

An overview of changes in pressure values of the middle ear using impedance audiometry among diver candidates in a hyperbaric chamber before and after a pressure test

J S Anoraga¹, B Bramantyo¹, S Bardosono¹, S H Simanungkalit² and J Basiruddin^{1*}

¹Department of Ear Nose Throat Head Neck, Faculty of Medicine, Universitas Indonesia, Jakarta, Indonesia

²Department of Hyperbaric, dr. Minto Harjo Hospital, Jakarta, Indonesia

*E-mail: jenny.bashiruddin@yahoo.com

Abstract. Impedance audiometry is not yet routinely used in pressure tests, especially in Indonesia. Direct exposure to pressure in a hyperbaric chamber is sometimes without any assessment of the middle ear or the Eustachian tube function (ETF) of ventilation. Impedance audiometry examinations are important to assess ETF ventilation. This study determined the middle ear pressure value changes associated with the ETF (ventilation) of prospective divers. This study included 29 prospective divers aged 20–40 years without conductive hearing loss. All subjects underwent a modified diving impedance audiometry examination both before and after the pressure test in a double-lock hyperbaric chamber. Using the Toynbee maneuver, the values obtained for changes of pressure in the middle ear were significant before and after the pressure test in the right and left ears: $p < 0.001$ and $p = 0.018$, respectively. The impedance audiometry examination is necessary for the selection of candidate divers undergoing pressure tests within a hyperbaric chamber.

1. Introduction

While diving, the pressure within the enclosed spaces inside the diver's body will be affected, to a greater or lesser extent, by the pressure around the diver. The difference in the magnitude of these differences depends on the depth. The pressure of the diver's surroundings also affects the middle ear, and, consequently, he or she will require equalization. Techniques for equalization can be performed, such as the Toynbee and Valsalva maneuvers, with certain autoinflation maneuvers that push air into the nasopharynx; then, the Eustachian tubes are moved forward in the middle ear. Middle ear barotrauma results from Eustachian tube failure in the equalization process. Therefore, it is important to have well-functioning Eustachian tubes while diving. There are many selection factors for diving candidates apart from the readiness of the Eustachian tubes, but the Eustachian tube function (ETF) is a main indicator of the body's ability to adapt to pressure [1-5].

Barotrauma often occurs among divers, and the most commonly affected area is the middle ear. In research examining 709 divers, the distribution of the types of barotrauma was as follows: middle ear barotrauma (52.1%), paranasal sinus barotrauma (34.6%), and tooth barotrauma (9.2%). The Divers Alert Network (DAN) also reported that 50.4% of barotrauma cases from 1995 to 2007 were in the middle ear, especially among age groups below 24 years and above 50 years. The risk of occurrence of



barotrauma generally begins within the first 10 meters below the surface, but the DAN identified the first 4.2 meters (14 feet) below the surface as the depth that presents the highest risk of barotrauma [6-8].

Impedance audiometry can evaluate the condition of the middle ear and ETF objectively through changes in pressure in this region when the Eustachian tubes are provoked by autoinflation maneuvers (i.e., Toynbee and Valsalva) [9]. Pressure can be applied to the body using the hyperbaric chamber, or a hyperbaric chamber, which can provide pressure up to 6 ata (more than 50 meters). The hyperbaric chamber is a diving simulation room that can be used to test the ability of hollow organs during pressure changes, especially the middle ear, using a pressure test. This pressure test was initially used by the U.S. Navy, and it is still widely used as a reference for prospective diver selection by providing a pressure of 2.8 ata, which is equivalent to a depth of 60 feet (or 18 meters) below sea level for 10 minutes. This procedure has also been adopted in Indonesia, but only in the military field [1,10,11].

Ashton, as quoted by Ozyurt [12], reported that, of the 80 research participants who underwent a simulated dive in a pressurized space, 23 experienced middle ear barotrauma. In the same year, Devine also reported (as quoted by Ozyurt [12]) that of the 31 divers examined, 14 ears (23%) were affected, showing the results of Type C tympanograms. Similarly, from his research in 1996, Miyazawa reported that 14 ears (17.5%) of 40 subjects who underwent a simulated dive in a pressurized chamber experienced congestion and tympanic membrane bleeding [12]. Uzun [13], also conducted a study of impaired ETF in divers using tympanometry, audiometry, and general ear, nose or throat (ENT) examinations on 31 participants. Uzun found that 45% of these divers experienced middle ear barotrauma, and the predictive value for the occurrence of middle ear barotrauma was 86%. Shupak's study [14], examined 34 divers in a hyperbaric chamber at a depth of 15 feet below sea level for 3 hours. According to the images obtained, changes in the tympanic membrane could be ascertained using pneumatic otoscopy and tympanometry in 63% and 42% of the divers, respectively, at 7 hours post-diving [12-15].

The above studies evaluated the state of the middle ear after the dive had already occurred, either post-diving in bodies of water or in simulated dives, but as yet, no studies have described the state of the middle ear and the ETF while it is intact. Such research still relies on tympanogram images, and examinations conducted after diving that use tympanometry are inaccurate due to the presence of water in the ear canal. In addition, tympanometry examinations are not performed immediately after the diver exits the hyperbaric chamber or the body of water (for wet diving), and the depth may be less than 60 feet. Hence, the function of the middle ear and the Eustachian tubes at a depth of 60 feet is still unknown, and data on the state of the middle ear and the function of the Eustachian tubes are insufficient.

Impedance audiometry has not been routinely used before or after the pressure test, especially in Indonesia. Prospective divers often receive direct exposure to pressure in a hyperbaric chamber without knowing the state of the middle ear and the function of the Eustachian tubes, so the situations that may be contraindications of diving and the risks of occurrence for middle ear barotrauma are not known. It is essential to conduct impedance audiometry before diving to determine the state of the middle ear and the ETF, but this test does not adequately describe the ETF when the diver is under real depth pressure. Furthermore, by testing the air pressure equality in the Eustachian tubes using impedance audiometry after the diver exits from the hyperbaric chamber, the state of the middle ear and the ETFs are expected to be the same as when the diver is at a real depth [16-20].

2. Materials and Methods

The design of this study was cross-sectional, with a special procedure simulating a dive of up to 60 feet below sea level (18 meters or 2.8 ata) in the hyperbaric chamber for 10 minutes. This research was conducted at a Hyperbaric Unit. Data collection was conducted from November 30, 2015 to January 25, 2016, and the study population consisted entirely of prospective divers aged 20 to 40 years, who underwent a pressure test in the hyperbaric chamber. The results of the ENT examination, which used pneumatic otoscopy, impedance audiometry, and normal audiometry, recorded the appropriateness of equalization through the Valsalva and Toynbee maneuvers. Subjects were withdrawn from the study if

their tympanograms from the post-pressure test using impedance audiometry did not display the pressure values of the middle ear. The subjects of this study used at least one mean difference for the population with type I error (5%), had a standard deviation of 11 (Therkildsen and Gaihede [21]), and had a difference in mean of 5 from initial pressure levels to Toynbee's maneuver (Therkildsen and Gaihede; 21 18.59; ~ 20 subjects). Thirty samples were taken to anticipate study dropouts.

Consecutive sampling was used. The prospective diver subjects were given an explanation of the purpose of the study, the examination stage of the research, and the techniques that would be used. Participants who were willing to act as a subject of the research signed the written/informed consent form and then filled in the research questionnaire with help and explanations from the researcher. The ENT examinations conducted on the research subjects included otoscopy, equalization tests (Valsalva and Toynbee), impedance audiometry, and pure tone audiometry. Research subjects with impedance audiometry results that showed a tympanogram image other than Type A or that had impaired ETF before the pressure test were excluded. Examinations of impedance audiometry (AT 235 Interacoustics [22]) were conducted by modifying the William test. Subsequently, the subjects underwent a pressure test up to a depth of 60 feet below sea level (18 meters or 2.8 ata) in the hyperbaric chamber (Oceaneering International, AEL-651, U.S.) for 10 minutes.

The total dive simulation time was 13 minutes, including the time it takes to a) descend to a depth of 60 feet (1 minute), b) remain at a depth of 60 feet (10 minutes), and c) rise to the surface (2 minutes). The research subjects were observed during the dive simulation in the hyperbaric chamber. The simulation was discontinued if the subject felt uncomfortable or incapacitated despite reaching equalization at a depth of less than 60 feet or spending less than 10 minutes at a depth of 60 feet. The subjects reached 60 feet below sea level (18 meters or 2.8 ata) in the hyperbaric chamber and remained there for 10 minutes. Otoscopic examinations and impedance audiometry were performed again after diving (i.e., just after the exit from hyperbaric chamber) on subjects that a) reached 60 feet below sea level (18 meters or 2.8 ata) in the hyperbaric chamber after 10 minutes, b) did not reach 60 feet below sea level (2.8 ata), or c) spent less than 10 minutes in the hyperbaric chamber.

The results of the examinations were documented, recorded in the research records, inputted into the computer, and then analyzed. Subjects who, at their own request, withdrew from the research (in written form) for any reason were not analyzed. All data were edited, coded, and then entered into the worksheet, which was processed in a computer using SPSS V.20. Data were presented in the form of text, tables, or graphics. Data were transferred into a numerical scale using the Shapiro-Wilk normality test if the number of subjects analyzed was less than 30 or using the Kolmogorov-Smirnov test if the sample size was at least 30. Normally distributed data were presented with the mean and standard deviation, while abnormally distributed data were presented with the median as well as minimum and maximum values. Analysis of numerical data that were normally distributed used a paired t-test whereas in data that were abnormally distributed, the Wilcoxon signed-rank test was used.

3. Results and Discussion

3.1 Results

Two research subjects left the study based on the dropout criteria, which left a remainder of 29 subjects. Of the 29 subjects, 3 did not pass the pressure test. The results of an otoscopic examination on the 29 prospective divers, which was conducted after the pressure test according to the modifications of Teed's classification, appear in Table 1. The results were as follows: 0 degrees of baro-myringitis in the right and left ears (19 and 18 ears, respectively), 1 degree of baro-myringitis in the right and left ears (9 and 10 ears, respectively), and 2 degrees of baro-myringitis in the right and left ears. Data of the research subject characteristics (i.e., of the prospective divers) before the pressure test in the hyperbaric chamber are presented in Table 1. The data present descriptions of the tympanogram types and pressure values of the middle ear both without a maneuver (ETF 1) and with a maneuver—Valsalva (ETF 2) and Toynbee (ETF 3)—from the impedance audiometry conducted on both ears. The data show an overview of the tympanogram types before the pressure test for all subjects (Type A), and on the ETF, there is an increase in ETF 2 and a decrease in ETF 3 in both ears.

Table 1. Prospective diver characteristics according to the results of the impedance audiometry conducted before the pressure test in the hyperbaric chamber; ETF: Eustachian tube function

Variable	Right Ear	Left Ear
Tympanogram		
Type A	29	29
Type B	0	0
Type C	0	0
Volume	1.09 [#]	1.03 [#]
(ml)	0.22	0.19
Pressure	-5.55 [#]	-4 [*]
(daPa)	11.53	(-78.119)
ETF (daPa)		
ETF 1	-4 [*]	4 [*]
(Without maneuver)	(-25.46)	(-13.87)
ETF 2	40 [*]	18 [*]
(Valsalva)	(-30.210)	(-50.246)
ETF 3	-25.21 [#]	-14.69 [#]
(Toynbee)	49.43	58.78

#mean; *median

The distribution data of the impedance audiometry results on the prospective diver subjects before and after the pressure test in the hyperbaric chamber are shown in Table 2. The data present the descriptions of the types of tympanogram and the pressure values of the middle ear both without a maneuver (ETF 1) and with a maneuver—Valsalva (ETF 2) and Toynbee (ETF 3)—in both ears. The data provide an overview of the tympanogram type for all subjects before and after the pressure test (Type A) with an increase in the middle ear volume after the pressure test for both ears. The statistical analysis using a paired *t*-test showed no significant relationships for changes in water volume before and after the pressure test on the right $p = 0.073$ ($p > 0.05$) and left $p = 0.546$ ($p > 0.05$) ears. For the pressure values of the middle ear before the pressure test is $\text{ETF2} > \text{ETF 1} > \text{ETF 3}$ for both ears. However, $\text{ETF 2} > \text{ETF 1} < \text{ETF 3}$ for the pressure values of the middle (right) ear after the pressure test is $\text{ETF 2} < \text{ETF 3} < \text{ETF 1}$ for those of the middle (left) ear after the pressure test. Based on the data, the ETF 1 and ETF 3 values for both ears increased in the post-pressure test in comparison with these values before the test; in contrast, the ETF 2 values for both ears decreased in the post-pressure test in comparison with its values before the pressure test.

Using the Wilcoxon test to conduct a statistical analysis of ETF 1 values regarding changes before and after the pressure test in the right $p = 0.236$ ($p > 0.05$) and left $p = 0.531$ ($p > 0.05$) ears showed no significant relationship. Statistical analysis with the Wilcoxon test of ETF 2 values regarding the changes before and after the pressure test also showed no significant relationships for the right $p = 0.106$ ($p > 0.05$) and left $p = 0.837$ ($p > 0.05$) ears. When a paired *t*-test was used for the statistical analysis of changes in ETF 3 values before and after the pressure test, a significant relationship was found for the right $p < 0.001$ and left $p = 0.018$ ($p < 0.05$) ears. Table 3 presents delta (Δ) values of the middle ear pressure in the prospective diver research subjects of before and after the pressure test in the hyperbaric chamber. These delta values are compared between ETF 1 and ETF 2 (Δ_1) and between ETF 1 and ETF 3 (Δ_2) for both ears.

Table 2. Distribution of middle ear pressure values for prospective divers before (B) and after (S) the pressure test in the hyperbaric chamber; ETF: Eustachian tube function

Variable	B	Right Ear		Left Ear		p-value
		S	p	B	S	
Tympanogram						
Type A	29	29		29	29	
Type B	0	0		0	0	
Type C	0	0		0	0	
Volume	1.09 [#]	1.14 [#]	0.073	1.03 [#]	1.06 [#]	0.546
(ml)	0.22	0.24		0.19	0.24	
Pressure	-5.55 [#]	6 [*]	0.001	-4 [*]	0.41 [#]	0.891
(daPa)	11.53	(-36.97)		(-78.119)	41.78	
ETF (daPa)						
ETF 1	-4 [*]	-1 [*]	0.236	4 [*]	13.72 [#]	0.531
	(-25.46)	(-68.89)		(-13.87)	57.14	
ETF 2	40 [*]	10 [*]	0.106	18 [*]	8 [*]	0.837
(Valsalva)	(-30.210)	(-500.264)		(-50.246)	(-63.192)	
ETF 3	-25.21 [#]	3.45 [#]	<0.001	-14.69 [#]	10.31 [#]	0.018
(Toynbee)	49.43	48.31		58.78	55.04	

#mean; *median

Table 3. The delta (Δ) values for pressure in the middle ear in the prospective divers before (B) and after (S) the pressure test in the hyperbaric chamber; ETF: Eustachian tube function

Variable	Right Ear		p-value	Left Ear		p-value
	B (daPa)	S (daPa)		B (daPa)	S (daPa)	
$\Delta 1$	34 [*]	8 [*]	0.099	22.90 [#]	17.45 [#]	0.642
(ETF 2-1)	(-34.215)	(-486.195)		57.38	60.22	
$\Delta 2$	-24.21 [#]	-1.14 [#]	0.006	-28.17 [#]	-3.41 [#]	0.026
(ETF 3-1)	48.71	41.93		54.23	44.93	

#mean; *median

There was a decrease in $\Delta 1$ values after the pressure test, but this did not have a significant relationship with the $\Delta 1$ values before the pressure test on both ears; conversely, the $\Delta 2$ values increased in the post-pressure test and had a significant relationship with the $\Delta 2$ values before the test. Statistical analysis of ETF 2-1 ($\Delta 1$) values using the Wilcoxon test to measure the changes before and after the pressure test obtained $p = 0.099$ ($p > 0.05$) for the right ear, and $p = 0.642$ ($p > 0.05$) was obtained from the statistical analysis of ETF 2-1 ($\Delta 1$) values using a paired t -test, which compared the changes in the left ear before and after the pressure test. Statistical analysis of changes in ETF 3-1 ($\Delta 2$) values before and after the pressure test (with a paired t -test) on the right and left ear were $p = 0.006$ ($p < 0.05$) and $p = 0.026$ ($p < 0.05$), respectively.

3.2 Discussion

A well-functioning Eustachian tube is necessary for ventilation while diving because the proper functioning of this tube allows a diver to equalize the sudden and changing pressure levels while submerged. Initial screening of the auditory system—mainly on the Eustachian tube ventilation function—needs to be carried out in the selection of prospective divers. Prospective divers also need to undergo a pressure-test examination during selection. Therefore, all prospective divers in this study were screened by impedance audiometry in an ENT examination, which is recommended by Edmonds [23], who affirms that impedance audiometry is necessary to determine the equalization ability of the diver's Eustachian tubes. A number of researchers, such as Ashton, Devine, Miyazawa (as quoted by Ozyurt [12]), Shupak [13], Uzun [14], and Bayliss [24], have conducted thorough examinations and studies on both divers and prospective divers using otoscopy and tympanometry, either by simulation in a pressurized air chamber (i.e., dry diving). In this study, impedance audiometry was used to screen 31 subjects, and changes in the pressure values of the middle ear were measured before and after the pressure test in an hyperbaric chamber at a pressure of 2.8 ata; this type of research had never before been done in Indonesia [1].

Normally, in impedance audiometry, a tympanogram is performed to examine ETF without any maneuvers, and then the subjects are required to perform the Toynbee maneuver followed by the Valsalva maneuver. According to Edmonds [2], however, it is necessary to modify the order of the tympanometric examination of prospective divers: They should be asked to perform the Valsalva maneuver after a tympanogram is taken without any maneuvers, and then they should be asked to perform the Toynbee maneuver. The Interacoustics AT 235 series of impedance audiometry is designed to allow the subject to perform the Valsalva maneuver first, followed by the Toynbee maneuver, to obtain greater shift curves for each tympanogram (through the modification or adaptation of the William test) [22,23,25]. In this study, the Interacoustics AT 235 [22], impedance audiometry was used in the examination of prospective divers, which is in accordance with Edmon procedures. The data provide an overview of the tympanogram type for all study subjects before the pressure test (Type A). Based on impedance audiometry, the ETF increased in ETF 2 and decreased in ETF 3. Previous study states that the Type A tympanogram is a diagram curve for pressure in the middle ear with good ETF. This condition shows that all study subjects at the time of examination had good ETF ventilation in both ears, which was reinforced by impedance audiometry. This study obtained ETF 1, ETF 2, and ETF 3 values for both ears, and these values were still within the normal range, according to Jerger's classification, both before and after the pressure test [26]. The pressure test in the hyperbaric chamber exposes the subject to compression and decompression pressures. Pressure compression occurs when subjects are exposed to increased pressure while diving downwards, volume decreases, and there is more negative pressure in the middle ear. Pressure decompression occurs as the diver rises to the surface, experiencing reduced pressure, increased volume, and more positive pressure in the middle ear [23,24,27]. These two phases were traversed by all subjects in our study, who were still trying to achieve equalization while in the hyperbaric chamber, as recommended in both the Valsalva and Toynbee maneuvers.

When compression occurs, the prospective diver must perform more Valsalva maneuvers than Toynbee maneuvers, and when decompression occurs as the diver comes back to the surface, the opposite is true (the diver must perform more Toynbee maneuvers than Valsalva maneuvers). The ability of the Eustachian tubes in each subject to adapt to such changes varies. These different capabilities are evident in the three research subjects in our study who could not continue with exposure to pressures up to 2.8 ata and who had to stop at a certain depth in accordance with their ability. All subjects—successful and unsuccessful—underwent decompression before returning to the surface through pressure tests [1,27]. Whether they had passed or failed the pressure test, all the subjects did not equalize immediately after the atmospheric pressure returned to normal (i.e., the post-pressure test), but they waited until the impedance audiometry examination was performed again. The pressure values were checked after this pressure test, and they were obtained at the end of the session in the form of post-decompression pressure, resulting in increased volume and pressure values in the middle ear compared to the values before the pressure test. This is evident by the increased post-

pressure volume in both ears. Volume changes in both ears both before and after the pressure test were not significant, showing that the changes did not affect the adaption ability of a prospective diver. Another observation was an increase that occurred in ETF 1 and ETF 3 values in the post-pressure test with greater values in both ears than those before the pressure test.

In ETF 2, the subjects performed a Valsalva maneuver. The amount of pressure produced by this maneuver can range from 20 to 40 mmHg. The Valsalva pressure gradient is opposite to the positive pressure gradient of the middle ear after the pressure test so that the ETF 2 value obtained after the pressure test was the result of the difference between the positive pressure of middle ear post-decompression and the positive pressure applied during the Valsalva maneuver. This condition suggests that there is a decrease in the value of ETF 2 in both ears after the pressure test. Interacoustics AT 235 [22] impedance audiometry presents a modified ETF examination based on the William test that allows for a greater shift in the pressure values of the middle ear [23] so that despite the decrease in ETF 3 values compared to ETF 2, these values may be greater than ETF 1. This occurred for ETF 3 values after the pressure test on the right ear, which decreased after the Valsalva maneuver was performed, but the ETF 3 values were still greater than the ETF 1 values in the post-pressure test. Changes in ETF 1 values before and after the pressure test on both ears were not significant. This suggests that the research subjects, in general, were able to adapt to the environment with various exposure to pressure according to their individual ability.

Decompression was the final state experienced by the subjects. After the pressure test, the changes in pressure values of the middle ear were most influenced by the Toynbee maneuver; as is evident from the ETF 2 values before and after the pressure test, which showed a change of value in both ears that was not significant, the pressure value of the middle ear before the pressure test—with the Valsalva maneuver—showed no significant difference from the pressure value of the middle ear after the pressure test for both ears. Although the Valsalva maneuver can open the Eustachian tubes in the right ear, this maneuver is not essential during the post-pressure test because it cannot open the Eustachian tube in the left ear. Consequently, the values of ETF 2 are smaller than those of ETF 1. This predicts the occurrence of inflammation in the middle ear and the Eustachian tubes. More incidences of bullous myringitis is found in the left ear than in the right ear, and the failure of three subjects in the pressure test showed similar findings.

The Toynbee maneuver, in contrast, is important in opening the Eustachian tubes of both ears after the decompression of the pressure test. This importance can be seen from the ETF 3 values of the left ear, which were smaller than both the ETF 1 values of the left ear and the ETF 2 values of the right ear. The change of ETF 3 values before and after the pressure test was significant for both ears. In this case, the ETF of a prospective diver would be generally good, and the subject would be able to adapt to existing exposure. The delta values in this study can be used to compare the differences in pressure value in the middle ear between subjects performing no maneuvers and subjects performing the Valsalva ($\Delta 1$ /ETF 2-1) and Toynbee ($\Delta 2$ /ETF 3-1) maneuvers. The delta magnitude is influenced by the magnitude of the pressure of each variable: ETF 1, ETF 2, and ETF 3. There has been no definite agreement about the delta pressure of the middle ear until now. In this research, the change of $\Delta 1$ values before and after the pressure test was not found to be significant for both ears, which showed that the subjects could still adapt to changes in environmental pressure.

This study obtained ETF 2-1 ($\Delta 1$) and ETF 3-1 ($\Delta 2$) values for both ears, which were still within a normal range after the pressure test, according to the Jerger classification, both before and after the pressure test [26]. The change in $\Delta 1$ values before and after the pressure test showed no significant differences. With the Valsalva maneuver, the pressure values of the middle ear before the pressure test showed no significant differences compared with these values after the pressure test in both ears; conversely, a statistically significant difference was found in the pressure values in both ears for the Toynbee maneuver. The significance of $\Delta 2$ showed that the ETF of the prospective divers was generally good, so the subjects could adapt to existing levels of pressure. The subjects participating in this study were all male. The subjects were recruited from military units, which provided prospective

divers with high-risk duties who were solely male. In general, this study was limited in terms of time constraints and the complexity of the examinations.

4. Conclusion

Based on impedance audiometry on the prospective divers in this research, which was conducted before and after a pressure test in an hyperbaric chamber, all pre- and post-tympanograms were classified as Type A, with pressure values of the middle ear that were still within the normal range, according to Jerger's criteria.

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