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DECOMPRESSION SICKNESS RATES IN USAF ALTITUDE CHAMBER TRAINING *BEFORE* AND *AFTER* CHANGING THE PEAK ALTITUDE FROM 43,000 FEET TO 35,000 FEET

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14. ABSTRACT
Each year, many aircrew members undergo altitude chamber training as part of their duty requirements. While necessary to trainees' understanding of reduced pressure environments, they do risk developing decompression sickness (DCS). Examining DCS incidence is important in evaluating training safety. In 1998, peak training altitude was decreased from 43,000 feet to 35,000 feet. General opinion, at the time, held that DCS risk would fall as well as DCS incidence. This study evaluated the overall incidence of DCS in trainees before and after the change. Data collected included chamber flight profile, altitude of DCS onset, and severity of symptoms; the data were collected from the AF Form 361 (Chamber Reactor Form). Cases of DCS from 1997-2000 were counted and classified as Type 1 or Type 2. Incidence rates (DCS cases per total exposures) prior to and following the change were calculated. There was no significant difference in the overall DCS incidence rates and there was no significant difference in the incidence rates of Type 1 or Type 2 DCS. The overall relative risk of DCS after the change was 1.3 ($p = 0.24$), while the relative risk of Type 1 DCS and Type 2 DCS was 1.2 ($p = 0.45$) and 1.6 ($p = 0.30$), respectively. Contrary to general opinion, the drop in peak altitude did not affect DCS rates. Explanation lay in the profiles themselves. Profile overlays, profile area-under-the-curve comparisons, and Altitude DCS Risk Assessment Computer analyses found no substantial exposure differences between training profiles, thus validating the DCS incidence rates found. This methodology may well prove useful in creating and/or customizing future altitude chamber training profiles.

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1.0 EXECUTIVE SUMMARY

Each year, many aircrew members undergo altitude chamber training as part of their duty requirements. While necessary to trainees' understanding of reduced pressure environments, they do risk developing decompression sickness (DCS). Here, DCS being the evolution of venous gas emboli from decompression of supersaturated tissues as opposed to the sudden efflux of arterialized air from pulmonary barotrauma. Examining DCS incidence is important in evaluating training safety. In 1998, peak training altitude was decreased from 43,000 feet to 35,000 feet. General opinion, at the time, held that both DCS risk and DCS incidence would fall.

This study evaluated the overall incidence of DCS in trainees before and after the change. Data collected included chamber flight profile, altitude of DCS onset, and severity of symptoms; the data were collected from the AF Form 361 (Chamber Reactor Form). Cases of DCS from 1997-2000 were counted and classified as Type 1 or Type 2. Incidence rates (DCS cases per total exposures) prior to and following the change were calculated.

There was no significant difference in the overall DCS incidence rates and there was no significant difference in the incidence rates of Type 1 or Type 2 DCS. The overall relative risk of DCS after the change was 1.3 ($p = 0.24$), while the relative risk of Type 1 DCS and Type 2 DCS was 1.2 ($p = 0.45$) and 1.6 ($p = 0.30$), respectively. Contrary to general opinion, the drop in peak altitude did not affect DCS rates.

Explanation lay in the profiles themselves. Profile overlays, profile area-under-the-curve comparisons, and Altitude DCS Risk Assessment Computer analyses found no substantial exposure differences between the training profiles, thus validating the DCS incidence rates found. Furthermore, when conjoined, these techniques appear to offer up a methodology that may well prove a powerful tool for creating and/or customizing future chamber training profiles, all the while keeping DCS risk in mind. However, without prospective validation, the methodology remains speculative.

2.0 INTRODUCTION/BACKGROUND

Decompression sickness (DCS) occurs when gases in the body are no longer held in solution due to a decrease in ambient, or surrounding, pressure. It results from ascent while flying or after diving; research has shown that the most serious cases of DCS occur in individuals who dive and then fly within 12-48 hours. (**Vann, 1993**) Symptoms of DCS generally range from the mild, such as joint pain or skin paresthesias (aka Type 1), to more serious symptoms including difficulty breathing, headache, mental confusion, reduced/impaired vision, or vertigo (aka Type 2). (**Golding, 1960; Vann, 1993**)

Aviators and other aircrew trainees are regularly exposed to reduced pressure in the chamber training environment to familiarize themselves with the hazards of high-altitude flight, most specifically hypoxia. Such training has proven effective. In fact, over an 11-year period, a full 25 of 29 aircrew (86%) either recognized they were hypoxic or recognized someone else was hypoxic. (**Cable, 2003**)

The physiological effects of altitude exposure are common and can vary greatly, ranging from relatively benign to clearly serious, even to life-threatening. Among these hazards are barotraumas, trapped gases, hypoxia, and hyperventilation. Ear pain (3.5-5.7%), sinus pain (0.9-1.5%), tooth pain ($\leq$ 0.1%), abdominal discomfort (0.1-0.3%), and hypoxia/hyperventilation (0.1-0.4%) are most commonly reported. (**Crowell, 1983; Al-Weydan, 1996; Ohrui, 2002**) But, it is DCS that is the most serious hazard, ranging from 0.01-0.7%. (**Furry, 1973; Bason, 1976; Davis, 1977; Piwinski, 1986; Weien, 1990; Bason, 1991; Ohrui, 2002; Rice, 2003; Smart, 2004**) In order to minimize the DCS threat, prior to any chamber training flight, trainees and inside observers breathe 100% oxygen over a 30-minute denitrogenation period (aka prebreathe).

Several factors increase the risk of altitude DCS. Most important among them are peak altitude, duration of exposure, prebreathe, and exercise at altitude. (**Webb; 2001; Pilmanis, 2001; Pilmanis, 2004**) Thus, it seems reasonable that a reduction in peak altitude and/or duration at altitude would cut the incidence of DCS. In 1998, the United States Air Force (USAF) dropped the peak training altitude from 43,000 feet to 35,000 feet and the time above 25,000 feet was reduced. General opinion, at that time, anticipated a lowered risk of DCS with a follow-on fall in the incidence of DCS.

This study sought to confirm that general opinion by examining DCS rates immediately before and after the policy change.

3.0 METHODS

This retrospective study evaluated the 2-year incidence of DCS associated with USAF chamber training profiles immediately before and after the policy change. The general policy change eliminated the *old* 43,000-feet profile (**Figure 1**) and modified the *old* 35,000-feet profile (**Figure 2**), the result being a single *new* 35,000-feet profile (**Figure 3**). The *new* profile no longer exposed trainees to 43,000 feet and abbreviated the duration of exposure at 35,000 feet. These changes were implemented at the end of 1998.

A pre-study power analysis estimated a sample size of ~55,000 exposures for each group (pre-change and post-change) would offer up a power of 0.80 to detect a significant ~30% change in DCS rate. Unfortunately, only two years of data were available before the change. Fortunately, the two years of data exceeded the requisite 55,000 exposures. As a result, records from the two-year time periods before and after the change were examined.

Review of AF Form 361s, maintained at the USAF School of Aerospace Medicine's Davis Hyperbaric Laboratory (DHL), for DCS case information (numerator data), to include symptoms, severity, onset altitude, and trainee status was performed. A DCS case was defined as a training chamber exposure to any altitude which generated DCS symptoms and was treated as DCS by the attending flight surgeon (essentially, the generation of an AF Form 361). The severity of a DCS case was also determined. Type 1 DCS was defined as pain in the joints or skin manifestations, such as rash, itching, non-specific paresthesias, or pain. Symptoms involving neurological, pulmonary, or cardiovascular systems were classified as the more serious Type 2 DCS. These criteria are in keeping with the conventional classification of DCS. (**Golding, 1960; Vann, 1993**)

USAF altitude chamber training monthly reports provided the total number of exposures (denominator data) for the years in question. Only data from training flights were included. Since interest was limited to the training environment, DCS cases resulting from both operational aviation and research were excluded. In fact, published research suggests that DCS risk for operational aircrew and research subjects may well be different from that of trainees and chamber personnel (**Weien, 1990; Krause, 2000; Hundemer, 2012**).

Each training unit's monthly report was used to determine the number of exposed trainees. There were 17 to 20 locations providing reports, varying from year-to-year. This variance was not considered an issue because the number of Air Force personnel requiring annual training is fixed and does not change regardless of the number of units available to provide training.

Although the original plan was to include the chamber personnel (aka inside observers), this proved difficult. While 13 cases of DCS were documented for inside observers, no solid denominator data was readily available because the chamber training profile information was incomplete or unavailable in almost all cases and the exact number of exposures was indeterminable. In other words, inside observers exposed in a given month could be determined, but the specific chamber training profile and number of exposures could not.

Other data inconsistencies were also encountered; however, most were resolved with detailed review of the monthly report. If the inconsistency could not be resolved, the data was excluded from the study. Several mismatches were noted when comparing DCS cases reported to DHL with those in the monthly reports. In those cases, the DHL data was favored, in keeping with the protocol parameters.

The null hypothesis, contrary to general opinion, asserted that the policy change would have no impact on the incidence rates of DCS in trainees. Continuous variables were described by mean (standard deviation) while categorical variables were described by number (percent). Comparison between groups used t-tests and chi-square tests as appropriate. Statistical significance was set *a priori* at $p < 0.05$. Throughout the study, data were cleaned, merged, and analyzed using IBM SPSS Statistics for Windows, Version 20.0 (Armonk, NY: IBM Corp).

Of note, this research was conducted by one of the authors (MLH) in partial fulfillment of the requirements for a Master of Public Health degree from the Uniformed Services University of the Health Sciences (USUHS) and was approved by the USUHS Institutional Review Board.

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4.0 RESULTS

Both the overall incidence of DCS and the incidence of Type 1 and Type 2 DCS, in trainees, do not appear different from before the change to after it. The 2-year incidence of DCS for trainees before the policy change was 38 cases in 57,366 exposures, or 0.00066. The 2-year incidence for trainees after the policy change was 50 cases in 58,737 exposures, or 0.00085. Relative risk for trainees after the change was 1.29; however, that difference did not prove significant (chi square = 1.37, p = 0.242). Thus, the null hypothesis was affirmed. See **Table 1** for details.

Table 1. Comparison of 2-Year Incidence Rates of Overall DCS

Decompression Sickness Incidence Rates					
Year	**Cases of DCS**	**Exposures**	**2-Year Incidence**	**Estimated Cases per 100,000 Exposures**	**Relative Risk**
1997	17	28,290	0.00060	60	
1998	21	29,046	0.00072	72	
Before the Change	**38**	**57,366**	**0.00066**	**66**	**1.3**
1999	35	30,756	0.00114	114	
2000	15	27,981	0.00054	54	
After the Change	**50**	**58,737**	**0.00085**	**85**	

Note: The difference in rates proved not significant (chi square = 1.37, p = 0.242).

Interestingly, there was a single chamber flight in 1999 that generated 9 DCS cases. There was no reason to eliminate these cases, as clusters of DCS do occasionally occur. (**Butler, 2002**) The trainees' clinical picture indicated DCS and the post-incident investigation reported no issues with chamber operation before, during, or after the incident. However, had that particular chamber flight not generated 9 cases, but rather had generated the more common single case, the relative risk becomes ~1.09 (chi square = 0.12, p = 0.733). Or, simply excluding that exposure and its 9 cases of DCS as an outlier, the relative risk becomes ~1.06 (chi square = 0.05, p = 0.816). For all intents and purposes, the cluster has very little impact on the statistical results.

Turning to DCS severity, the 2-year incidence of Type 1 DCS in trainees before the policy change was 30 cases in 57,366 exposures, or 0.00052, and after the change, 0.00063. The 2-year incidence of Type 2 DCS in trainees before the policy change was 8 cases in 57,366 exposures, or 0.00014, and after the change, 0.00022. The relative risk for Type 1 DCS after the policy change was 1.21 (chi square = 0.58, p = 0.448). Similarly, the relative risk for Type 2 DCS after the policy change was 1.57 (chi square = 1.08, p = 0.299). See **Table 2** for details.

Table 2. Comparison of 2-Year Incidence Rates of Type 1 and Type 2 DCS

Type of Decompression Sickness Incidence Rates					
DCS Type 1	**DCS**	**No DCS**	**2-year Incidence**	**Estimated Cases per 100,000 Exposures**	**Relative Risk**
Before the Change	30	57,366	0.00052	52	**1.2**
After the Change	37	58,737	0.00063	63	
DCS Type 2	**DCS**	**No DCS**	**Point Prevalence**	**Estimated Cases per 100,000 Exposures**	**Relative Risk**
Before the Change	8	57,366	0.00014	14	**1.6**
After the Change	13	58,737	0.00022	22	

Note: The difference in rates of Type 1 and Type 2 DCS, before and after the policy change, proved not significant (chi square = 0.58, p = 0.448 and chi square = 1.08, p = 0.299, respectively).

5.0 DISCUSSION

In the USAF, cases of DCS resulting from operational flight are uncommon, often concealed by career-protective under-reporting. Of DCS cases treated with hyperbaric oxygen therapy (HBO), Davis et al reported 14 of 145 cases (~10%) from operational flights, Weien and Baumgartner 21 of 528 cases (~4%), and Butler et al 42 of 480 cases (~9%). (**Davis, 1977; Weien, 1990; Butler, 2001**) Over those several decades, the operational flight risk has been remarkably stable despite an apparent rise in risk with operations involving high altitude airdrop, unpressurized flight (e.g., CV-22), or high altitude flight in airframes such as the U-2. (**Muehlberger, 2004**)

In contrast, chamber training is where DCS is most commonly reported. In the USAF, a full 93% of DCS treated with HBO originates within the altitude chamber. (**Davis, 1977; Weien, 1990; Butler, 2001**) From 1968-1986, incidence rates for USAF trainees averaged around 38 cases per 100,000 exposures. (**Bassett, 1973; Davis, 1977; Weien, 1990**) From 1959-2002, US Navy (USN) trainees averaged around 87 cases per 100,000 exposures. (**Furry, 1973; Bason, 1976; Bason, 1991; Rice, 2003**) Notably, the USAF reported cases of DCS treated with HBO, while the USN reported overall cases of DCS independent of treatment. This difference in reporting may well explain most of the difference in incidence rates, though there is some variation in altitude and prebreathe protocols. Interestingly, other countries have reported on their trainees' DCS incidence rates. Canada (1977-1981) reported 353 cases per 100,000 exposures and Australia (1984-2001) reported 387 cases per 100,000 exposures as opposed to Jordan (1986-1994), Japan (1960-1998), Italy (2003-2009), and Turkey (2010-2018) at 0, 50, 81, and 90 cases per 100,000 exposures, respectively. (**Crowell, 1983; Al-Weydan, 1996; Ohrui, 2002; Smart, 2004; Maorgagni, 2010; Ercan, 2020**) See **Table 3** for details. Canada attributed their relatively higher rates of DCS to an inadequate prebreathe, increased emphasis on reporting, and a relocation of a training site to a higher elevation (*authors' opinion*: the relocation to a higher elevation would most likely reduce the rate of DCS as the amount of baseline dissolved tissue nitrogen would be less, making nitrogen supersaturation with altitude exposure more difficult to achieve). (**Crowell, 1983; Ercan, 2020**) In any event, all chamber training DCS incidence rates were well under 1%.

Table 3. Historic Training Chamber DCS Rates in Trainees

Altitude Chamber DCS Rates						
Institution	Year	Altitude (ft)	Trainees			Source
			Exposures	Cases	Rate (%)	
USAF	1968-1972	---	337,971	42	0.012	Bassett, 1973 (in Bason, 1976)
	1973-1976	≤ 25,000	2,618	4	0.153	Davis, 1977
		> 25,000	191,586	35	0.018	
	1979-1986	≥ 35,000	601,126	348	0.058	Weien, 1990
	1980-1987	≥ 35,000	350,000	579	0.165	Neubauer, 1988
	1997-1998	≥ 35,000	57,366	38	0.066	Hancock, 2020
	1999-2000		58,737	50	0.085	
	Total*		**1,599,404**	**1096**	**0.069**	
USA	1980-1985	25,000	10,754	7	0.065	Piwinski, 1986
		35,000	1,200	1	0.083	
		45,000	642	0	0.000	
	Total*		**12,596**	**8**	**0.064**	
USN	1959-1968	≥ 30,000	252,564	266	0.105	Furry, 1973
	1972-1975	25,000 & 40,000	73,561	22	0.030	Bason, 1976
	1976-1977	25,000 & 40,000	31,645	10	0.032	Furry, 1988 (in Bason, 1991)
	1978-1981	25,000 & 40,000	47,380	39	0.082	Bason, 1982 (in Bason, 1991)
	1981-1988	25,000	111,674	78	0.070	Bason, 1991
	1998-2002	25,000	7,470	33	0.442	Rice, 2003
		35,000	7,575	13	0.172	
	Total*		**531,869**	**461**	**0.087**	
Outside the United States (Trainees)						
Country	**Year**	**Altitude (ft)**	**Exposures**	**Cases**	**Rate (%)**	**Source**
Canada	1977-1981	≥ 25,000	19,573	69	0.353	Crowell, 1983
Jordan	1986-1994	≥ 25,000	705	0	0.000	Al-Weydan, 1996
Japan	1960-1998	≥ 35,000	58,454	29	0.050	Ohrui, 2002
Australia	1984-2001	15,000	3,671	12	0.327	Smart, 2004
		25,000	6,129	22	0.359	
		45,000	912	7	0.768	
		All Australia	**10,712**	**41**	**0.383**	
Italy	2003-2009	≥ 25,000	1,241	1	0.081	Morgagni, 2010
Turkey	2011-2018	25,000	6,657	6	0.090	Ercan, 2020
	Total*		**96,101**	**145**	**0.151**	

Note: * USAF → Cases from 1968-1972, 1973-1976, 1979-1986 are HBO-treated DCS; Cases from 1980-1987 and 1997-2000 include all DCS. USA → Cases from 1980-1985 include all DCS. USN → Cases include all DCS; Prebreathe was instituted in 1984; Cases from 1998-2002 (25,000 feet) did not prebreathe. Outside the United States → Cases include all DCS. USAF (United States Air Force), USA (United States Army), USN (United States Navy), ft (feet), % (percent), HBO (hyperbaric oxygen), DCS (decompression sickness).

Even though operational and chamber DCS are infrequent, they can have serious impact. In fact, there have been 19 reported deaths; 11 were chamber-related. (**Davis, 1977; Dixon, 1992**) Fortunately, only one death has been reported since the introduction of an oxygen prebreathe period. (**Macmillan, 1999**) Remarkably, it was a 1959 chamber training case that defined the treatment of altitude DCS as recompression. In a last-ditch effort, Donnell and Norton treated a near-death pilot in a USN recompression chamber. The pilot fully recovered. (**Donnell, 1960**)

With this spectacular success, aggressive therapy with recompression and oxygen became the standard. As a result, complete resolution is now the routine (95-98%), with only rare and relatively minor residuals. (**Davis, 1997; Weien, 1990; Butler, 2001**) Indeed, in 801 cases of research chamber DCS less than 1.4% developed recurrent symptoms and there were no cases with residual. In fact, ground level 100% oxygen (GLO) proved therapeutic in over 98% of cases. (**Krause, 2000**) Similarly, Rudge reported GLO success in over 96% of training chamber cases *sans* symptoms upon return to ground level. (**Rudge, 1992**) With the more resistant and/or serious cases (that is, those treated with HBO), residual, though infrequent, is more common; Davis et al reported 2%, Weien and Baumgartner 1.5%, and Butler et al 3.5%. (**Davis, 1977; Weien, 1990; Butler, 2001**) Clearly, the risk of residual or, for that matter, death due to chamber training is very low, most likely the consequence of the natural recompression of descent and today's timeliness of treatment. (**Muehlberger, 2004**)

Ambient pressure drop, subsequent to increasing altitude, is generally considered the most important factor in development of DCS. For example, during World War II, researchers found that an increase of altitude from 30,000 feet to 38,000 feet not only brought on DCS symptoms sooner, but also upped the DCS incidence. These findings were independent of even a doubling of physical work. (**Cook, 1944**) Likewise, a series of Air Force Research Laboratory studies have demonstrated higher levels of and shorter latencies to DCS with increasing altitude, despite 1-hour prebreathes. (**Webb, 1990**) More importantly, a number of studies have exhibited this higher-altitude, higher-DCS relationship in chamber training. Piwinski et al reported such with Army chamber training as did Smart et al with Australian chamber training. (**Piwinski, 1986; Smart, 2004**) Interestingly, Rice et al did not confirm this relationship with USN chamber training; however, upon closer examination, his 25,000-feet profile trainees did not perform a prebreathe as opposed to his 35,000-feet profile trainees who did. (**Rice, 2003**) In contrast, an earlier USN look at the 25,000-feet profile, this with a prebreathe, did indeed produce lower rates of DCS than Rice et al's 35,000-feet training profile. (**Bason, 1991**) See **Table 3** for details.

With this in mind, it was expected the policy change would reduce the incidence of DCS. That did not happen. The 2-year incidence of DCS before the change proved statistically no different from the 2-year incidence of DCS after the change. Taking a critical look at the differences in each chamber training profile may provide an explanation.

Prior to the policy change, all profiles were designed to last no more than 90 minutes, required a pre-training 30-minute prebreathe period, and were designed for trainees during their first exposure to Aerospace Physiology training. The *old* 43,000-feet profile required an ascent to peak altitude followed by a rapid descent to 25,000 feet where an hypoxia demonstration occurred *en masse*. See **Figure 1**.

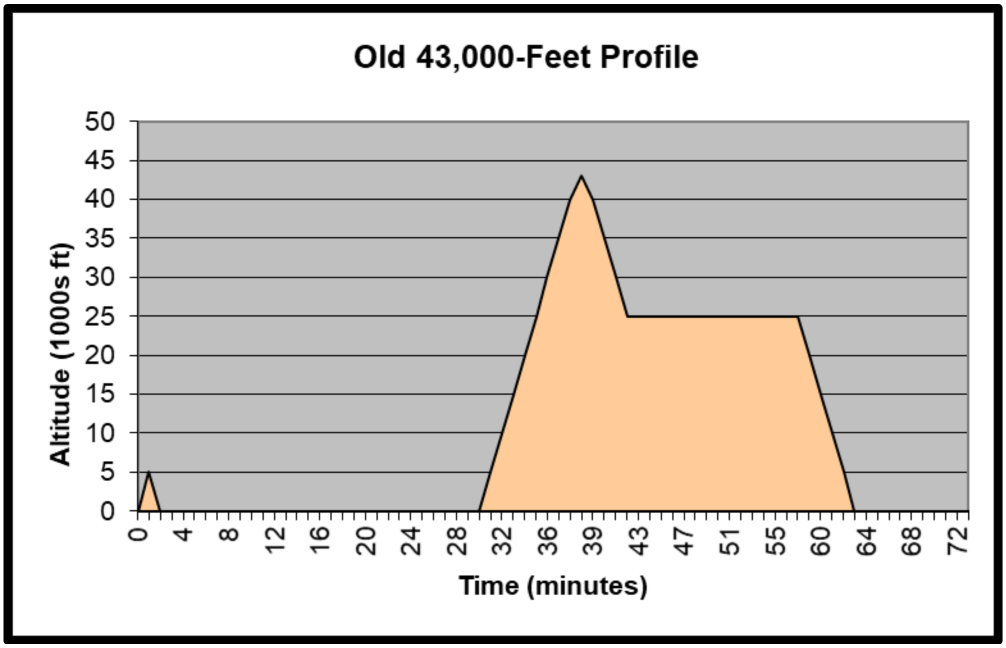


Figure 1. The *Old* 43,000-Feet Profile (Pre-1998)

The *old* 35,000-feet profile differed only slightly in that a single-trainee hypoxia demonstration occurred at peak before descent to 30,000 feet. Upon reaching 30,000 feet, another single-trainee hypoxia demonstration took place. All remaining trainees then performed hypoxia demonstrations at 25,000 feet. In the *old* 35,000-feet profile a night vision demonstration was added on descent through 18,000 feet. There was no night vision demonstration in the *old* 43,000-feet profile. See **Figure 2**.

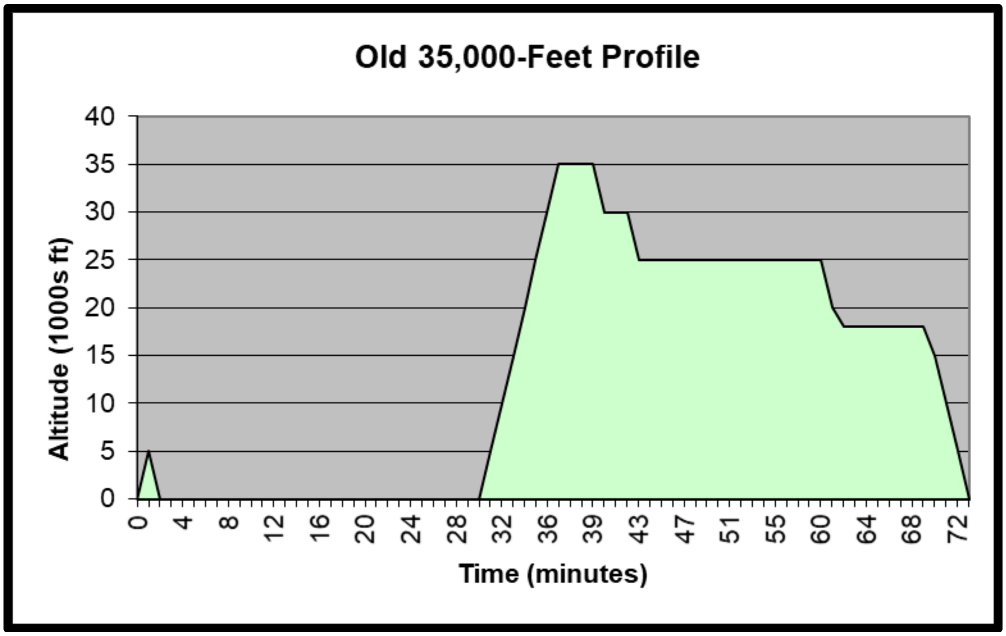


Figure 2. The *Old* 35,000-Feet Profile (Pre-1998)

After the policy change, the *new* 35,000-feet profile consisted of an ascent to 35,000 feet, followed by a descent to 25,000 feet where the *en mass* hypoxia demonstration occurred. As descent continued, there was a night vision demonstration at 18,000 feet. See **Figure 3**.

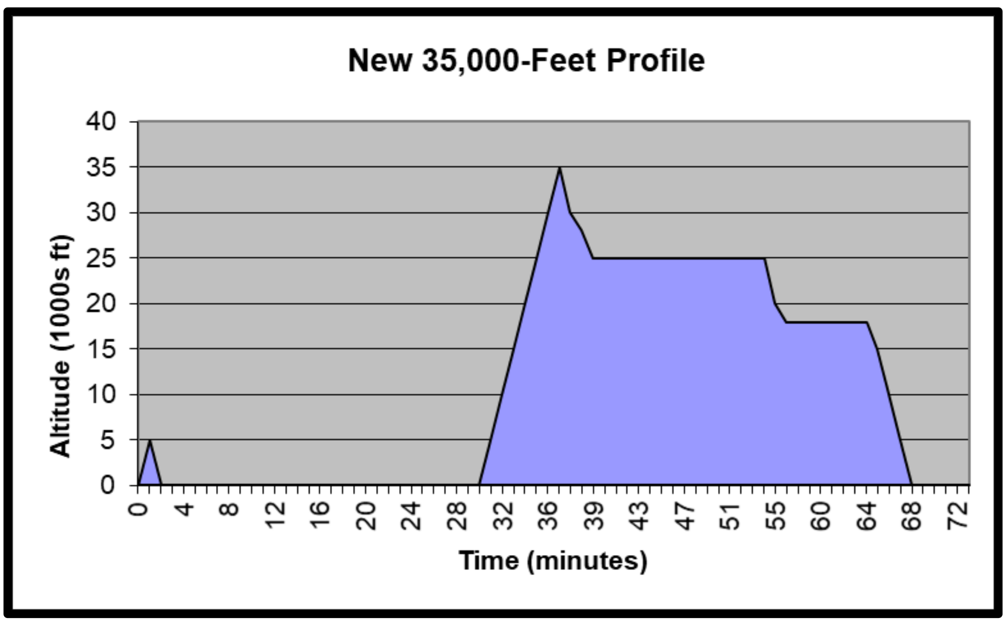
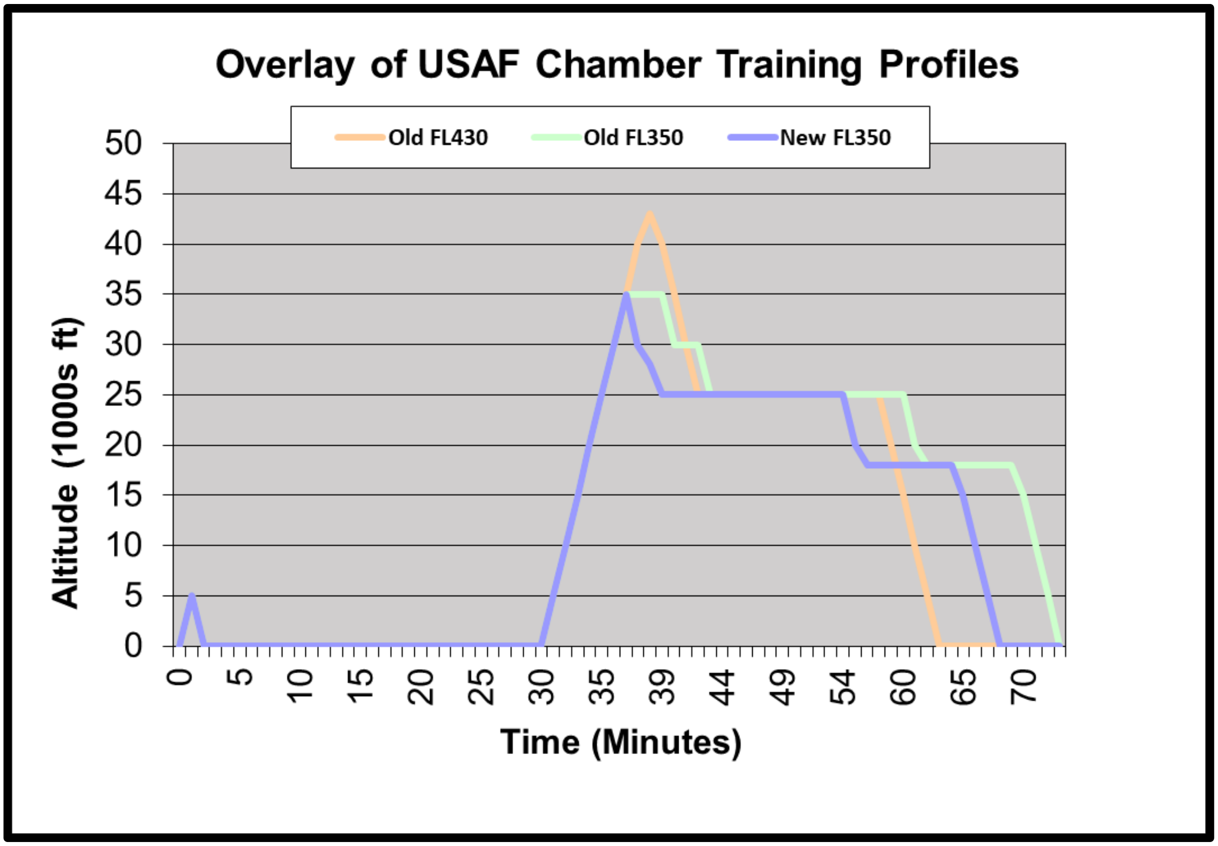


Figure 3. The *New* 35,000-Feet Profile (Post-1998)

Despite the policy change, there was no difference in the overall DCS incidence rates or the incidence rates of Type 1 and Type 2 DCS. This was probably due to the essential lack of difference between the three training profiles. First off, this was readily seen by overlaying the chamber training profiles one upon the other. The only variance between the profiles was peak altitude and terminal descent time and these differences appeared small. See **Figure 4**.



Note: USAF (United States Air Force), FL430 (43,000 feet), FL350 (35,000 feet).

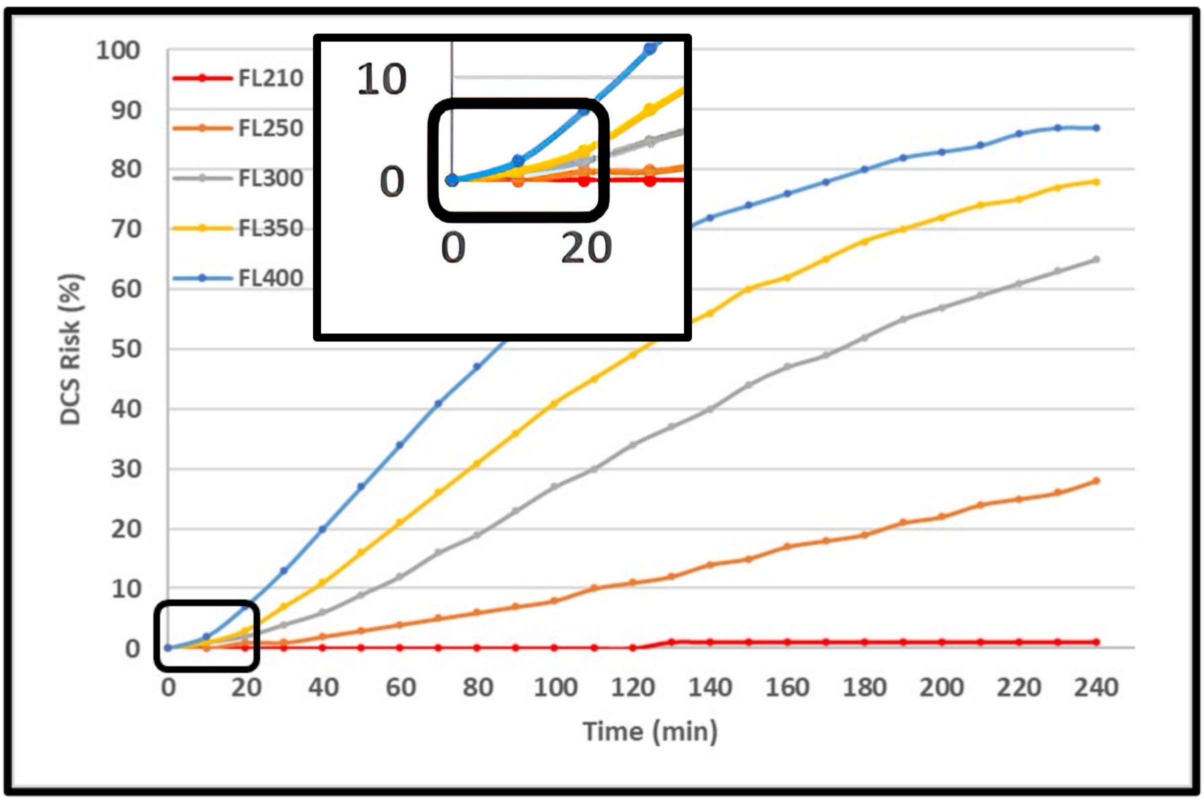
Figure 4. Overlay of Chamber Training Profiles (*old* and *new*)

Second, examining the areas-under-the-curve encompassed by each profile revealed little difference. The *old* 43,000-feet profile area was 96% that of the *new* 35,000-feet profile; the *old* 35,000-feet profile was 121% of the *new* profile. As the areas-under-the-curve are not experimental data, statistical comparison of them is not really applicable; however, as an exercise, the t-test of independent means was applied to the areas-under-the-curve using each minute of the chamber training profiles as a feet-minute data-point. For example, the data-point of 43,000 feet at minute 39 was depicted as 43 feet-minutes. Comparing the areas-under-the-curve in this way found no statistical difference between the *old* chamber training profiles and the *new* one (*old* 43,000-feet profile versus *new* 35,000-feet profile: $t(63,68) = -0.310$, $p = 0.757$; *old* 35,000-feet profile versus *new* 35,000-feet profile: $t(73,68) = -0.693$, $p = 0.489$). Since the experimental, zero-prebreathe 5% DCS threshold appears to be 20,500 feet, looking at the areas-under-the-curve specifically above 20,000 feet seemed reasonable. (**Webb, 1998**) The *old* 43,000-feet profile area was 122% and the *old* 35,000-feet profile was 133% of the *new* 35,000-feet profile. Area-under-the-curve comparison once again suggested no significant difference (*old* 43,000-feet profile versus *new* 35,000-feet profile: t(26,22) = -1.48, p = 0.145; *old* 35,000-feet profile versus *new* 35,000-feet profile: t(27,22) = -1.18, p = 0.244).

Third, applying the Altitude DCS Risk Assessment Computer (ADRAC) to the chamber training profiles did not expose serious DCS risk differences. The ADRAC was built from a database of 2,500^{+} experimental exposures into a combined loglogistic statistical and bubble growth deterministic model. It was then prospectively validated with 150 subjects. (**Pilmanis, 2001; Pilmanis, 2004**) The primary predictive variables were altitude, exposure time, prebreathe time, and exercise at altitude.

All trainees were at rest and all performed a 30-minute prebreathe. Each chamber training profile's altitude-plateau was modeled for risk; the altitude-plateaus' risks were then added together, generating an overall profile risk. Since the ADRAC has an altitude ceiling of 40,000 feet, the 43,000-feet profile was evaluated as 40,000 feet. Granted, this made for an underestimate of ADRAC risk, but the underestimate, probably small, had to be accepted.

Comparing the ADRAC DCS risk of both the *old* 43,000-feet profile and the *old* 35,000-feet profile with that of the *new* 35,000-feet profile was illuminating. Each *old* profile's risk was < 3% while the *new* profile risk was < 2%, for all intents and purposes, no difference. See **Figure 5**.

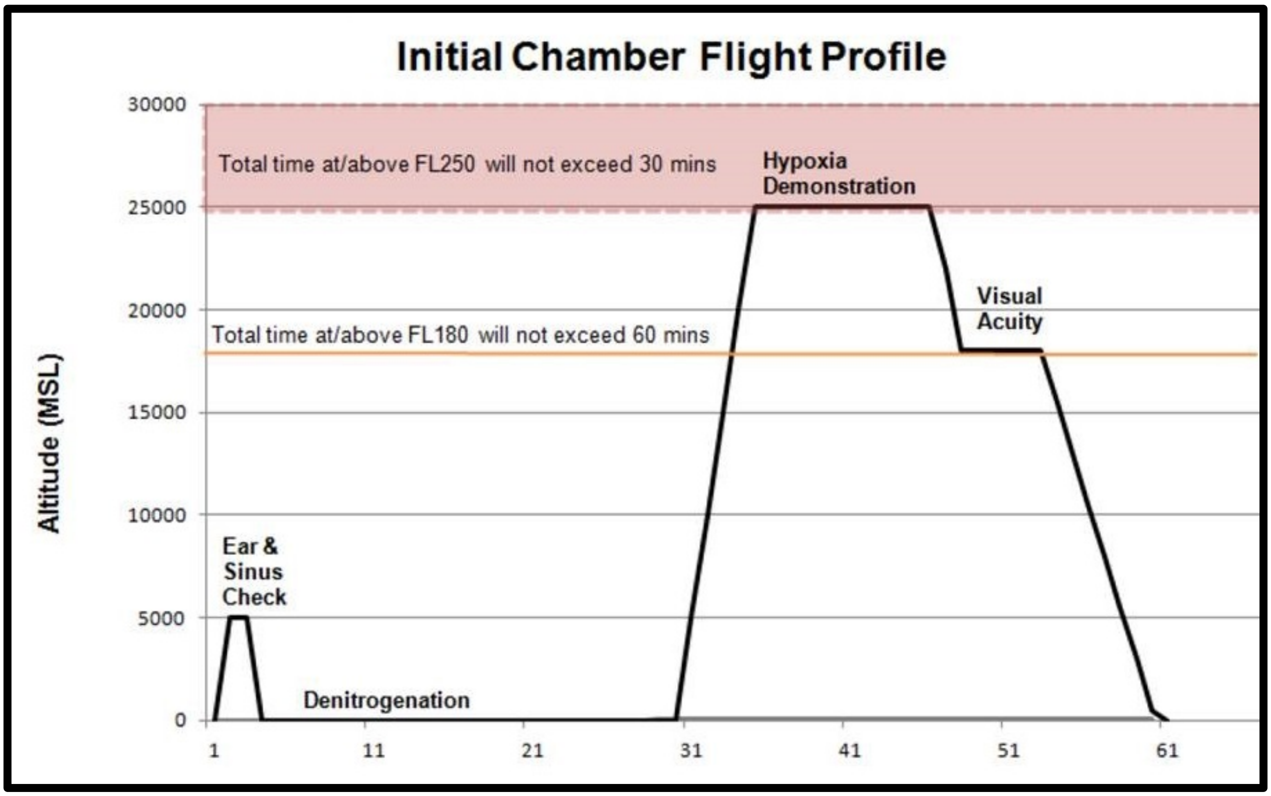


Note: This graphic was created with the direct tabular output from the ADRAC itself (prebreathe = 30-minutes and exercise = rest). The **black** rectangle denotes the time frame where the various chamber training risks originate; see enlarged insert. ADRAC (Altitude DCS Risk Assessment Computer), DCS (decompression sickness).

Figure 5. ADRAC Risk Curves for the Various Chamber Training Altitude-Plateaus

Thus, the general gestalt from the profile overlays, profile area-under-the-curve comparisons, and ADRAC analyses suggest little overall difference between training profiles. Consequently, it should not be surprising that the 2-year incidence rates of DCS, before and after the policy change, were not significantly different, nor should it be surprising that there was no significant difference in the before and after 2-year incidence rates of both Type 1 and Type 2 DCS.

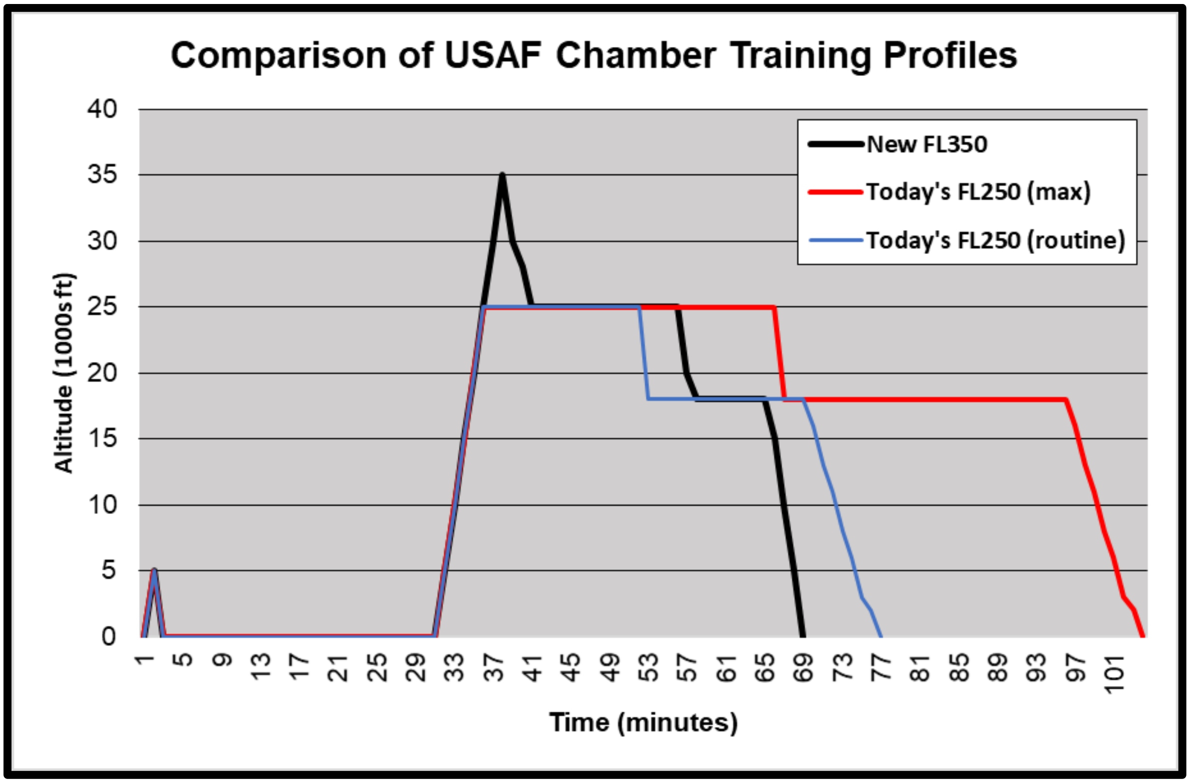
Accordingly, in order to truly reduce the incidence of chamber training DCS, it appeared requisite that peak altitude be dropped further. Indeed, this happened in October 2008; the result, *today's* 25,000-feet profile. See **Figure 6**.



Note: Graphic is taken from Aerospace Physiological Training Program Air Force Instruction, a government publication not subject to copyright. (**AFI 11-403, 2020**) MSL (Mean Sea Level), FL250 (25,000 feet), FL180 (18,000 feet), mins (minutes).

Figure 6. *Today's* 25,000-Feet Initial Chamber Training Profile

The chamber training profile peak was revised down to 25,000 feet. The time spent at that altitude was limited to 30 minutes and the time spent at or above 18,000 feet was limited to 60 minutes, making the maximum altitude duration no more than around 60 minutes. Overlay of this profile onto the *new* 35,000-feet profile reveals the primary differences to be the peak altitude and the relatively innocuous 18,000-feet segment (remember the zero-prebreathe 5% DCS threshold at 20,500 feet). See **Figure 7**. Comparison of profile areas-under-the-curve reveals little difference (*new* 35,000-feet profile versus *today's* 25,000-feet profile: $t(68,103) = 1.30$, $p = 0.197$). And, ADRAC puts *today's* 25,000-feet profile DCS risk at ~1%, not dissimilar from the *new* 35,000-feet profile's < 2%. Consequently, no change in DCS incidence would be expected. That said, *today's* 25,000-feet chamber training profile routinely stays ~16 minutes at 25,000 feet and ~17 minutes at 18,000 feet (personal communication, Lt Col Nathan B. Maertens, USAF, BSC, CAsP). Even with these abbreviated times, no serious difference in DCS risk can be identified between *today's* 25,000-feet profile and the *new* 35,000-feet profile or, for that matter, the *old* 35,000-feet chamber training profile.

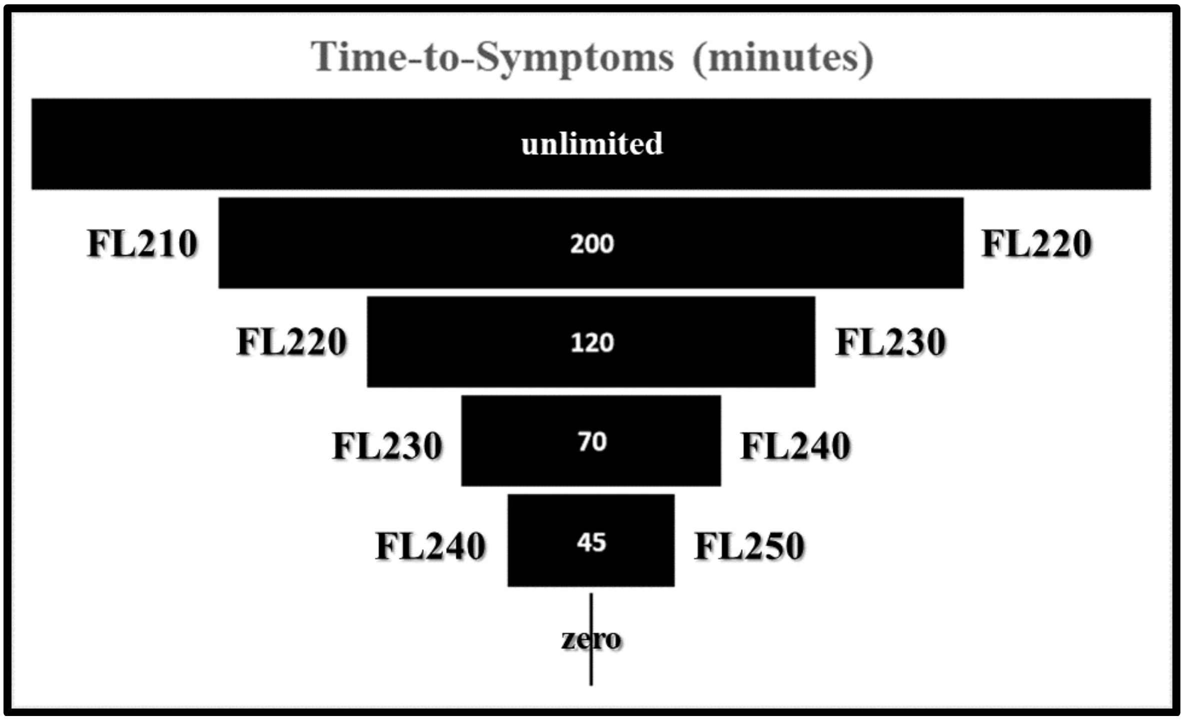


Note: *Today's* FL250 (max) refers to the maximum time at altitude per AFI. (**AFI 11-403, 2020**) *Today's* FL250 (routine) refers to the average time at altitude operationally (see the discussion above). USAF (United States Air Force), FL350 (35,000 feet), FL250 (25,000 feet).

Figure 7. Overlay of Chamber Training Profiles (*new* and *today's*)

Increasingly, the desire to eliminate DCS risk has focused attention on reduced oxygen breathing device (ROBD) training in both commercial and military aviation. (**Snyder, 2006; Mather, 2020**) Unfortunately, it is not completely clear whether the normobaric hypoxia and hypobaric hypoxia are equivalent training methodologies. (**Millet, 2012; Self, 2011; Coppel, 2015**). So, to essentially do away with DCS, yet retain the altitude experience and the at-altitude hypoxia demonstrations, transitioning to a lower chamber training profile seems a logical evolution, for instance 18,000 feet. In fact, Cable et al suggest the majority (70^{+}% in their study) of operational hypoxia is seen at or below 19,000 feet. (**Cable, 2003**) While the hypoxia demonstration would likely require more exposure time, this exposure would be at a virtually "no risk altitude." Indeed, Haske et al created a series of DCS time-to-symptom curves. Accepting a 20% DCS risk, the ADRAC predicted a zero-prebreathe symptom latency ranging from 45 to 70 to 120 to 200 minutes over a range of 1,000-foot increments from 25,000 to

24,000 to 23,000 to 22,000 to 21,000 feet, respectively. There was essentially no latency above 25,000 feet and unlimited time below 21,000 feet. (**Haske, 2002**) See **Figure 8**. These predictions are consistent with the experimental 5% DCS, zero-prebreathe threshold of 20,500 feet. (**Webb, 1998**)

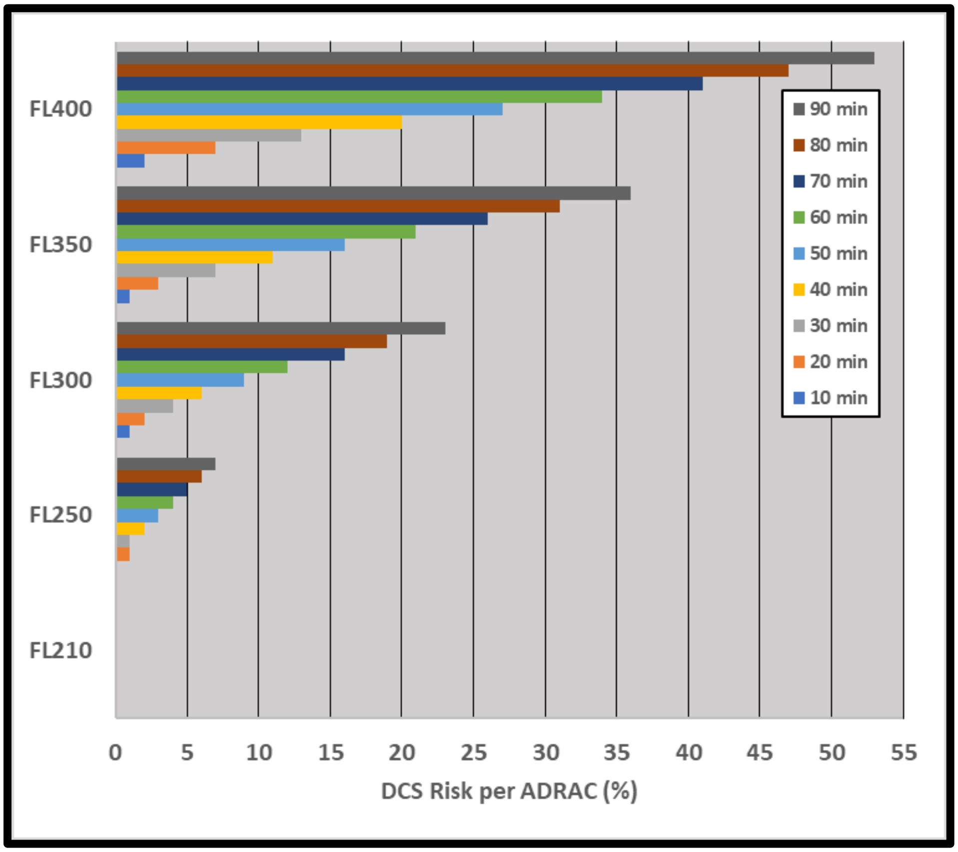


Note: This graphic was created from data presented by Haske et al. (**Haske, 2002**) Refer back to **Figure 5 →** 18,000 feet, 240 minutes, 30-minute prebreathe, and rest puts the DCS risk at 0%. FL210 (21,000 feet), FL220 (22,000 feet), FL230 (23,000 feet), FL240 (24,000 feet), FL250 (25,000 feet).

Figure 8. ADRAC Time-to-Symptom Prediction, 20% DCS Risk over 21,000-25,000 Feet

Keeping this in mind, training at 18,000 feet following a 30-minute prebreathe, all the while remaining at rest, almost guarantees the trainees little to no risk of DCS. See **Figure 5**. However, it also guarantees a lengthy exposure time. The downside with more exposure time is lapsed trainee engagement. In fact, this was observed with an Air Force 18,000-feet hypoxia chamber training profile for helicopter pilots. Even with no prebreathe, it was a challenge for inside observers to keep the trainees attentive over the entire 30 minutes (personal communication, Lt Col Nathan B. Maertens, USAF, BSC, CAsP).

To counter this sort of chamber training issue, a more tailored approach employing the ADRAC can be devised where a given DCS risk level can be defined and the various requisite training altitude-plateaus adjusted as needed. For instance, a 5% DCS risk profile requiring a 35,000-foot plateau followed by a 25,000-foot plateau and ending with an 18,000-foot plateau is deemed necessary. Ten minutes at 35,000 feet, 50 minutes at 25,000 feet, and an essentially unfettered time limit at 18,000 feet should produce a chamber training profile with no more than a 5% DCS risk. See **Figure 9**. Of course, Figure 9 can help fashion any customized chamber training profile, targeting specific training goals, mission needs, and present/future airframe capabilities. At the same time, profile overlays and profile area-under-the-curve comparisons can function as supplements to also estimate and minimize DCS risk.



Note: DCS (decompression sickness), ADRAC (Altitude DCS Risk Assessment Computer), % (percent), min (minute), FL400 (40,000 feet), FL350 (35,000 feet), FL300 (30,000 feet), FL250 (25,000 feet), FL210 (21,000 feet).

Figure 9. ADRAC-Determined Risk in an Altitude-Time Framework

6.0 LIMITATIONS

This study is retrospective research subject to the limitations any after-the-fact data collection is subject to, that is missing data, incomplete data, and/or inaccurate data. Great care was taken to optimize data quality.

The data collected was limited to trainees. Inside observers were not included because the chamber training exposure data was not reported with any consistency. That said, inside observers' data would impact overall chamber training DCS incidence rates, but not affect DCS incidence rates of the trainees, making this limitation less of an issue. In addition, the focus being trainees makes it impossible to comment on chamber-exposure/DCS-risk as related to the excess cerebral white matter hyperintensities recently found in inside observers with 50^+ exposures at > 25,000 feet. (**McGuire, 2014**) However, investigations into inside observer chamber exposure/DCS-risk are ongoing.

Using historic chamber training DCS rates as comparators was problematic. For example, Weien and Baumgartner report only DCS cases treated with HBO, contrary to those tallied here which included all DCS cases. Where possible, these differences were clearly delineated. Only appropriate comparator studies were employed in the Discussion.

Evaluating the chamber training profiles was not exact science and, as such, open to interpretation. Profile overlays, profile area-under-the-curve comparisons, and the ADRAC analyses, though none stand alone conclusively, seemed to validate one another's conclusions. When conjoined, they appear to suggest a more weighty methodology for evaluating chamber training profiles. Furthermore, they appear to offer up a means for creating and/or customizing chamber training profiles while keeping DCS risk in mind. However, without prospective validation, this methodology remains speculative.

7.0 CONCLUSION

In 1998, chamber training policy changed; peak altitude was dropped from 43,000 feet to 35,000 feet and time above 25,000 feet was reduced. Contrary to general opinion, there was no significant change in the overall 2-year incidence of DCS or that of either Type 1 or Type 2 DCS in trainees. The overall relative risk of DCS after the change was 1.3 (chi square, $p = 0.24$) while the relative risk for Type 1 DCS and Type 2 DCS was 1.2 (chi square, $p = 0.45$) and 1.6 (chi square, $p = 0.30$), respectively. The null hypothesis was affirmed.

Profile overlays, profile area-under-the-curve comparisons, and ADRAC risk analyses offer up little material difference between the three profiles, explaining the lack of material difference in the incidence of DCS before and after the policy change.

In 2008, chamber training peak altitude was once again dropped; this time from 35,000 feet to 25,000 feet. The various profile analyses suggest, once again, no material difference between chamber training profiles, predicting no difference in DCS incidence rates.

This prediction should prompt an examination of the overall incidence rates of DCS as well as the incidence rates of Type 1 and Type 2 DCS. If, indeed, no difference in DCS rates is found between the *new* 35,000-feet and *today's* 25,000-feet profiles, then a validated approach for creating and/or customizing requisite chamber training will be had.

8.0 REFERENCES

1. Air Force Instruction (AFI) 11-403, Aerospace Physiological Training Program, 30 November 2012, last update 15 April 2020. Figure A2.1, page 39.

2. Al-Weydan IA, Shahin BH, Ghosh HMA, Al-Aqqad SS, Al-Qura'an MS. Physiological training in Jordan. Aviat Space Environ Med. 1996; 67(9):882-884.

3. Bason R, Pheeny H, Dully Jr FE. Incidence of decompression sickness in Navy low-pressure chambers. Aviat Space Environ Med. 1976; 47(9):995-997.

4. Bason R and Yacavone D. Decompression sickness: US Navy altitude chamber experience 1 October 1981 to 30 September 1988. Aviat Space Environ Med. 1991; 62(12):1180-1184.

5. Bassett BE. Decompression sickness in female students exposed to altitude during physiologic training. 44th Annual Scientific Meeting of the Aerospace Medical Association, 1973. As reported in: Bason R, Pheeny H, Dully Jr FE. Incidence of decompression sickness in Navy low-pressure chambers. Aviat Space Environ Med. 1976; 47(9):995-997.

6. Butler WP, Wolf Jr EG, Krock LP. USAF experience with hyperbaric therapy of altitude decompression sickness (1941-1999). In: Operational Medical Issues in Hypo- and Hyperbaric Conditions. North Atlantic Treaty Organization, Research and Technology Organization (RTO). RTO-Human Factors and Medicine Panel Symposium, Toronto, Canada, 16-19 October 2000. RTO-MP-062 (AC/323(HFM-050)TP/34). 2001:1-1 through 1-9.

7. Butler WP. Epidemic decompression sickness: case report, literature review, and clinical commentary. Aviat Space Environ Med. 2002; 73(8):798-804.

8. Cable, G. In-flight hypoxia incidents in military aircraft: causes and implications for training. Aviat Space Environ Med. 2003; 74(2):169-172.

9. Cook SF, William OL, Lyons WR, and Lawrence JH. A Comparison of altitude and exercise with respect to decompression sickness. War Medicine. 1944; 6:182-187.

10. Coppel J, Hennis P, Gilbert-Kawai E, Grocott MPW. The physiological effects of hypobaric hypoxia versus normobaric hypoxia: a systematic review of crossover trials. Extrem Physiol Med. 2015; 4(2): eCollection (open access, accessed 28 September 2020: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4342204/pdf/13728_2014_Article_21.pdf)

11. Crowell LB. A five year survey of hypobaric chamber physiological incidents in the Canadian Forces. Aviat Space Environ Med. 1983; 54(11):1034-1036.

12. Davis JC, Sheffield PJ, Schuknecht L, Heimbach RD, Dunn JM, Douglas G, Anderson GK. Altitude decompression sickness: hyperbaric therapy results in 145 cases. Aviat Space Environ Med. 1977; 48(8):722-730.

13. Dixon JP. Death from altitude-induced decompression sickness: major pathophysiologic factors. In: Pilmanis AA. The Proceedings of the 1990 Hypobaric Decompression Sickness Workshop. Armstrong Laboratory, Brooks AFB, TX, 16-18 October 1990. AL-SR-1992-0005 (DTIC: AD-A257 612). 1992:97-105.

14. Donnell Jr AM and Norton CP. Successful use of the recompression chamber in severe decompression sickness with neurocirculatory collapse. Aerosp Med. 1960; 3(12):1004-1009.

15. Ercan E, Demir AE, Sabaner E, Toklu AS. Incidence of decompression sickness in hypobaric hypoxia training. UHM. 2020; 47(2):203-210.

16. Furry DE. Incidence and severity of altitude decompression sickness in Navy hospital corpsmen. Aerosp Med. 1973; 44(4):450-452.

17. Golding FC, Griffiths P, Hempleman HV, Paton WDM, Walder DN. Decompression sickness during construction of the Dartford Tunnel. Brit J Industr Med 1960;17:167-80.

18. Haske TL and Pilmanis AA. Decompression sickness latency as a function of altitude to 25,000 feet. Aviat Space Environ Med. 2002; 73(11):1059-62.

19. Hundemer, GL, Jersey SL, Stuart RP, Butler WP, Pilmanis AA. Altitude decompression sickness incidence among U-2 pilots: 1994-2010. Aviat Space Environ Med. 2012; 83(10):968-974.

20. Krause KM and Pilmanis AA. The effectiveness of ground level oxygen treatment for altitude decompression sickness in human research subjects. Aviat Space Environ Med. 2000; 71:115-118.

21. Macmillan AJF. Decompression illness and hyperbaric therapy. In: Ernsting J, Nicholson AN, Rainford DJ (eds.). Aviation Medicine, 3rd edition. Oxford: Arnold; 1999; 522-527.

22. Mather J. Combatting hypoxia: Robins flight prepares aircrews to recognize signs. Robins Public Affairs, 29 January 2020. (open access, accessed on 28 September 2020: https://www.robins.af.mil/News/Article-Display/Article/2068211/combatting-hypoxia-robins-flight-prepares-aircrews-to-recognize-signs/)

23. McGuire SA, Sherman PM, Wijtenburg SA, Rowland LM, Grogan PM, Sladky JH, Robinson AY, Kochunov PV. White matter hyperintensities and hypobaric exposure. Ann Neurol. 2014; 76:719-726.

24. Millet GP, Faiss R, Pialoux V; Mounier R, Brugniaux JV. Point:Counterpoint: Hypobaric hypoxia induces/does not induce different responses from normobaric hypoxia. J Appl Physiol. 2012; 112:1783-1787.

25. Muehlberger PM, Pilmanis AA, Webb JT, and Olson JE. Altitude decompression sickness symptom resolution during descent to ground level. Aviat Space Environ Med. 2004 June; 75(6):496-499.

26. Neubauer JC, Dixon JP, Herndon CM. fatal pulmonary decompression sickness: a case report. Aviat Space Environ Med. 1988; 59(12):1181-1184.

27. Ohrui N, Takeuchi A, Tong A, et al. Physiological incidents during 39 years of hypobaric chamber training in Japan. Aviat Space Environ Med. 2002 April; 73(4):395-398.

28. Pilmanis AA, Petropoulos L, Kannan N, Webb JT. Altitude decompression sickness risk prediction research. In: Operational Medical Issues in Hypo- and Hyperbaric Conditions. North Atlantic Treaty Organization, Research and Technology Organization (RTO). RTO-Human Factors and Medicine Panel Symposium, Toronto, Canada, 16-19 October 2000. RTO-MP-062 (AC/323(HFM-050)TP/34). 2001:36-1 through 36-3.

29. Pilmanis AA, Petropoulos LJ, Kannan N, Webb JT. Decompression sickness risk model: development and validation by 150 prospective hypobaric exposures. Aviat Space Environ Med. 2004; 75(9):749-759.

30. 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.

31. Rice GM, Vacchiano CA, Moore Jr JL, Anderson DW. Incidence of decompression sickness in hypoxia training with and without 30-min O_2 prebreathe. Aviat Space Environ Med. 2003; 74(1):56-61.

32. Rudge FW. The role of ground level oxygen in the treatment of altitude chamber decompression sickness. Aviat Space Environ Med. 1992; 63(12):1102-1105.

33. Self DA, Mandella JG, Prinzo OV, Forster EM, Shaffstall RM. Physiological equivalence of normobaric and hypobaric exposures of humans to 25,000 feet (7,620 m). Aviat Space Environ Med. 2011; 82(2):97-103.

34. Smart TL and Cable GG. Australian Defense Force hypobaric chamber training, 1984-2001. ADF Health. 2004; 5:3-10.

35. Snyder Q. Insight: Hypoxia training risks. Aviation safety World. 2006; 1(2): 20-21. (open access, accessed 28 September 2020: https://flightsafety.org/wp-content/uploads/2016/12/asw_aug06.pdf)

36. Vann RD, Denoble P, Emmerman MN, and Corson KS. Flying after diving and decompression sickness. Aviat Space Environ Med. 1993; 65(9):801-807.

37. Webb JT, Krutz Jr RW, Dixon GA. An annotated bibliography of hypobaric decompression research conducted at the Crew Technology Division, USAF School of Aerospace Medicine, Brooks AFB, Texas from 1983 to 1988. Brooks AFB, TX: USAF School of Aerospace Medicine; October 1988 (Revised June 1990). USAFSAM-TP-88-10R (DTIC: AD-A231 355).

38. Webb JT, Pilmanis AA, O'Connor RB. An abrupt zero-preoxygenation altitude threshold for decompression sickness symptoms. Aviat Space Environ Med. 1998; 69(4):335-340.

39. Webb JT, Krause KM, Pilmanis AA, et al. The effect of exposure to 35,000 feet on incidence of altitude decompression sickness. Aviat Space Environ Med. 2001; 72(6):509-512.

40. Weien R. and Baumgartner N. Altitude decompression sickness: hyperbaric therapy results in 528 cases. Aviat Space Environ Med. 1990; 61(9):833-836.

LIST OF ABBREVIATIONS AND ACRONYMS

ADRAC	Altitude DCS Risk Assessment Computer
CAsP	Certified, Aerospace Physiology
DCS	decompression sickness
DHL	Davis Hyperbaric Laboratory (Brooks AFB, Texas)
GLO	ground level 100% oxygen (supplemental oxygen)
HBO	hyperbaric oxygen therapy
ROBD	reduced oxygen breathing device
USA	United States Army
USAF	United States Air Force
USN	United States Navy
USUHS	Uniformed Services University of the Health Sciences