Experimental trials to assess the risks of decompression sickness in flying after diving.

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Vann RD, Gerth WA, Denoble PJ, Pieper CF, Thalmann ED. Experimental trials to assess the risks of decompression sickness in flying after diving. Undersea Hyperb Med 2004; 31(4):431-444 We conducted experimental trials of flying after diving using profiles near the no-decompression exposure limits for recreational diving. The objective was to determine the dependence of DCS occurrence during or after flight on the length of the preflight surface intervals (PFSI). One to three dives were conducted during a single day with dry, resting subjects in a hyperbaric chamber at depths of 40, 60, or 100 fsw (224, 286, 408 kPa). The dives were followed by PFSI of 3 to 17 hrs and a four-hour altitude exposure at 8,000 ft (75 kPa), the maximum permitted cabin altitude for pressurized commercial aircraft. Forty DCS incidents occurred during or after flight in 802 exposures of 495 subjects. The DCS incidence decreased as PFSI increased, and repetitive dives generally required longer PFSI to achieve low incidence than did single dives ($p=0.0159$). No DCS occurred in 52 trials of a 17 hr PFSI, the longest PFSI tested. The results provide empirical information for formulating guidelines for flying in commercial aircraft after recreational diving.

INTRODUCTION

Divers usually begin and end their dives at or near sea level (101 kPa), but they sometimes fly after diving. Most flying after diving takes place in pressurized commercial aircraft with cabin altitudes no greater than 8,000 ft (equivalent to a barometric pressure of 75 kPa by the 1976 U.S. Standard Atmosphere (1)), the maximum commercial aircraft cabin altitude permitted by the Federal Aviation Administration (2). Exposure to reduced barometric pressure after diving could increase a diver's risk of decompression sickness (DCS) unless the diver remained at sea level long enough to allow elimination of excess inert gas from tissue.

Flying after diving history

The first evidence that flying after diving increased DCS risk was found in a 1960 U.S. Navy study that tested altitude exposure as a possible method for assessing the adequacy of decompression after diving (3). The first reported operational incidents of DCS while flying after diving occurred in 1961 when the pilot and copilot aboard an intercontinental commercial aircraft at a cabin altitude of 8-10,000 ft (75-70 kPa) were incapacitated by DCS less than four hours after diving not deeper than 30 fsw (193 kPa) (4). The flight engineer, who had been diving about 12 hrs earlier, was less affected and landed the aircraft safely.

In 1967, Furry et al. provided experimental evidence indicating that DCS risk was related to the preflight surface interval (PFSI) at sea level before flying (5). They exposed dogs to 53-88 fsw (264-372 kPa) for seven hours followed by a 1, 3, 6 or 12 hour preflight surface interval (PFSI) at sea level pressure before decompression to a simulated altitude of 10,000 ft for 2 hours. Signs interpreted as DCS included scratching, limping, leg lifting, respiratory difficulty, or change in disposition. The DCS incidence was 93% with a one-hour PFSI and gradually decreased to zero as the PFSI was lengthened to 12 hours.

In 1969, Edel et al. conducted the first human trials to estimate how long divers should wait before flying (6). Dives to the U.S. Navy no-decompression limits of 15 min at 120 fsw (470 kPa) and 200 min at 40 fsw (224 kPa) (7) were followed by PFSIs of 5 min, 30 min, 1 hr, 2 hrs, or 3 hrs before an altitude exposure of 112 min at 8,000 ft and a subsequent 5 min excursion to 16,000 ft (55 kPa). The 5 min exposure at 16,000 ft was designed to provoke latent DCS should it be incipient as in the earlier Navy study (3). In 39 exposures, there were two DCS incidents at 8,000 ft after a 5 min PFSI following a 200 min dive to 40 fsw, and nine incidents at 16,000 ft after PFSIs of 5 min to 2 hrs (eight incidents after 200 min at 40 fsw and one after 15 min at 120 fsw). Edel's trials were the basis of the two-hour U.S. Navy guideline for flying after no-decompression diving that was in effect from 1985-1999 (8).

There are few other human trials of flying after diving relevant to exposures of 8,000 ft or less (9) although Balldin (10) and Bassett (11) conducted studies at somewhat higher altitudes. Balldin found no DCS in 20 trials of no-decompression dives at the U.S. Navy limits of 10 min at 130 fsw (500 kPa) or 100 min at 50 fsw (255 kPa; (12)) followed by a three-hour PFSI and a two-hour exposure at 9,843 ft (3,000 m; 70 kPa). Balldin's study may have underestimated the DCS risk because his subjects were given prophylactic hyperbaric oxygen upon descent to preclude delayed-onset DCS. Bassett investigated dives that might allow immediate ascent to altitude with low DCS risk (11). He tested two altitude exposures: (a) 10,000 ft for four hours followed by one hour at 16,000 ft; and (b) 8,500 ft (74 kPa) for four hours followed by one hour at 14,250 ft (59 kPa). His dives were based on an analysis of the U.S. Navy Standard Air Decompression Tables (12) indicating that an adjustment to the theoretical tissue ratios would compensate for reduced pressure at altitude. Dives tested were 24 hours at 10.75 fsw (134 kPa), 34 min at 40 fsw, 20 min at 60 fsw, 14 min at 80 fsw (347 kPa), 10 min at 100 fsw, and 7 min at 130 fsw. These were followed by immediate ascent to altitude. In 167 exposures, there was one DCS incident at 10,000 ft after a dive to 80 fsw, one at 14,250 ft and one 16,000 ft after dives to 60 fsw and four at 16,000 ft after dives to 10.75 fsw, 40 fsw, 60 fsw, and 100 fsw. He also monitored his subjects with Doppler ultrasound for precordial signals of venous gas emboli (VGE) and terminated the altitude exposures of nine subjects (two for 10.75 fsw, one for 40 fsw, two for 60 fsw, three for 80 fsw, and one for 100 fsw), who had Spencer VGE scores of 3 at rest or 4 with movement (13). Thus, Bassett also may have underestimated the DCS risks of flying after diving.

Current guidelines

The limited trials described above provide little basis for comprehensive PFSI guidelines, and published recommendations vary widely (8). The first flying after diving guideline was promulgated by the U.S. Navy in 1972 and recommended a 12 hr PFSI before flying after a decompression dive (14). In 1985, the recommended PFSI after no-decompression dives was decreased to 2 hrs (12). No delay was required for altitudes of less than 2,300 feet (93 kPa) based on work by Boni et al(15). The U.S. Air Force required a 24 hr PFSI after any diving in 1990 (8). In 1991, the Divers Alert Network published guidelines for recreational diving that recommended at least 12 hours before flying and longer than 12 hours after repetitive multi-day or decompression dives (16). In 1999, the Navy introduced new guidelines based on preliminary reports of the work described here (Dr. E.T. Flynn, personal communication) with PFSI ranging from 0 to 24 hours depending on the flight altitude and post-dive Repetitive Group Designator

(RGD; (17)). These guidelines were computed by applying the Cross corrections (18) to the U.S. Navy Standard Air Decompression Tables (17).

Objectives

We sought to estimate the longest PFSI that might be required before flying with low DCS risk after recreational air dives near the single and repetitive no-decompression exposure limits. We expected the 'safe' PFSI necessary to achieve low DCS risk would be longest near these limits. In addition, we sought information on how the DCS risk would change with decreasing PFSI. We conducted the study to provide further data on which flying after diving guidelines might be based.

METHODS

Subjects and medical supervision

Experiments were conducted at 2-3 week intervals with 5-12 subjects per study at the Center for Hyperbaric Medicine and Environmental Physiology of Duke University Medical Center from 1993-1999. Male and female subjects were certified recreational divers or individuals with hyperbaric or hypobaric experience. They were fully briefed and signed a Consent document that had been approved by the Duke University Medical Center Institutional Review Board. About 2% of the subjects were rejected for conditions including prosthetic joints, pulmonary dysfunction, or neurological abnormality. Subjects were required to avoid diving and strenuous activity for 48 hours before and after participation in an experiment. Subjects were allowed to participate in multiple experiments.

The subjects' physical characteristics are presented in Table 1. This table was computed by treating subjects who had made repeated experiments over several years as separate individuals to account for changing characteristics. The study was open to males and females and no effort was made to recruit divers of a particular gender. There were 495 individual subjects who completed 802 simulated flying after diving exposures. Sixteen subjects did not complete the entire dive and flight profile due to ear barotrauma or DCS developing during the PFSI. Twenty-seven percent of the subjects were female, and females made 27% of the exposures. Of subjects completing the dives and flight, 368 participated in a single trial while 127 participated in at least two or as many as 12 trials. Fifteen subjects participated in two trials of the same pressure profile, and one subject participated in three trials of the same profile.

Table 1. Subject characteristics.

	Age (years)	Weight (kg)	Height (cm)	BMI* ($kg \cdot m^{-2}$)
Male (n=594)				
Mean	36.9	83.6	175.3	25.9
S.D.	10.3	13.6	7.5	3.7
Minimum	18.0	52.2	155.0	18.0
Maximum	69.0	147.4	208.3	43.0
Female (n=224)				
Mean	33.8	64.0	165.1	23.4
S.D.	9.8	11.2	7.3	3.7
Minimum	19.0	45.3	147.3	16.0
Maximum	60.0	99.8	198.1	36.0

* Body Mass Index: weight (kg)/height $(m)^2$

Physicians experienced in the diagnosis and treatment of DCS provided medical coverage for each experiment. A physician administered a baseline interview and neurological examination before each exposure to identify pre-existing conditions that might later be confused with DCS. The same physician interviewed the subjects immediately after each dive and again at 1 and 4 hours before releasing them for the remainder of the PFSI, usually overnight. The same physician interviewed the subjects again immediately before flight. During the flight, a study attendant in the altitude chamber asked each subject at 30 min intervals if there were any symptoms to report. Subjects were encouraged to report all symptoms even if very mild or apparently unrelated to the dives or flight. The physician, who remained outside the chamber, interviewed subjects who reported symptoms to assess the possibility of DCS. Subjects with suspected DCS were recompressed to ground level for further evaluation and possible therapy. Subjects who completed the flight without symptoms were interviewed immediately after the flight, four hours post-flight, and the next morning. A study technician familiar with the signs and symptoms of DCS interviewed the subjects by telephone at about 48 hours post-flight.

Flying after diving exposure

For our simulated flight, we selected the FAA maximum cabin altitude of 8,000 ft (2). A four-hour altitude exposure was chosen based on our unpublished experience that most altitude DCS symptoms occur within four hours (19).

Preliminary trials

Prior to beginning the study, we conducted preliminary trials of a dive to 60 fsw for 55 min followed by a PFSI of three hours to assess the safety of PFSIs in the range of the two hour U.S. Navy guideline that was in effect at the time the study began (12). When these trials resulted in three cases of DCS (one cerebral; Case 13, Appendix B) and four additional cases occurred with PFSIs of 6, 9, and 10 hours, the experimental design described below was introduced.

Experimental design

A sequential experimental design was adopted to minimize the number of individuals exposed to DCS risk (20) while still finding the shortest PFSI. The diving physician diagnosed clinical DCS based on signs and symptoms at the time of occurrence, and a decision to recompress was made independently of scientific objectives. The decision to accept and continue testing or reject and suspend testing of a given dive profile/PFSI combination was made in accordance with *a priori* accept/reject criteria. These criteria, described below, were arbitrary and used only to decide when to stop testing one dive profile/PFSI combination and move to another. The criteria were not used to judge the 'safety' of any profile.

DCS was classified as mild, moderate, or serious in severity. Mild symptoms were defined as limb or joint pain and/or patches of abnormal sensation unrelated to peripheral nerve or dermatome distribution. Moderate signs or symptoms were defined as neurological findings such as specific sensory deficit or motor weakness only obvious on detailed examination. Serious signs or symptoms were defined as respiratory, cardiovascular, cerebral, motor weakness obvious to observation, or disorders of gait or balance.

A PFSI was accepted for a given dive profile if there was no clinically assessed DCS in 23 subject exposures (95% binomial upper confidence limit [BUCL] 0.122), one mild DCS incident in 35 exposures (0.128 BUCL), two in 46 (0.131 BUCL), or three in 56 (0.132 BUCL).

A PFSI was rejected if there were two mild incidents in 10 or fewer subject exposures (95% binomial lower confidence limit [BLCL] 0.037) or three mild incidents in 26 or fewer exposures (0.032 BLCL). PFSIs were also rejected if there were four mild incidents, two moderate incidents, or one serious incident at any time. (The Institutional Review Board approved one Moderate incident for the first half of the study and two Moderate incidents for the second half.)

For the first dive on a given profile, a PFSI was chosen which was expected to have a low risk of DCS based on available data. If the first PFSI met the acceptance criteria, PFSI were shortened on subsequent profiles until the reject criteria were met. Testing of that dive profile was then stopped. If the first PFSI was rejected, subsequent PFSI were lengthened until one met the accept criteria.

Definition of DCS

Since treatment decisions had to be made rapidly and in real time, we anticipated that there might be occasional false positives or negatives in equivocal cases. Therefore, all symptoms were reviewed *post hoc* and a standard definition applied in deciding if symptoms were indeed due to DCS. We chose a U.S. Navy definition of DCS that had been used in a retrospective review of 918 case reports (21). We modified this definition to accommodate flying after diving as described below.

Unless another cause could be identified such as illness, injury, or pre-existing symptoms, signs and symptoms were defined as DCS if: (a) they remained constant or showed progression within the next 10 min at 1 ata (post-dive) or with continued altitude exposure; (b) they improved or resolved with descent from altitude, oxygen breathing, or hyperbaric oxygen therapy; or (c) they resolved spontaneously after persisting for at least one hour. In addition, "marginal DCS" or "niggles" were defined as minor symptoms that persisted for less than one hour. "Skin bends" were defined as rash or itching without marbling. Recompression therapy was not given for niggles or skin bends, and these were not classified as DCS.

Upon completion of the study, all signs and symptoms were carefully reviewed under this definition with special attention to cases not considered clinical DCS at the time of the trials. DCS was attributed to diving alone if relevant signs or symptoms occurred during the PFSI. DCS that first occurred during the flight or within 24 hours after flying was attributed to the combined effects of diving and flying.

Flying after diving profiles

The diving exposures consisted of one or more simulated dives in a hyperbaric chamber with seated subjects under dry, resting conditions. Dive depths were chosen to reflect shallow, moderate, and deep recreational dives, defined as 40, 60, and 100 fsw. Dive times included descent and were generally chosen to reflect dives at or near the no-decompression exposure limits of the Recreational Dive Planner (22, 23). Four single dive profiles and five repetitive dive profiles were tested (Appendix B). A one-hour surface interval between repetitive dives was chosen to reflect common recreational diving practice. Both descent and ascent rates were 30 fsw/min, the rate used by the Navy (24) and most dive tables and computers (25). Safety stops were not used as they are not universally applied and were not used in previous flying after diving studies (3, 6, 10, 11).

The depths and times of the planned dive profiles were followed closely unless a subject had difficulty equalizing his or her ears. If equalization difficulty developed, the chamber was returned to the surface, the affected subject removed from the chamber and the dive restarted.

For analytical purposes, the time of the aborted descent was ignored. Eight dives were aborted due to ear barotrauma. The aborted dives were short and shallow with mean depths and times (±S.D.; range) of 17.5 fsw (±8.2; 7-30) and 4.3 min (±1.6; 3-7). Actual dive profiles were available from the logs or digital recordings. Only one experiment did not adhere closely to plan and was conducted with only 12 min at 100 fsw rather than the planned bottom time of 15 min (Appendix B).

The dives in each experimental trial were followed by PFSIs at the Durham, NC ground level altitude of 398 ft (nominal barometric pressure 749 mmHg or 99.9 kPa) after which the altitude exposure took place. The chamber pressure was reduced in four minutes to an altitude equivalent to 8,000 ft for four hours. The subjects were seated or resting supine while at altitude except for two deep knee-bends every 30 min during precordial Doppler monitoring. Doppler data will be reported separately.

Statistical analysis

Descriptive measures were reported as means and standard deviations for normally distributed data and as medians and Interquartile Ranges (IQR) for non-normal data.

The relationship of PFSI to DCS risk was evaluated by logistic regression implemented in SAS Version 8.0 (Cary, NC). The analysis was controlled for potentially confounding covariates such as subject characteristics, dive profile characteristics, and estimated dive profile severity. Subject characteristics tested included age, gender, height, weight, and body mass index (BMI; weight (kg)/height(m)^2). Dive profile characteristics tested included dive depth, individual dive time, total bottom time, and whether a dive profile was single or repetitive.

Using logistic regression, four measures of dive profile severity were tested for possible association with DCS. These included the PFSI in combination with: (a) the Repetitive Group Designators (RGD) according to the U.S. Navy Standard Air Decompression Tables (24); (b) the RGDs according to the Repetitive Dive Planner (22); (c) the theoretical nitrogen tensions in an exponential (half-time) tissue compartment either post-dive or at end-PSFI; or (d) DCS risks estimated either post-dive or at end-PSFI by a probabilistic decompression model from exact dive profiles (26). A p-value of 0.05 was considered significant.

The above analysis assumed identical DCS susceptibility for all subjects other than as related to reported (age, gender, weight) or computed (BMI) subject characteristics. Because some subjects participated in multiple experiments, we also conducted a repeated measures analysis using the General Estimating Equation and the General Linear Model (SAS Version 8.0) to test the hypothesis that each subject might have a unique susceptibility that was distinct and detectable from other subjects.

RESULTS

DCS after diving

The overall DCS incidence during the PFSI (i.e., before flying) was 1.4%. Two of these DCS cases had symptoms that were not reported when they first occurred, and they recurred or became worse during flight. These were attributed to DCS from the dive alone. Two cases resolved before flying, did not recur during flight, and were not reported until after symptom-free flights. These were also counted as post-dive DCS while the flights were counted as symptom-free. Nine DCS cases resolved during a single treatment (four on USN Table 6 and five on USN

Table 5), and one case had minor residual symptoms that resolved over two days after a single treatment.

Appendix A summarizes the 11 DCS cases that occurred before the flight. An additional 13 signs or symptoms were classified as niggles, 13 as skin bends, and six as not DCS. Of the 13 divers with skin bends (one rash and 12 itching, all after dives to 100 fsw, and all resolving spontaneously within one hour), one developed post-dive DCS, and none had in-flight or post-flight DCS. Six cases with limb-pain, headache, or numbness were judged to be the result of pre-existing injury or a concurrent condition rather than DCS.

DCS during or after flight

The overall DCS incidence due to flying after diving was 5.0%. The difference between male and female incidences (6.9% and 4.3%, respectively) was not significant. A repeated measures analysis found no effect for subjects who participated in multiple experiments. Eight DCS cases resolved spontaneously, three resolved during descent from altitude, 27 cases resolved during a single treatment (22 on USN Table 6 and five on USN Table 5), and two cases received an additional treatment with oxygen at 2 ata.

Appendix B summarizes the 40 subjects who reported signs and symptoms during flight or within 24 hrs after flight that were classified as DCS. An additional 24 incidents of signs or symptoms were classified as niggles, two as skin bends, and 10 as not DCS. Three subjects developed DCS twice on different flying after diving profiles. One subject had post-dive DCS and in-flight DCS during the same pressure profile. Ten cases with limb pain, back pain, abdominal pain, or bladder pressure were judged to be the result of pre-existing injury or a concurrent condition rather than DCS.

When tests of two repetitive dives to 60 fsw for 55 min with a 1 hr SI followed by 60 fsw for 30 min resulted in two post-dive DCS cases relatively early in the trials, the second dive time was reduced from 30 to 20 min. Time constraints prevented completion of testing of the single dive to 40 fsw for 120 min and for the two repetitive 40 fsw dives with a 13 hr PFSI.

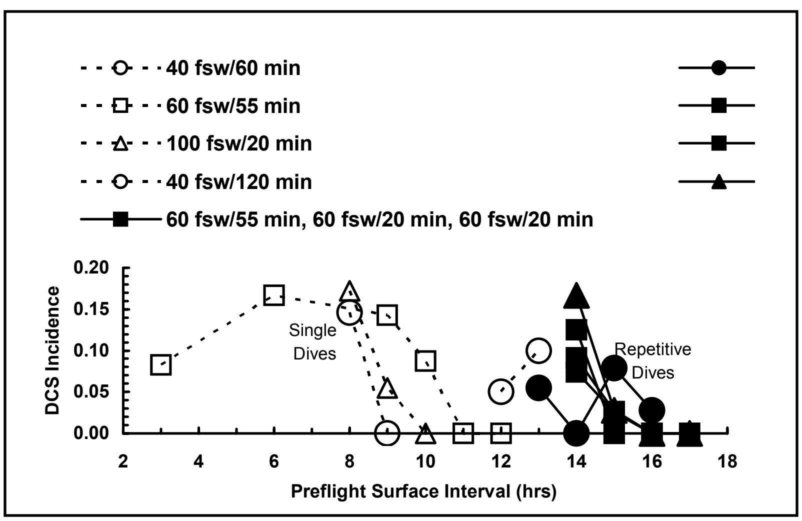

Fig. 1. Raw DCS incidence and PFSI as a result of flying after four single dive profiles and after five repetitive dive profiles.

Relationship of PFSI to DCS

Figure 1 shows the observed DCS incidences during or after flight for each flying after diving profile as a function of PFSI. For all single dives (except 40 fsw for 120 min not completed due to time constraints) the DCS incidence decreased to zero after a PFSI of 9-12 hours. For repetitive dives, the DCS incidence decreased from above 0.1 to zero over PFSI of 15-17 hours. Except for 40 fsw for 120 min, repetitive dives required longer PFSI for a given DCS incidence than did single dives. DCS was significantly associated with PFSI and repetitive diving. DCS tended to decrease as PFSI increased and repetitive dives formed a separate group from single dives (p=0.0159). DCS was not associated with subject characteristics, individual subjects, or any dive profile characteristic other than repetitive diving.

The only measure of the combined dive/PFSI that was significantly associated with DCS during or after the flight was the tissue nitrogen tension at the end of the PFSI in a perfusion-limited tissue compartment with a 300 min half-time (p=0.0209).

DISCUSSION

Flights with no dives and dives with no flights

We observed no DCS in 52 exposures at a 17 hr PFSI but did not conduct control experiments of flights without dives. Studies of altitude exposure without previous diving have indicated thresholds for DCS and Doppler-detected venous gas emboli of 18,000 fsw (51 kPa; (27)) and 12,000 ft (64 kPa; (28)), respectively. Thus, our 8,000 ft simulated flight by itself would not appear to be associated with significant DCS risk.

To address the question of whether the DCS cases we attributed to flight might have been caused by diving alone, we used the probabilistic decompression model BVM3 to estimate the number cases expected in the absence of flight (26). This model had been calibrated to a database of 3,322 dive profiles of known outcome (DCS or no DCS) and gave good estimates of DCS probability for air dives in the range conducted here. Eleven DCS cases were predicted to occur as a result of diving alone and 11 were observed, many fewer than the 40 cases reported during or after flight. This was consistent with the conclusion that flying was the factor responsible for the DCS.

PFSI and DCS risk

PFSI can be brief and even omitted with little DCS risk if the dives are short or shallow (e.g., (11)). Our objective, however, was to acquire data from which to estimate the longest PFSIs needed to achieve low DCS risk during or after flight following dives near no-decompression limits such as specified by the Recreational Dive Planner (22). We found that DCS decreased significantly as PFSI increased and that repetitive dives were grouped separately from single dives with regard to the zero-incidence PFSI (Fig. 1). Single dives generally needed PFSI of 11-12 hrs for low DCS risk while repetitive dives needed up to 17 hours. The single dive to 40 fsw for 120 min was a possible exception to this observation, but there were insufficient dives to estimate where the zero-incidence PFSI might fall, except that it would probably be longer than 13 hours.

The relationship of PFSI to DCS could not be resolved for individual dive profiles as subject safety, embodied in the Accept/Reject criteria, limited the number of DCS incidents that were tolerable for each dive profile. Because of this limitation, we adopted a dose-response design to help identify, in aggregate, the PFSI range over which the transition from near zero DCS risk to the steep part of the dose/response curve might be resolved. Figure 1 shows this was largely achieved, and it appeared that a PFSI of 17 hrs or greater should ensure a very low DCS risk during a subsequent flight for most no-decompression dives. As the trials were conducted in a dry chamber with resting subjects, however, the results may not apply to recreational divers who are immersed and exercising in warm water.

Comparison of old and new data

Our findings of DCS incidences as great as 17% for PFSI of 3-13 hours (Fig. 1) contrast with the results of Edel et al. (6) and Balldin (10) where the combined DCS incidence at PFSI of 2-3 hours for altitudes of 8,000 ft or above was 3%. Two methodological differences might explain this discrepancy. First, their altitude exposures were only about two hours in duration, while ours were four hours. Seven of our 40 DCS cases (18%) occurred in the third and fourth hours of flight. Second, Balldin's subjects received prophylactic hyperbaric oxygen after flying while ours did not. As 17 of our 40 DCS cases (43%) occurred post-flight, these might not have been observed if hyperbaric oxygen had been administered after the flight.

DCS severity

Of the 40 flying after diving DCS cases, the 12 cases that resolved during descent from 8,000 ft or persisted for more than 60 min before resolving spontaneously might be described as "decompression related" rather than as clinically significant. However, these cases met the U.S. Navy definition of DCS (21) that we chose as appropriate for a study designed to provide data on which safety guidelines might be based. In addition, 24 other subjects had mild symptoms that persisted for less than 60 min. Temple et al. (21) defined these as "marginal DCS" or "niggles" (29). If niggles were counted as DCS, the relationship of PFSI to DCS would still remain significant suggesting that niggles were flight-related, even if clinically unimportant.

Limitations

Only nine recreational dive profiles were tested, so we cannot state with confidence that 17 hours would be a low risk PFSI for all possible no-decompression dive profiles. Because only one altitude was investigated (8,000 ft), our results represent an upper bound for commercial, pressurized flight or for or unpressurized flight or mountain travel at lower altitudes where low DCS risk might be achieved at shorter PFSI. For example, Emmerman found that the average maximum cabin altitude of 123 commercial airline flights was 5,500 ft (81 kPa; (30)). At cabin altitudes greater than 8,000 ft, longer PFSI would likely be needed. As the dives were conducted during a single day with dry, resting subjects, longer PFSI might be required after multi-day diving by immersed, exercising divers or after dives requiring decompression.

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APPENDICES

Appendix A. DCS after diving.

Dive Profiles										
D (fsw)	BT (min)	SI, (hrs)	D (fsw)	BT (min)	SI (hrs)	D (fsw)	BT (min)	# of Trials	Case #	DCS Signs, Symptoms, Treatment, and Resolution
100	20							109	1	Pain in hip on ascent. Improved on Table 5. Gone in 2 days. Did not fly.
									2	Ache in tempromandibular joint on ascent persisted for 60 min & resolved. Flew without problem.
									3	Ache & burning in hip/leg after dive. Resolved but not reported. Recurred in-flight with positive calf extension reflex. Resolved on Table 6.
40	60	1	40	60				119	4	Calf pain during 1st dive. Numbness in foot in surface interval. Resolved on 2nd dive. Flew without problems.
									5	Post-dive pain in sternum. Resolved on Table 5. Did not fly.
									6	Tingling & numbness post-dive in arm. Decreased pin-prick over C6-C7 dermatome. Resolved on Table 6. Did not fly.
60	55	1	60	30				36	7	Shoulder pain post-dive. Gone after Table 5. Did not fly.
									8	Arm tingling post-dive. Resolved on Table 6. Did not fly.
100	15	1	60	35				111	9	Neck pain on leaving chamber. Cracking & popping on neck rotation. Neck stiff & sore next AM. Ache in calf. All resolved on Table 5. Did not fly.
									10	Pain, tingling & decreased sensation in hand after 1st dive. Resolved on Table 6. Did not fly.
60	55	1	60	20	1	60	20	100	11[a]	R shoulder pain after bowling after 3 asymptomatic dives. Pain present when flight began & unchanged during flight. Resolved on Table 6.

D=depth; BT=bottom time; SI=surface interval
a – This subject also reported in-flight symptoms described in Case 40 of Appendix B.

Appendix B. DCS In-Flight or Post-Flight.

Dive Profiles												
D (fsw)	BT (min)	SI, (hrs)	D (fsw)	BT (min)	SI (hrs)	D (fsw)	BT (min)	PFSI (hrs)	Expo-Sures	% DCS	Case #	DCS Signs, Symptoms, Treatment, and Resolution
40	60							8	41	14.6	1	Cramp in calf began on leaving chamber & lasted 4 hrs. Resolved spontaneously.
											2	Foot pain 23.8 hrs post-flight became worse. Resolved on Table 6.
											3	Abnormal sensation in elbow 22 hrs post-flight. Unchanged for a day. Resolved on Table 6.
											4	Knees sore & tingling 9.8 hrs post-flight. Worse next day with pin-prick deficit on leg. Resolved on Table 6.
											5	Arm pain & paresthesias 2 hrs in-flight. Improved on descent but returned over next 12 hrs. All but mild soreness resolved on Table 6.
											6	Shoulder pain & abnormal arm sensation post-flight. Resolved on Table 6 except for residual tightness in shoulder.
								9	24	0	NA	
40	120							12	20	5	7	Tingling foot 3 hrs in-flight, no change on descent. Progressed to thigh. Resolved on Table 6.
								13	30	10	8	Tingling on R side of body 1 hr inflight until resolving 30 min post-flight.
											9	Hand tingling while driving 12 hrs post-flight. Arm sore & tingling with fullness & stiffness in wrist & hand. Persisted for 12 hrs & resolved spontaneously.
											10	Tingling, warm sensation on ball of foot at 3 hr, 32 min in-flight. Resolved on descent 30 min later.
60	55							3	36	8.3	11	Moderate arm pain 2 hrs inflight. Decreased on descent. Resolved on Table 5 .
											12	Hand tingling & mild shoulder pain 1 hr in-flight. No change on descent. Resolved on extended Table 6.
											13	Shoulder pain inflight resolved after 23 min. Disoriented, 'spaced-out', and nauseated 1 hr, 30 min post-flight. Difficulty with serial-7s. Resolved on Table 6.
								6	6	16.7	14	Hand numb, tingling & decreased grip strength 3 hrs post-flight. Improved on Table 6. Resolved on HBO (2 hrs at 2 ata) next day.
								9	7	14.3	15	Numb foot 4 hrs post-flight. Resolved on Table 6.
								10	23	8.7	16	Knee pain on drive 5 hrs post-flight. Pain 1/10 seated, 3/10 standing, and 5/10 walking. Present at bedtime. Resolved by morning.
											17	Transient arm pain 3 hrs post-flight progressed to tingling & returned 4-5 times overnight. Resolved by morning. No recompression.
								11	23	0	NA	
								12	27	0	NA	

100	20							8	29	17.2	18	Intermittent foot cramp at 30 min inflight persisted until resolving on descent.
											19	At 24 hr post-flight call, reported mild fatigue & dull ache in shoulder that lasted 2 hrs starting 5.75 hrpost-flight.
											20	Inflight hip pain, leg tingling, calf cramping & knee ache. Nearly normal after treatment on Table 5. Completely resolved next day.
											21	Inflight paresthesias in hand, episode of forearm tingling occurred. Symptoms lasted 60 min & resolved before descent. Table 5 given anyhow.
											22	Elbow pain & hand sensory deficit at 11 min in-flight. Improved on descent. Resolved on Table 6 except for subtle decreased fine touch on palm.
								9	55	5.5	23	Calf pain 1 hr inflight improved during descent. Decreased pinprick on calf. Resolved on Table 6.
											24	Hip pain 6.5 hr post-flight. Resolved on Table 6.
											25	Burning, fullness & tingling in hand 40 min inflight. Complete resolution on descent at 4000 ft. Table 5 given to ensure complete relief.
								10	23	0	NA	
40	60	1	40	60				13	18	5.5	26	Knee pain 30 min in-flight. Improved on descent & nearly resolved with surface O2. Full resolution occurred on Table 5.
								14	25	0	NA	
								15	38	7.9	27	Mild steady knee pain 1.5 hr in-flight. Resolved 1.35 hr later before descent.
											28	Abnormal sensation in hand 7.75 hr post-flight. Decreased in intensity 25 hrs after onset on extended Table 6. Resolved by next day.
											29	Decreased arm sensation & pin-prick in C5 distribution 5.2 hrs post-flight. Resolved on Table 6 except for mild numbness which resolved by next day.
								16	36	2.8	30	Mild elbow pain 3.5 hrs in-flight. Improved on descent & resolved on Table 6.
60	55	1	60	20[a]				14	27	7.4	31	Pain & paresthesias in both forearms 2.2 hrs in-flight. Improved on descent, improved with surface O2 & resolved on Table 6.
											32	Shoulder & elbow pain 1.5 hrs in-flight, improved on descent. Sensory deficit in hand. Resolved with surface O2 but given Table 5.
								15	39	2.6	33	Elbow pain 3.6 hrs in-flight resolved in 30 min. Recurred post-flight. Resolved on surface O2. Returned & increased in hot shower. Numb area on deltoid. Resolved on Table 6.
								16	32	0	NA	
60	55	1	60	30				14	8	12.5	34	Dull shoulder ache 20 min in-flight. Improved on descent. Improved further on Table 6. Resolved by 48 hr check.
								15	26	0	NA	

100	15[b]	1	60	35				14	18	16.7	35	Mild elbow pain 1 hr in-flight, lasted 2 hr, resolved spontaneously before descent.
											36[b]	Arm pain, tingling, numbness & abnormal temperature sensation 4 hrs post-flight. Resolved with surface O2, returned on air. Resolved on Table 6.
											37[b]	Tingling & numbness 2.3 hrs post-flight in hand, forearm & foot. Foot resolved on Table 6. Residual numbness in hand resolved on HBO (60' for 90 min).
								15	36	2.8	38	Sharp arm pain 26 min in-flight. Progressed to numbness. Decreased on descent. Resolved on Table 6 except for shoulder soreness. Resolved by next day.
								16	27	0	NA	
								17	28	0	NA	
60	55	1	60	20	1	60	20	14	10	9.1	39	Tingling, numbness, coldness & decreased strength in arm occurred 11 hrs post-flight. Resolved on Table 6.
								15	39	2.6	40[c]	Discomfort in R elbow 2.5 hrs in-flight progressed in severity. After descent, tingling and numbness in the R hand. Resolved on Table 6.
								16	27	0	NA	
								17	24	0	NA	

D=depth; BT=bottom time; SI=surface interval, PFSI=pre flight surface interval

a – Dive profile rejected due to two post-dive DCS cases

b – 10 of these exposures were conducted with a 12 min dive time.

c – This subject also reported post-dive symptoms described in Case 11 of Appendix A.