Mitigating Risks of Altitude Chamber Training

Idan Nakdimon; Oded Ben-Ari

INTRODUCTION: Altitude chambers are used for training aircrews in a hypobaric hypoxic environment to better prepare them for pressurization and oxygen malfunction incidents during flights. However, adverse effects may occur during training sessions, with decompression sickness (DCS) being a major concern. The aim of this study was to examine the risks of different adverse effects during altitude chamber trainings (ACT) in the Israeli Air Force (IAF) facility and to compare them to other training facilities.

METHODS: We retrospectively reviewed the records of 1627 individuals in the IAF who were trained in the altitude chamber between 2015 and 2019. Data regarding adverse effects and training safety were extracted. Literature review of altitude chamber trainings was performed and adverse effects rates were compared.

RESULTS: There were a total of 91 adverse effects cases in the IAF during the study period. The overall risk rate for an adverse effect was 5.59%. The most common adverse effect was middle ear and sinus barotrauma (69.3% of adverse effects cases), followed by breathing problems (14.3%) and DCS cases (9.9%).

CONCLUSIONS: Mitigating the risk for DCS should be major concern during ACT. We recommend setting a standard protocol for an ACT which includes a 45-min preoxygenation period, a maximal ascent rate of 3000 ft · min^{-1} (914 m · min^{-1}), and setting a maximum altitude of 25,000 ft (7620 m) for fixed-wing trainees.

KEYWORDS: altitude chamber, barotruama, decompression sickness, dentirogenation, hypobaric chamber, pre-oxygenation.

Nakdimon I, Ben-Ari O. *Mitigating risks of altitude chamber training*. Aerosp Med Hum Perform. 2022; 93(11):811–815.

Altitude chamber training (ACT), also known as hypobaric chamber training, for military aircrew is important for flight safety.[11] Therefore, this training is a mandatory part of the aviation physiology training syllabus for aircrew and auxiliary aircrew in the Israeli Air Force (IAF) and among other air forces. In this training, trainees are exposed to hypoxic and hypobaric environments.

ACT has several goals. The main goal of this training is to familiarize the trainees with their own combination of signs and symptoms of hypoxia. The second goal is to instruct trainees about the correct use of oxygen delivery equipment and its function of positive pressure breathing.[2] Other goals of this training are recognizing the pressure changes in hollow body organs involving trapped gases and the ability to equalize pressure in the middle ear.[5]

An altitude chamber is not free of risks and it may cause several medical adverse effects. Adverse effects during ACT can be classified as effects which result from either a change in atmospheric pressure or due to hypoxia.[7] A major adverse risk of atmospheric pressure changes during ACT is decompression sickness (DCS), which is a condition caused by the reduction in barometric pressure along with a subsequent release of nitrogen gas bubbles. DCS can cause limb or joint pain, lymph node enlargement, and cutaneous manifestations such as pruritus, tingling, or rash. These symptoms are classified as DCS Type 1. Some of the less common symptoms include the appearance of neurological (headache, visual deficit, cognitive impairment, mental status changes, sensory or motor deficit), cardiopulmonary (cough, chest pain, tachypnea, and cardiac involvement), or inner ear symptoms. These are classified as DCS Type 2.[15] Another adverse effect related to pressure changes is barotrauma, which can manifest as either middle ear pain (barotitis media), sinus pain (barosinusitis), or toothache (barodontalgia).

From the Israeli Air Force Aeromedical Center, Tel-Hashomer, Ramat Gan, Israel.

This manuscript was received for review in January 2022. It was accepted for publication in August 2022.

Address correspondence to: Idan Nakdimon, Head of Department, Aviation Physiology, Israeli Aeromedical Center, Aaron Katzir 1, Ramat Gan 5265601, Israel; nadidim@gmail.com.

DOI: https://doi.org/10.3357/AMHP.6048.2022

Hypoxia related adverse effects include hyperventilation and delayed recovery from hypoxia.

Due to the major adverse effects related with pressure changes which can generate criticism over the safety of this training, it is possible to induce hypoxic conditions in which to train aircrew, but without pressure changes (normobaric environment), using the Reduced Oxygen Breathing Device (ROBD).[10] However, ACT is still considered to be the golden standard for simulation of flight conditions.

The goal of this study was to investigate the risks for adverse effects during ACT in the IAF and to compare them with previous published data from other facilities around the world. We hypothesize that the risk rate for an adverse effect in IAF ACT would be similar to the risk rate of other facilities around the world.

METHODS

In this retrospective study we reviewed our database of ACT sessions from January 2015 to December 2019.

Subjects

The subjects of this study were all aircrew and auxiliary aircrew personnel from the IAF who trained in the altitude chamber as part of the IAF standard physiology training program between 2015 and 2019. Additional subjects were the physiology instructors (PI), who supervised the trainees in the chamber.

Equipment

All training sessions were conducted in the altitude chamber of the aviation physiology section in the Israeli Aeromedical Center (AMC). The altitude chamber was built by Vacudyne Corporation (model 9A9, Chicago Heights, IL, USA), and was reconstructed by Environmental Tectonics Corporation (ETC; Southampton, PA, USA) in 2009. The chamber is located at a height of 213.3 ft (65.0 m). Capillary oxygen hemoglobin saturation level (S_pO_2) was monitored using a standard Nonin pulse oximeter.

Procedure

All individuals who participated in the training sessions were medically qualified for all flight duties by the Israeli AMC and specifically for the training in the chamber. The IAF protocol for ACTs is presented in **Fig. 1**. The maximal altitude for the training is 25,000 ft (7620 m), with ascent and descent rates of 5000 ft · min^{-1} (1524 m · min^{-1}). Preceding the training is a 30-min preoxygenation period (also called denitrogenation) of 100% oxygen breathing.

Statistical Analysis

Cases defined by the physician supervising the training as DCS, barotrauma, hyperventilation, or delayed recovery from hypoxia were considered adverse effects. PI were not exposed to hypoxic conditions during the ACT and were, therefore, excluded from the study cohort for calculation of risk for hyperventilation and delayed recovery from hypoxia.

Total risk rate for the ACT and specific risk rates for each adverse effect were calculated. Graphs were conducted using MS-Excel ver. 2016. Significance was calculated using Chi-squared and Fisher's exact tests for comparisons between the different study groups. All statistical tests were performed using SPSS version 22 (IBM, Armonk, NY, USA). *P*-values < 0.05 were considered statistically significant.

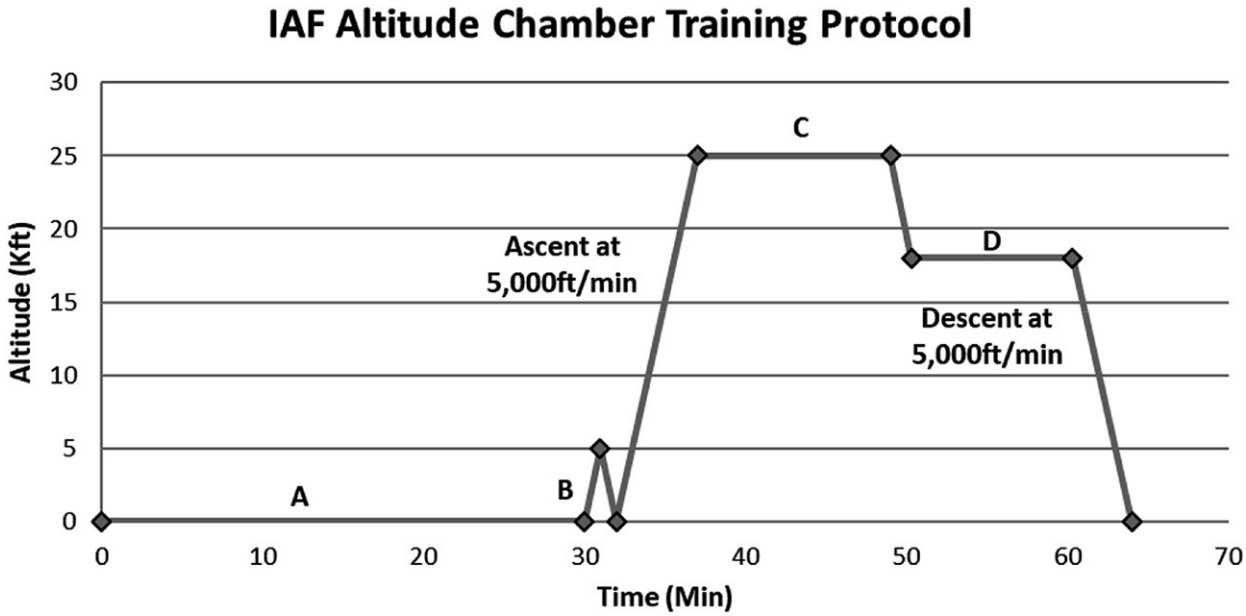

Fig. 1. Israeli Air Force altitude chamber training protocol. A) Pre-oxygenation time; B) ears and sinus pressure equalization check; C) hypoxic exposure at 25,000 ft (7620 m); D) night vision drill at 18,000 ft (5486 m).

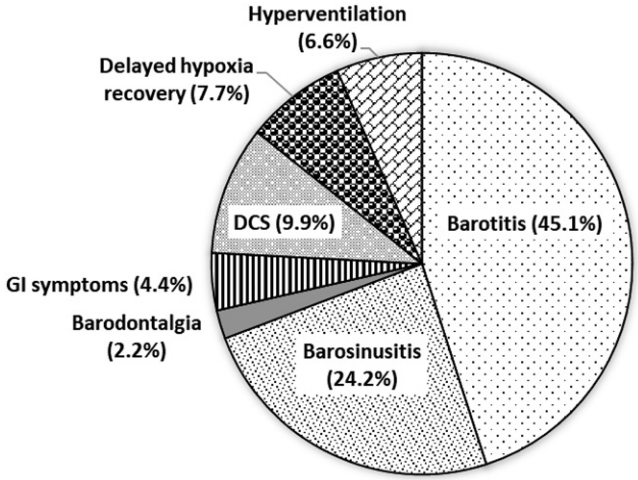

Fig. 2. The distribution of adverse effects during IAF altitude chamber training.

RESULTS

During the study period, 185 training sessions were performed with a total of 1627 individuals. A total of 91 adverse effects were recorded. The distribution of adverse effects is shown in **Fig. 2**. Barotitis was the most common adverse effect (45.1%).

The overall risk rate for an adverse effect in our facility was 5.59%. The majority of trainees were aircrew and auxiliary aircrew personnel (1263, 77.6%), and the overall risk rate for this group was 6.57%. However, the overall risk rate for an adverse effect in the PI group (364, 22.4%) was significantly lower (2.20%, $P = 0.001$). The specific risk rate for barotitis was significantly lower among PIs (0.55%) in comparison to trainees (3.09%, $P = 0.004$). The specific risk rate for DCS was equal between the two groups (0.55%). The specific risk rates for other adverse effects are presented in **Table I**.

A literature review of altitude chamber protocols and adverse effects is shown in **Table II**.[1–14] Maximum altitude in the different protocols ranged between 25,000 to 43,000 ft (7620 to 13,106 m). Rate of ascent ranged between 2000 to 5000 ft · min^{-1} (610 to 1524 m · min^{-1}). Descent rate, for the majority of the facilities, was equal or lower than the ascent rate in the same facility. The overall adverse effect risk rate varied dramatically between facilities and ranged between 1.37–11.37%. The most common adverse effect in all facilities was barotitis, with a specific risk rate ranging from 0.93 to 11.11%. DCS risk rate was less than 1% in all facilities. Overall risk rate was found to be significantly higher among our trainees in comparison to the calculated data from previous studies ($P = 0.000$), especially due to the higher risk rate for DCS in our facility ($P = 0.000$).

DISCUSSION

ACT is an important physiological training for aircrew, but nevertheless it is not risk free. In this study we analyzed our adverse effects data in a 5-yr time frame (2015–2019). We found the risk rate for an adverse effect to be 5.59%, with the most common manifestation being barotitis.

A literature review of different ACT protocols revealed substantial differences. The three parameters which dictate the risk for adverse effects are maximal altitude (ranging from 25,000 to 43,000 ft), ascent rate (ranging from 2000 to 5000 ft · min^{-1}), and descent rate [ranging from 2000 to 10,000 ft · min^{-1} (610 to 3048 m · min^{-1})]. Maximal altitude and ascent rate are related to the risk for DCS. Another parameter which may influence the risk for DCS is preoxygenation time. The standard duration is 30 min and it is usually identical throughout training facilities. Descent rate is a risk factor for barotitis and barosinusitis. The review we conducted showed a wide range of overall risk rate for an adverse effect, ranging from 1.37 to 11.37%, with the weighted average being 1.59%.[7,14]

The IAF ACT protocol is moderate regarding the maximal altitude reached (25,000 ft); however, it is relatively challenging with regard to both ascent and descent rates (5000 ft · min^{-1}). This might explain our relatively high overall risk rate for an adverse effect (5.59%).

Equalization of pressure on both sides of the tympanic membrane is needed in order to prevent barotitis. The technique improves with training and experience. Our data indeed

Table I. Risk Rates for Different Adverse Effects.

RISK RATE (%)	OVERALL RISK ($N = 1627$)	TRAINEES ($N = 1263$)	PHYSIOLOGY INSTRUCTORS ($N = 364$)	*P*-VALUE
Total	5.59	6.57	2.20	0.001
Barotrauma	4.24	4.99	1.65	
Barotitis	2.52	3.09	0.55	0.004
Barosinusitis	1.35	1.42	1.10	0.799
Barodontalgia	0.12	0.16	0	1.000
GI symptoms	0.25	0.32	0	0.581
DCS	0.55	0.55	0.55	1.000
Breathing problems	–	1.03	–	–
Delayed hypoxia recovery	–	0.55	–	–
Hyperventilation	–	0.48	–	–

GI, gastrointestinal; DCS, decompression sickness.
P-values compare trainees to physiology instructors.

Table II. Altitude Chamber Protocols and Adverse Effects in the Literature.

	HYPOBARIC CHAMBER PROTOCOLS				ADVERSE EFFECTS RISK RATE (%)							
AUTHOR	NUMBER OF PARTICIPANTS	MAXIMUM ALTITUDE (Kft)	RATE OF ASCENT TO 15,000 ft (ft/min)	RATE OF DESCENT FROM 15,000 ft (ft/min)	OVERALL	BAROTITIS	BAROSINUSITIS	BARODONTALGIA	GI SYMPTOMS	DCS	DELAYED RECOVERY FROM HYPOXIA	HYP
al-Wedyan[1]	705	25-32	4000	4000	6.10	3.97	1.70	0	0	0	0.28	0.14
Bason[2]	88,520	25-40								0.09		
Bason[3]	136,696	25	5000	2500						0.10		
Cheok[4]	3259	25	4000-RD	2000-4000						0.12		
Crowell[5]	21,423	25-43		10,000	7.87	5.75	1.12	0.12	0.06	0.32	0.42	
Davenport[6]	5851	25	5000	2500	3.30	2.31	0.43	0.05		0.21	0.05	
DeGroot[7]	23,656	29	2000	2000	1.37	0.93	0.16	0.03	0.01	0.12	0.01	
Ercan[8]	7272									0.11		
Morgagni[10]	1241	25-43	4000	2500	2.60	1.53	0	0	0.16	0.08		
Morgagni[9]	314	25-35	4000	2500		11.10						
Ohrui[11]	58,454	43		5000	6.29	4.79	0.86	0.03	0.34	0.05	0.08	0.08
Piwinski[12]	12,408	25								0.10		
	1380	35								0.36		
	757	45								0.40		
Rice[13]	28,094	25	5000	2500						0.26		
	8823	35	5000	2500						0.19		
Valdez[14]	1725	25	2000	2000	7.71	6.14	1.10	0	0.06	0		0.17
	3034	29	3000	2000	11.37	8.17	2.67	0.20	0.16	0		0.10
Weighted risk rate					1.59	4.12	0.79	0.05	0.19	0.13	0.17	
Current study	1627	25	5000	5000	5.59	2.52	1.35	0.12	0.25	0.55	0.55	0.47

GI, gastrointestinal; DCS, decompression sickness; HYP, hyperventilation; RD, rapid decompression.

show lower risk for barotitis in the PI group, who are more trained and experienced in the technique of pressure equalization. In spite of our relatively high descent rate, our risk rate for barotitis is low (2.52%) compared with the literature weighted risk rate for barotitis (4.12%).

No doubt DCS is a major concern of ACTs and may even lead to fatalities. The risk for DCS was found to be less than 1% (weighted average of 0.13%) in all the facilities we reviewed. Our risk for DCS was found to be 0.55%, which was the highest in this series. We explain this high risk rate by the fact that the diagnosis of DCS (especially Type 1), is clinical by nature and, to some extent, subjective (as opposed to barotitis, for example). A high index of suspicion is warranted, in our opinion, due to the risks posed by this syndrome. The proximity of a hyperbaric chamber facility may be another consideration, leading to possible over-diagnosis.

In light of our relatively high risk rate for DCS, we have decided to implement some precautionary measures in order to mitigate this risk. We started extending the preoxygenation time from 30 to 45 min. Additionally, we decreased the ascent rate from 5000 ft · min^{-1} (1524 m · min^{-1}) to 3000 ft · min^{-1} (914 m · min^{-1}). We also lowered the maximum altitude of an ACT for rotary-wing platform trainees (both aircrew and auxiliary aircrew) from 25,000 ft (7620 m) to 13,000 ft (3962 m), as there is no operational scenario in which this platform reaches 25,000 ft. We did not change our descent rate (which is relatively high), due to the fact that no excessive risk rate for barotitis was noticed. We also started monitoring our trainees using pulse-oximetry throughout the hypoxic exposure. Following the implementation of these precautionary measures, we experienced no DCS events in trainees over the last 18 mo.

The limitations of this study are the relatively small cohort size, the lack of objective criteria for the diagnosis of some of the above mentioned adverse effects, and the absence of a standard protocol for ACT, which makes comparison between risk rate ratios more difficult.

In conclusion, mitigating the risk for DCS should be a major concern during ACT. This goal can be achieved by extending the preoxygenation period, reducing the ascent rate, and limiting the maximum altitude of the training where possible. We recommend setting a standard protocol for an ACT which includes a 45-min preoxygenation, a maximal ascent rate of 3000 ft · min^{-1}, and limiting the maximum altitude to 25,000 ft for fixed-wing trainees.

ACKNOWLEDGMENTS

Financial Disclosure Statement: The authors have no competing interests to declare.

Authors and Affiliation: Idan Nakdimon, M.Sc., and Oded Ben-Ari, M.D., M.H.A., The Israeli Air Force Aeromedical Center, Tel-Hashomer, Ramat Gan, Israel.

REFERENCES

1. al-Wedyan IA, Shahin BH, Abu Ghosh HM, al-Aqqad SS, al-Qura'an MS. Physiological training in Jordan. Aviat Space Environ Med. 1996; 67(9): 882–884.
2. Bason R, Pheeny H, Dully FE Jr. Incidence of decompression sickness in Navy low-pressure chambers. Aviat Space Environ Med. 1976; 47(9):995–997.
3. Bason R, Yacavone D. Decompression sickness: U.S. Navy altitude chamber experience 1 October 1981 to 30 September 1988. Aviat Space Environ Med. 1991; 62(12):1180–1184.
4. Cheok LJ, Ying Goh BL, Soh FW, Boon Chuan BT. Decompression illness incidence and hypoxia symptoms after prebreathing in hypobaric hypoxia training. Aerosp Med Hum Perform. 2021; 92(5):289–293.
5. Crowell LB. A five-year survey of hypobaric chamber physiological incidents in the Canadian Forces. Aviat Space Environ Med. 1983; 54(11):1034–1036.
6. Davenport NA. Predictors of barotrauma events in a Navy altitude chamber. Aviat Space Environ Med. 1997; 68(1):61–65.
7. DeGroot DW, Devine JA, Fulco CS. Incidence of adverse reactions from 23,000 exposures to simulated terrestrial altitudes up to 8900 m. Aviat Space Environ Med. 2003; 74(9):994–997.
8. Ercan E, Demir AE, Sabaner E, Toklu AS. Incidence of decompression sickness in hypobaric hypoxia training. Undersea Hyperb Med. 2020; 47(2):203–210.
9. Morgagni F, Autore A, Landolfi A, Ciniglio Appiani M, Ciniglio Appiani G. Predictors of ear barotrauma in aircrews exposed to simulated high altitude. Aviat Space Environ Med. 2012; 83(6):594–597.
10. Morgagni F, Autore A, Landolfi A, Torchia F, Ciniglio Appiani G. Altitude chamber related adverse effects among 1241 airmen. Aviat Space Environ Med. 2010; 81(9):873–877.
11. Ohrui N, Takeuchi A, Tong A, Ohuchi M, Iwata M, et al. Physiological incidents during 39 years of hypobaric chamber training in Japan. Aviat Space Environ Med. 2002; 73(4):395–398.
12. Piwinski S, Cassingham R, Mills J, Sippo A, Mitchell R, Jenkins E. Decompression sickness incidence over 63 months of hypobaric chamber operation. Aviat Space Environ Med. 1986; 57(11):1097–1101.
13. Rice GM, Vacchiano CA, Moore JL Jr, Anderson DW. Incidence of decompression sickness in hypoxia training with and without 30-min O2 prebreathe. Aviat Space Environ Med. 2003; 74(1):56–61.
14. Valdez CD. Ten-year survey of altitude chamber reactions using the FAA training chamber flight profiles. Aviat Space Environ Med. 1977; 48(8): 718–721.
15. Vann RD, Butler FK, Mitchell SJ, Moon RE. Decompression illness. Lancet. 2011; 377(9760):153–164.