33], the tympanometric studies were performed on a group of 60 divers as well as on 90 non-divers, yielding the mean MEP and mean susceptibility of 23.07 daPa and 0.51 for divers, and –13.48 daPa and 0.74 for non-divers. The results of both groups were within the normal range, which is consistent with the research described in this paper; however, the divers' results were statistically significantly lower [33]. Sames et al. [18], Skogstad et al. [34] and Goplen et al. [31] investigated the long-term effects of diving on hearing thresholds in professional divers. In fact, Sames et al. [18] did not associate changes in the hearing thresholds with diving, and found no statistically significant differences between age-related hearing changes. On the other hand, Skogstad et al. [34] observed a deterioration in the hearing thresholds for low and high frequencies following 12 years of professional diving. However, only hearing loss at high frequencies of 4 kHz and 8 kHz was associated with diving. Similarly, a study by Goplen et al. [31] found a shift in hearing thresholds at 4 kHz after 6 years of working underwater, although this deterioration was not related to diving itself, but rather to work-related noise. No barotrauma of the inner ear was found in spite of the fact that barotrauma of the middle ear was frequently observed [31]. The authors also suggested that hearing loss might be associated with the noise generated by vibrating tools used in the underwater work [31,34]. A study of recreational divers was performed by Taylor et al. [35] who did not observe statistically significant differences between the mean hearing thresholds of the non-diving group. The hearing thresholds in their study also did not exceed 20 dB_{HL}.

The absorbance spectra obtained for both the diver and reference groups were close to the normative values with a maximum of 2–4 kHz, a decrease above the frequency of 4 kHz up to a minimum of about 6.7 kHz, and an increase as the frequency approached 8 kHz [21].

CONCLUSIONS

The analyzed results of all individuals involved in this study were normal. According to the results of this research, significant changes in the environmental pressure in divers did not negatively affect the condition of the middle ear. The lack of the long-term negative effects on the condition of the middle ear is possible as long as diving is performed following the safety measures (adequate speed of a descent and resurfacing, coupled with proper maneuvers of MEP equalization). In the course of the divers' periodic medical examinations, otoscopic control and anamnesis are sufficient although impedance audiometry may constitute an additional examination. The results of the research indicate that the systematic practice of diving does not negatively affect the condition of the middle ear. Nevertheless, these observations should be verified in a larger group of divers, and particularly in divers who complain of otolaryngological problems.

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