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Decompression Sickness and U-2 Operations: Summary of Research Findings and Recommendations Regarding Use of Exercise during Prebreathe

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14. ABSTRACT
This report is designed to review the incorporation of methods and procedures for reducing the incidence of decompression sickness (DCS) during U-2 high altitude reconnaissance missions. Exercise During Prebreathe (EDP) during procedures used for some pilots preparing for U-2 high altitude operations is reviewed in detail. The published basis for enhancing prebreathe effectiveness with exercise is summarized along with an operational test with one U-2 pilot and survey results from 2 pilots. Successful incorporation of EDP on the International Space Station prior to extravehicular activity (EVA; space walks) is also reviewed. Procedures for its incorporation and variants in exercise equipment are summarized and equations for calculating individualized exercise parameters are shown. Included are summaries of peer-reviewed publications supporting this information and personal remarks about prebreathe procedures with EDP by National Aeronautic and Space Administration (NASA) Mission Specialists.

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DECOMPRESSION SICKNESS AND U-2 OPERATIONS: SUMMARY OF RESEARCH, FINDINGS, AND RECOMMENDATIONS REGARDING USE OF EXERCISE DURING PREBREATHE

SUMMARY

A survey of previous and current U-2 pilots revealed that decompression sickness (DCS) is a common hazard with historical impact on high altitude reconnaissance mission accomplishment for some pilots. Mission impact is defined here as any degradation in pilot ability to accomplish the mission, including early termination from the U-2 program as a pilot option to avoid DCS symptoms. Early withdrawal of a pilot from the U-2 program means loss of expensive training and time. For those pilots who appear to be more susceptible to DCS, several procedures could reduce the mission impact. Increasing denitrogenation by increasing the preoxygenation or prebreathe time (breathing 100% oxygen) before takeoff from 60 min to as much as 90 min has been used by some pilots. However, this provides only moderate additional protection at the expense of increased fatigue due to a longer duty day. Inflight denitrogenation has been shown to be as effective at 16,000 ft as at sea level. Application of some suit pressure early in the mission would effectively keep the pilot below 16,000 ft, thereby increasing the effective denitrogenation time without increasing preflight preoxygenation. However, this option may decrease mobility during a portion of the climb and early cruise due to effects of suit pressure. A third option is to include a 10-min period of strenuous, upper- and lower-body exercise at the beginning of a 60-min prebreathe. This procedure is called Exercise During Prebreathe (EDP) and was shown to provide significantly better protection from DCS than an equal period of resting preoxygenation for most subjects tested. An operational test and evaluation of exercise enhancement of preoxygenation was accomplished with one pilot who developed DCS in the U-2 during two of his first seven operational high flights using normal, resting preoxygenation even with 90 min of preoxygenation. Following incorporation of EDP, the same pilot did not report any further symptoms during his remaining, multi-year career in the U-2. Survey responses from this pilot and another who used EDP are summarized. This report documents the background, actions, results, and recommendations relating to enhancement of preoxygenation with exercise for pilots who require additional protection from the symptoms of DCS.

INTRODUCTION

Decompression Sickness (DCS), DCS Risk Factors, and Denitrogenation

Venous gas emboli (VGE) and tissue gas emboli are formed due to supersaturation with nitrogen during decompression on ascent from ground level. Formation and growth of gas emboli are accepted as having a central role in the clinical manifestations of DCS. Almost all VGE are resolved by the lungs. Rarely, left ventricular gas emboli have been observed during research chamber exposures (Pilmanis et al., 1996). Exposure to the altitude equivalent of 30,000 ft (4.3 psia; 9,144 m) during high altitude U-2 reconnaissance flights involves a risk of DCS (Sherman, 1992; Bendrick et al., 1996). Anonymous surveys of the U-2 community (both active and retired) have revealed that over 75% had experienced DCS and that 4.2% of the flights involved symptoms, many with neurologic involvement (Bendrick et al., 1996).

Factors Influencing DCS Risk

Factors influencing the susceptibility to DCS have been evaluated and four were selected as the basis for AFRL's Altitude DCS Risk Assessment Computer (ADRAC) model. Those factors, **altitude**, **time at altitude**, **level of physical activity while at altitude, and prebreathe time**, have been shown to have far more influence on DCS incidence than factors previously given considerable attention (Webb et al., 2003, 2005; Webb, 2010). Appendix A describes the effects of several potential factors, some of which have been shown to have a "significant" effect on DCS risk. However, statistical significance was not found to have any value in predicting the DCS susceptibility of any one individual (Webb et al., 2005), only in showing that it is a factor in a population study.

Altitude and Time at Altitude. It is somewhat obvious that higher altitudes result in higher incidences of DCS, although the shape of the curve relating altitude to DCS incidence is less well known. That shape is sigmoidal, with zero incidence until a threshold altitude of about 21,000 ft is reached (Webb et al., 2003). Conditions of that study used a 4-h exposure time with no prebreathe, consistent, and moderate activity at altitude. The DCS database includes information on 65 exposures to 30,000 ft (±500 ft) with moderate activity (approximately 15-25% of $\mathbf{VO}_{2peak}$) for 4 h preceded by one h of prebreathe. The average incidence of DCS was 83% by 4 h, ranging from 77% (20/26) to 86% (32/37). Figure 1 displays the cumulative incidence of DCS versus duration of exposure throughout these 4-h exposures. The sigmoidal relationship reveals a time lag before symptoms begin to appear followed by a rapid increase in incidence and a leveling as the incidence reaches close to 100% DCS. Since some individuals are highly resistant to DCS, this type of curve is typical at all altitudes, although leveling at much lower levels at lower altitudes.

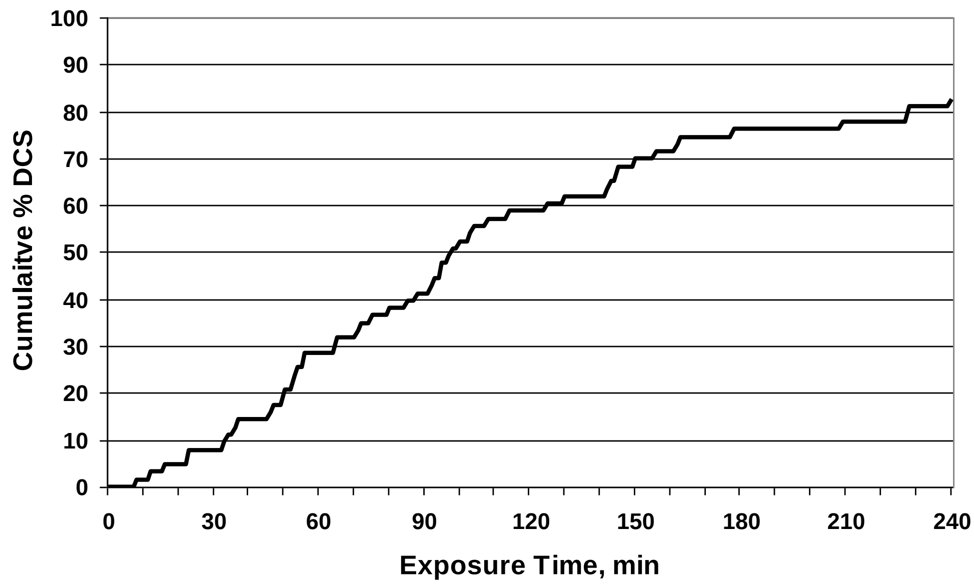

Figure 1. Cumulative DCS Incidence at 30,000 Feet vs. Duration of Exposure
Note: Moderate exercise (activity) was accomplished throughout the exposures following 1 h of resting prebreathe.

Level of Physical Activity while at Altitude. The high level of DCS reported during research exposures such as those in Figure 1 appears to be inconsistent with operational reporting in the U-2 community and requires explanation. The 53 cases of DCS were observed in subjects walking and performing moderate exercise during exposure. Other exposures with less activity (approximately 10-15% of $\mathbf{\dot{V}O}_{2peak}$) resulted in 62% DCS. Other information in the database indicates that, had the subjects remained seated at rest during the exposure, as pilots are during flight, even fewer would have experienced symptoms.

A paper on metabolic rate vs. DCS by Webb et al. (2010), shows a significant correlation between the highest 1 min of metabolic rate ($\mathbf{\dot{V}O}_2$) during an activity while decompressed and DCS incidence. Thus, the difference in activity at altitude could make up a very considerable amount of the difference between research and operational DCS incidence. Figure 2 demonstrates this factor in the three bars on the left. Note that the second bar, corresponding to mild activity and predicted U-2 pilot DCS risk from the ADRAC model, is still considerably higher than normal pilot activity.

Even though a low percentage of DCS incidence is shown in the Abort column of Figure 2, it could result in a significant loss of pilots from U-2 operations. The cost and lead time to train each pilot makes them a critical resource. If the operational incidence of significant symptoms is truly around 4% as shown in Figure 2, it may indicate that fixing the problem could mean only providing a better procedure for a relatively small percentage of pilots.

1. Since subjects in the Brooks DCS research protocols were required to report ANY change in their “well-being” and the protocols were written to provide a high level of

protection for the subjects, they reported and we documented DCS symptoms that would go largely undetected, and nearly always unreported, by U-2 pilots accomplishing operational missions. Therefore, only a few of the symptoms would have been noticed by U-2 pilots and very few would have been reported due to the high level of mission orientation and the fact that most of the symptoms would disappear during descent (Muehlberger et al., 2004).

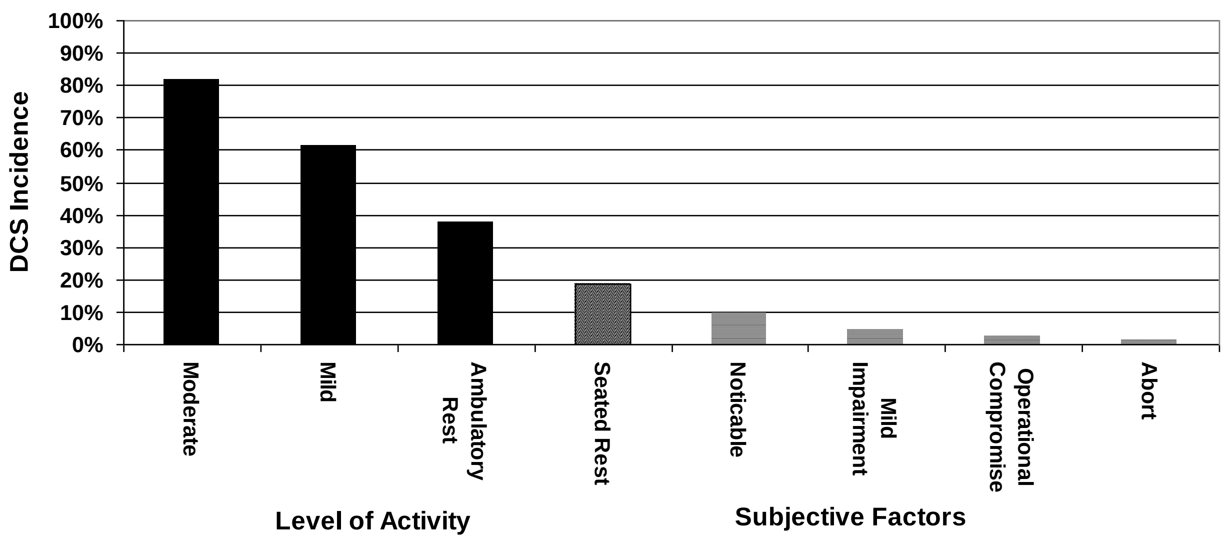

Figure 2. Effect of Level of Activity (Oxygen Consumption) and Subjective Factors on DCS Risk Reported by Research Subjects and U-2 Pilots

Note: The determination of Subjective Factors effects on DCS risk (bars with dots) is less than rigorous. Those logically begin after plotting incidence from known research chamber data (black bars) and involve an attempt to explain the relevance of research reports to U-2 operational reports. The barber-pole bar represents a measured level of activity for which no research exposures have been accomplished to allow a corresponding level of DCS (a recommended area for future research).

2. U-2 pilot symptoms likely represent no more than the 4% incidence of symptoms mentioned in a preliminary survey of U-2 pilots (Bendrick et al., 1996). However, since that 1996 report, increased mission duration could increase that incidence. Although the large majority of the symptoms reported by the research subjects occurred before 4 h during 8-h exposures while performing moderate exercise, lower levels of activity result in onset curves which may not indicate the DCS risk levels even after 4 h of exposure as shown in Figure 3. The total incidence of DCS while decompressed appears to be related to the oxygen consumption (metabolic rate) during the highest 1 min of activity repeated during an exposure as shown in Figure 4 (Webb et al., 2010).

Enhancement of prebreathe efficiency may be achieved by using Exercise During Prebreathe (EDP). This procedure involves a 10-min period of strenuous exercise at the beginning of a 60-min prebreathe and has been used by several U-2 pilots to increase denitrogenation effectiveness and successfully reduce the risk of DCS. See Increasing Prebreathe Effectiveness under Methods for a more complete description.

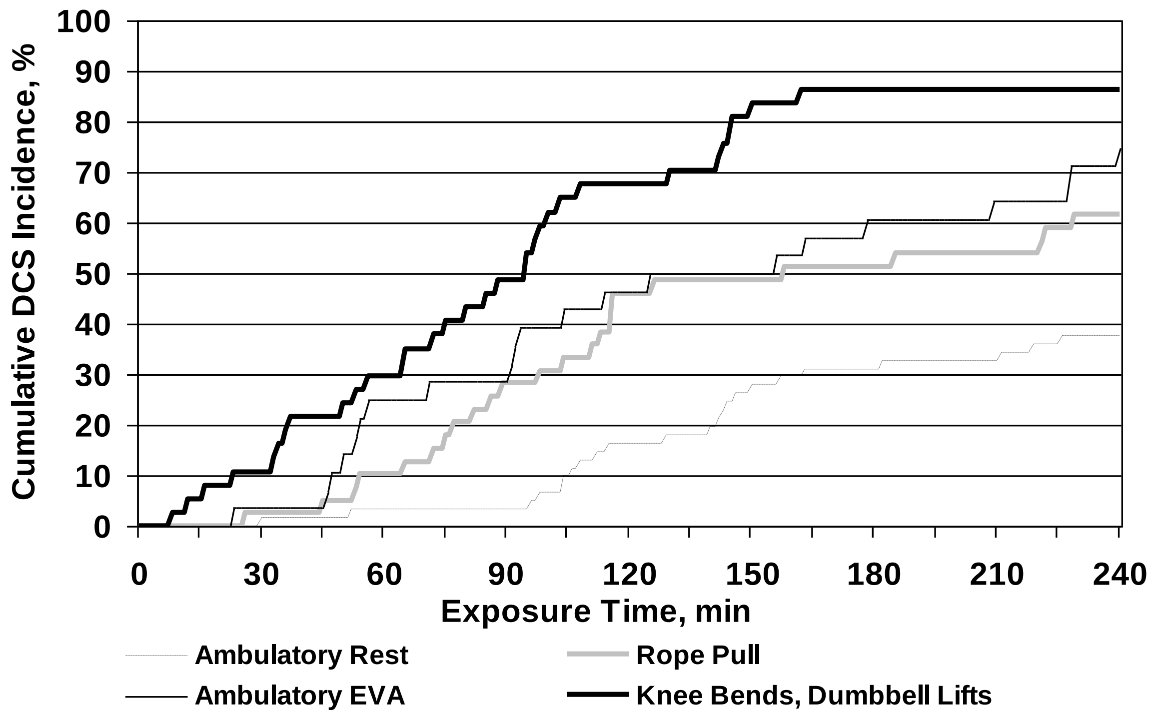

Figure 3. Cumulative DCS Incidence in Altitude DCS Research Exposures to 30,000 ft for 4 h Following 1 h of Resting Prebreathe While Performing Different Activities

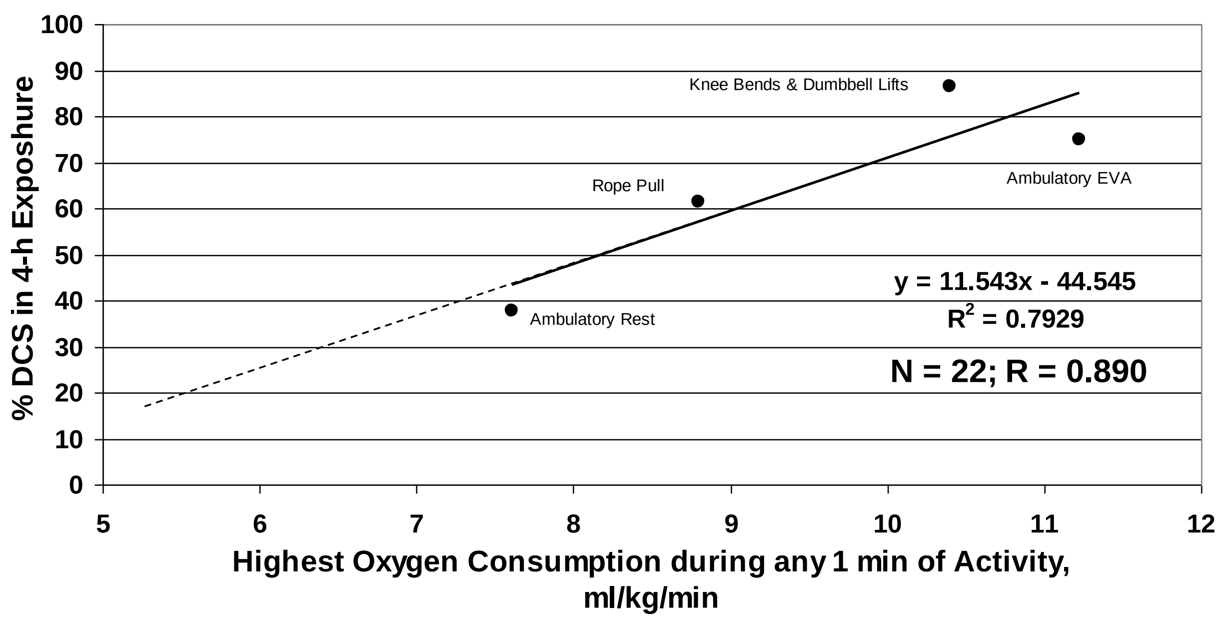

Figure 4. Relationship of Oxygen Consumption to DCS Incidence with all Other Conditions Constant (29,500 - 30,000 ft; 4-h exposure; 1-h prebreathe)

Denitrogenation

Denitrogenation is the process of removing nitrogen from the tissues by breathing in a gas mixture with a lower partial pressure of nitrogen than contained in the body fluids and tissues. Breathing 100% oxygen prior to decompression (preoxygenation or prebreathing) is a common method of denitrogenating to reduce the risk of DCS (Webb and Pilmanis, 1999; Webb et al., 2002b). During prebreathe, the nitrogen flows down its concentration gradient from the rapidly-denitrogenated blood into the alveoli where it is exhaled during expiration. Denitrogenation reduces the potential for nitrogen supersaturation and subsequent gas emboli formation during decompression.

Articles on denitrogenation (Webb and Pilmanis, 1999; Webb et al., 2002b) reported that increasing preoxygenation time increased protection, albeit with decreasing efficiency as shown in Figure 5. Increasing preoxygenation from 1 to 4 h prior to 30,000-ft research chamber exposures only results in reducing DCS incidence from about 77% to 47% (Figure 5; Webb and Pilmanis, 1999). The data for developing Figure 1 is contained in the Air Force Research Laboratory Hypobaric DCS Research Database developed at Brooks AFB, TX, which has detailed information on over 3,000 research chamber exposures of volunteer human subjects.

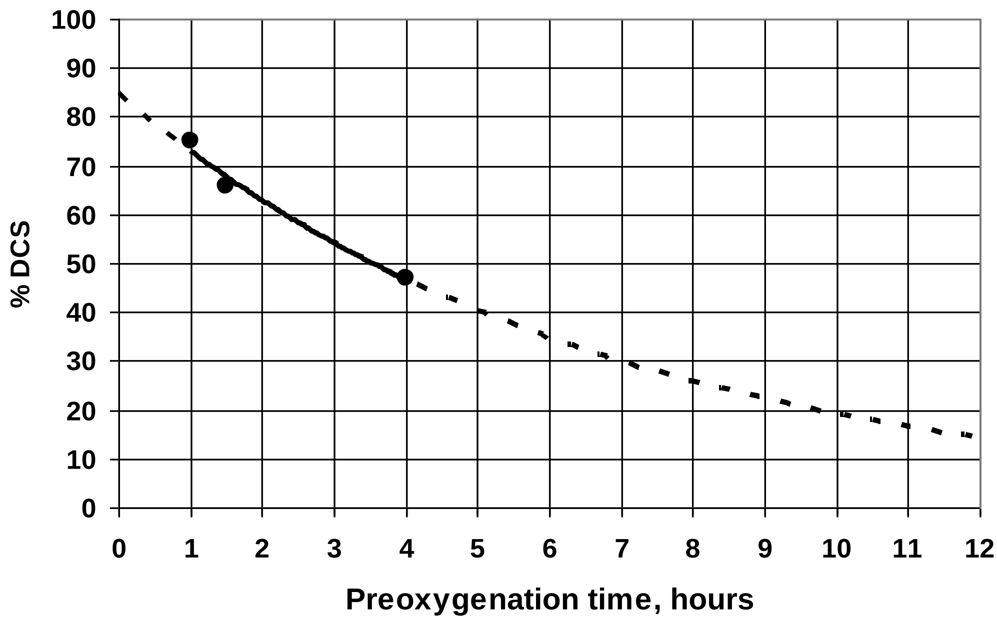

Figure 5. DCS Incidence at 30,000 Feet versus Duration of Preoxygenation
From AFRL DCS Research Database information (Webb and Pilmanis, 1999)

CURRENT AND POTENTIAL PROCEDURES TO REDUCE DCS RISK

Current Denitrogenation Procedure in the U-2

A 1-h resting preoxygenation is presently required prior to most high-altitude reconnaissance flights. For some individuals, this is not sufficient for DCS protection. Indeed, the current ADRAC model predicts 60% DCS risk during 4 h of exposure to 30,000 ft following 60 min of resting prebreathe (Pilmanis et al., 2004; calculation from https://biodyn1.wpafb.af.mil/login/Login.aspx).

The degree of current preoxygenation insufficiency acceptable in an operational environment is a function of acceptable risk and DCS susceptibility. The question "What is acceptable risk?" must be answered by operational commanders and pilots. To provide an informed answer, the commanders must have information about the level and severity of the symptoms experienced by the pilots and how they impact the mission.

The answer must address at least the following:

- Effect on the mission (aborts),
- Consequences of increased preoxygenation time (effectiveness and impact on crew rest),
- Effect on pilot retainability (pilots not wanting to put up with the pain or fatigue or discomfort, etc.),
- Consequences of reporting DCS incidents (treatment time, grounding), and
- Risk of incidences involving aircraft damage and/or pilot injury/death.

Equipment-Based Potential DCS Countermeasures

Better Cabin Pressurization

Future aircraft should be capable of sustaining a cockpit/cabin pressure of no less than 6.8 psia (about 20,000 ft, 6,096 m) based on the findings of Webb et al. (2003) which indicated that the 5% DCS threshold altitude was 19,500 ft. Using this criteria, during which the subjects performed moderate intensity activity while decompressed, military aircraft would not need a pressurization system if they do not exceed 20,000 ft, although adequate supplemental oxygen would be required when above 10,000 ft. Aircraft which can sustain altitudes higher than 20,000 ft would require a cockpit/cabin pressurization system; e.g. an aircraft capable of flight at 60,000 ft would need a cockpit/cabin differential of about 5.7 psi to achieve this goal. Achieving this goal would preclude the need for prebreathe to avoid DCS.

Improved Full-Pressure Suit Technology

If redesign of the full-pressure suit could provide improved comfort while allowing a sufficient differential pressure in the suit, the U-2 program and other high altitude aircraft and space operations could benefit. The result could be continued denitrogenation during the early portion of each flight when suit pressurization could keep the occupant below an effective altitude of about 16,000 ft, where in-flight denitrogenation has been shown to be as effective a ground-level prebreathe (Webb et al., 2000). Regulating suit pressure by an automated system could allow the pilot to utilize this method for reduction of DCS risk with little distraction. Although denitrogenation effectiveness decreases above 16,000 ft (Webb et al., 2000), a combination of suit pressure and cockpit pressurization in the U-2 could allow the pilot to continue denitrogenation at an in-suit pressure equivalent of 16,000 ft during the early portion of the flight. This procedure would reduce DCS risk later in the flight if the suit pressure is reduced to zero differential yielding a cockpit pressure of approximately 30,000 ft. However, as the suit pressure increased during the climb, mobility issues could limit the time spent at or below an effective in-suit altitude of 16,000 ft.

METHODS

Several options may be of use in reducing the risk of DCS. They are based on potential changes in factors which have been shown to influence that risk.

Pilot-Based Potential DCS Countermeasures

As discussed earlier, BMI and physical fitness are factors which influence DCS risk. While not a reasonable metric for pilot selection or retention, encouragement to maintain AF standards of weight (potential lowering of BMI) and to increase level of physical fitness could reduce the effect of these risk factors.

Procedure-Based Potential Current DCS Countermeasures

Manually Increasing Suit Pressure

Since the U-2 maintains a cockpit differential pressure of 3.8 psi (psid), pilot exposure is in the altitude range where DCS occurs unless the pressure suit is inflated to reduce the effective exposure altitude. TABLE 1 is based on two concepts (Webb and Pilmanis, 1997) of maintaining suit pressure as necessary to keep the pilot at an equivalent altitude. The Suit Pressure column in TABLE 1 represents the differential needed to maintain >8.0 psia (<16,000 ft) early in a high flight and >6.5 psi (<21,000 ft) during the high altitude portion. The Pilot's Effective Altitude column shows what the pilot experiences inside the pressure suit (physiologic altitude), assuming the full 3.8 psid cockpit pressurization system is operating correctly.

TABLE 1. Potential for Reduction of DCS: Partial Inflation of the Pressure Suit

Aircraft Altitude (ft)	Cabin Altitude (ft)	Suit Pressure (psid)	Pilot's Effective Altitude (ft)
31,000*	16,000	0.0	≤16,000†
38,000†	19,900	0.0	≤20,000†
42,000†	21,800	0.5	≤20,000†
47,000†	23,800	1.0	≤20,000†
53,000†	25,800	1.5	≤20,000†
62,000†	28,100	2.0	≤20,000†
77,500†	30,500	2.5	≤20,000†
Space	33,000	3.0	≤20,000†

* Effective prebreathe up to this altitude.

† DCS-safe altitude, ≤5% DCS; **not** an altitude that will **resolve** existing DCS (possible, but unknown and very inconsistent):

- Ensure effective prebreathe during ascent (≤16,000 ft, ≥8.0 psi total); and
- Ensure protection from DCS (≤20,000 ft; ≥6.75 psi; Webb et al., 2003).

Manual regulation of suit pressure could allow the pilot to utilize in-flight denitrogenation for reduction of DCS risk with some distraction. This would require some form of feedback relative to the suit pressure needed to keep in-suit pressure at or below 16,000 ft for as long as feasible while avoiding any discomfort due to the added pressure. The added suit pressure is arbitrarily incremented by 0.5 psi and may or may not be relevant to operations depending on what level of suit pressure is functional and possible.

Increasing Prebreathe Time

Increasing preoxygenation time prior to high altitude reconnaissance flights is a matter of operational policy rather than total avoidance of DCS risk based on scientific results (Sherman, 1992). As reviewed earlier, prebreathe effectiveness is reduced with each increment of increase in prebreathe time (Webb & Pilmanis, 1999). If the longest operationally-acceptable increase in preoxygenation time does not provide adequate protection, an alternative may be enhancing the effectiveness of the available time for preoxygenation.

Increasing Prebreathe Effectiveness

EDP was shown to be protective, exercise during exposure has repeatedly been shown to result in more DCS, and exercise after exposure did not result in more recurring or delayed DCS (Webb et al., 2002a). However, heeding the AFI 11-403 chamber flight post-flight restriction “No physical exercise, strenuous or extended duty for a period of 12 hours” could make diagnosis of joint or muscle pain DCS much easier in the absence of such pain resulting from untimely strenuous exercise.

The incorporation of 10 min of upper- and lower-body exercise performed at 75% of each subject's peak oxygen consumption ($\mathbf{VO}_{2peak}$) at the beginning of a 1-h preoxygenation was shown to result in significantly less DCS than a 1-h resting preoxygenation (Webb et al., 1996; Webb et al., 1999; Hankins et al., 2000). The study published in 1996 was based, in part, on previous efforts dating back to 1943 which also showed a beneficial effect of exercise on denitrogenation and DCS prevention (Webb et al., 1943; Balke, 1954). The EDP study was described in a 1989 paper (Webb et al., 1989), approved in 1990, and initiated in mid-1992. The study design criteria were that the procedure be: 1) acceptable to the pilot in that it does not cause pain or fatigue and does not impair safety; 2) acceptable to flight surgeons from the physiologic and clinical viewpoint; 3) compatible with crew procedures, personal equipment, and aircraft equipment; and 4) economically viable.

The increased perfusion and ventilation caused by the exercise apparently increased denitrogenation rate of the active muscles and skin resulting in increased diffusion rate of nitrogen from neighboring tendons and joints where many of the symptoms occur. The physiologic results shown in Figure 5 indicates that even 15 min of preoxygenation beginning with 10 min of exercise provides protection (10E+5R; 64% DCS) comparable to the protection provided by a 1-h resting preoxygenation (60R; 77% DCS). Beginning a 1-h preoxygenation with 10 min of exercise provided a significant ($P<0.05$) reduction in symptoms (10E+50R; 42% DCS) as compared to a resting preoxygenation of the same duration (60R; 77% DCS). When tested at 25,000 ft, EDP also proved to be an effective DCS countermeasure (Webb et al., 2004). The DCS incidence following a four-hour preoxygenation (240R in Figure 5) shows the advantage of enhancing the preoxygenation with exercise even when the prebreathe duration is much less.

During the experiment showing the reduction in DCS from 77% to 42% (Webb et al., 1996), there were 2 of 26 subjects who did not develop DCS following a resting prebreathe, but did develop DCS following EDP. This negative finding was overcome by the fact that 11 of the 26 subjects who did develop DCS following a resting prebreathe did not develop DCS following EDP. Of the remaining 13 subjects in that study, 4 did not develop DCS on either profile and 9 developed DCS on both profiles. It is therefore important to note that EDP does not work for everyone. If a pilot has no reported history of DCS, use of EDP could result in DCS symptoms.

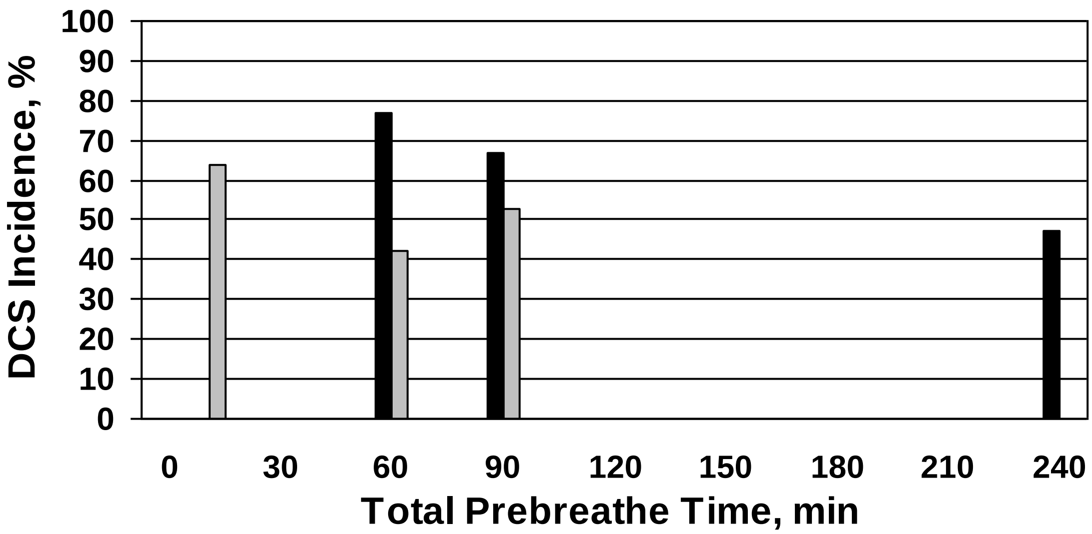

Figure 6. Incidence of DCS with Variable Preoxygenation Parameters
Note: The grey bars represent profiles using EDP for 10 min at the beginning of 15 and 60 min total prebreathe times and 15 min at the beginning of the 90 min total prebreathe time. The black bars represent supine resting prebreathe.

It must also be stressed that increasing the duration of exercise has not been shown to provide any increase in protection from DCS (Webb et al., 2002b). Indeed, there was a slight (Not Significant) increase in the final DCS incidence even with 90 min of total prebreathe (15 min of EDP + 75 min resting prebreathe).

Probably at least 75% of the nitrogen in someone's body is exhaled during 10 min of EDP. Unfortunately, the first 75% of the nitrogen exhaled isn't the nitrogen that causes most of the DCS symptoms, because the symptom-causing nitrogen (esp. joint pain) is located in the deep, slow tissues that are denitrogenated one to four hours later.

The level and duration of exercise has been shown to cause no pain or lasting fatigue. Our feasibility study (Webb et al., 1996) showed that strenuous exercise performed during the first 10 min of a 60-min preoxygenation resulted in no change in perceived level of fatigue over the next 6 h. The 15 min of exercise likewise produced no detectable increase in fatigue relative to a total preoxygenation of the same duration

(Webb et al., 2002b) although the longer EDP did produce some increase in core temperature based on analogous studies of thermal loading during exercise (Saltin & Hermansen, 1966). The exercise may cause some additional heating, although it should not result in a physiologically significant increase in core temperature.

Attempts to breath-hold during suit donning following EDP have usually been successful. Those which have occurred were nearly always for less than two min (Personal Communication, Maj Sean Jersey, Beale AFB, CA). A recent report (Pilmanis et al., 2010; in review) indicates that an air-breathing break of 10-min or more after 30 min of a 60-min total prebreathe time versus no break results in about twice the DCS occurring within the first hour of exposure (Figure 7). The type (pain, skin, respiratory, or neurologic) of symptoms observed were not different between the controls and any of the break conditions.

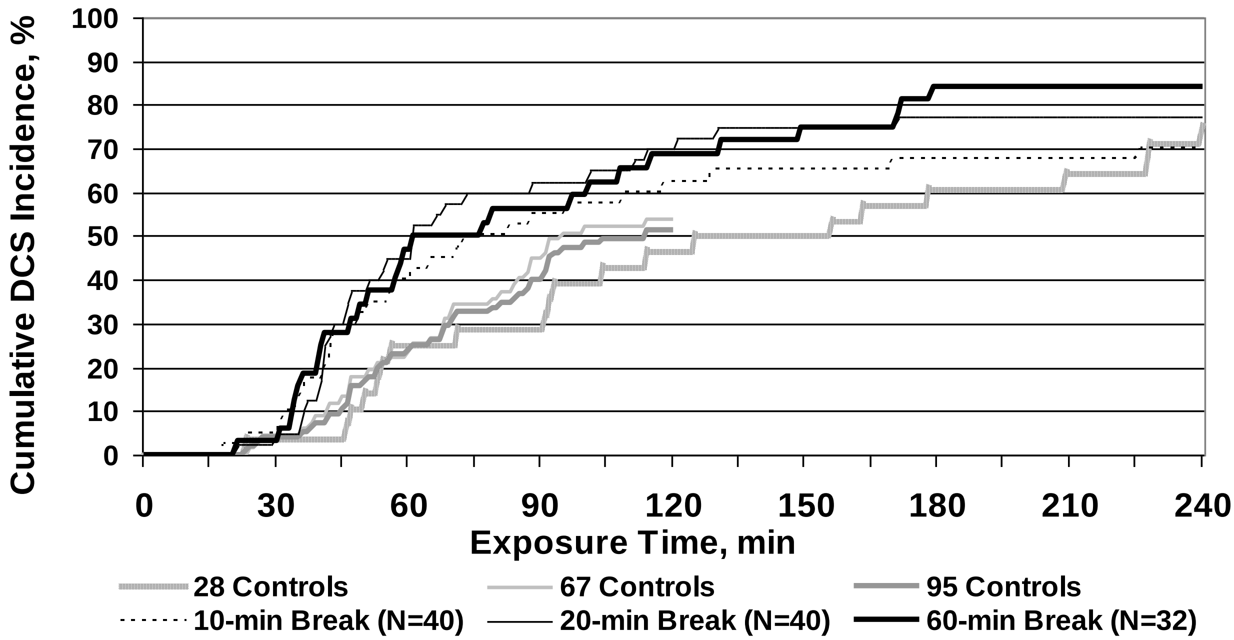

Figure 7. Cumulative % DCS vs. Time at Altitude for Controls and 3 Air Break Conditions

From: Pilmanis et al. (2010)

However, there are several reasons why these research results, while valid based on the conditions of the experiment, may not be relevant to the U-2 program:

1. The breaks in prebreathe tested were for at least 10 min versus the typical break of a few breaths or, at the most, two minutes.
2. The highest level of physical effort by the research protocol subjects was about twice the level seated U-2 pilots likely expend during operational missions. The physical effort of the research subjects included standing up, walking, and upper-body exercises for at least 75% of their total exposure time. That additional effort, as measured by Webb et al. (2010) yielded a much higher level of DCS than ambulatory rest resulting in 38% DCS (Pilmanis et al., 1999; Webb and Pilmanis, 2005) versus control exposures in Figure 7 which produced 75% DCS.

3. The breaks in prebreathe by the subjects were after 30 min of prebreathe, not near the beginning of prebreathe as is the case with nearly all breaks experienced by U-2 pilots.

The definitive answer for the increase in DCS risk due to a short, 1 to 2-min break in prebreathe near the beginning of a 1-h resting prebreathe (or one with EDP) could only come through research yet to be accomplished. That research should utilize the seated level of activity experienced by U-2 pilots during operational missions and should occur at a more relevant point in the prebreathe. However, the researchers involved in the break-in-prebreathe study (Pilmanis et al., 2010) and in over 15 years of additional DCS research believe up to a 1-min break in prebreathe would not result in increased DCS risk. This is contingent on being followed by a few slow, **deep** breaths of 100% oxygen and continued prebreathe for the planned total period; adding the lost prebreathe time, e.g. 1 min. The breaths described would remove considerable nitrogen from the lungs and circulation, negating much of the effect of the short nitrogen intake. These researchers emphasize that their belief is not based on specific, relevant research findings because there are no such reports.

Project Initiation

On August 17, 1998 funding was received from ACC/SG for the initiation of a project to support U-2 pilots with a procedure involving EDP (see Acknowledgments). The 9th Reconnaissance Wing at Beale AFB, CA subsequently requested short-suspense support in the form of consulting and equipment provisioning for EDP by one U-2 pilot who had previously developed DCS during 2 of his first 7operational missions (TABLE 3).

1998-1999 Test and Evaluation (T&E)

The author traveled to Beale AFB, CA in September 1998 to consult on incorporation of exercise with the existing preoxygenation procedure. Exercise equipment in the form of a dual-cycle ergometer and support assembly was shipped to Beale AFB for use prior to high flights.

The dual-cycle ergometer used (Appendix C) consisted of a Monark® (Varberg, Sweden) Ergomedic 818E professional ergometer (leg ergometer) and a Monark® (Varberg, Sweden) Rehab Trainer 881E (arm ergometer). Use of this calibrated device results in quantifiable levels of exercise for the arms and legs while exercising major muscle groups to enhance perfusion and ventilation during preoxygenation as described in Webb et al. (1996).

Key 9th Physiological Support Squadron (PSPTS) personnel at Beale AFB were briefed on the use of the dual-cycle ergometer and the pilot practiced the procedure prior to the first actual high flight using 10 min of dual-cycle ergometry during preoxygenation. A checklist was developed to guide incorporation of the procedure (Appendix D).

The intensity of the dual-cycle ergometry, or another upper- and lower-body EDP, was designed to be sub-maximal and should not contribute to fatigue during the subsequent mission. The intensity level was similar to the USAF cycle ergometry fitness test on which it is based and should not result in a detrimental increase in core temperature in normal, healthy individuals (Noble, 1986; Saltin et al., 1966). The 10-min preoxygenation exercise was not as long as the typical USAF cycle ergometry fitness test. Monitoring heart rate aided in maintaining exercise intensity close to 75% of $\mathbf{VO}_{2peak}$.

The first Operational T&E (OT&E) of the EDP procedure developed at Brooks AFB, TX occurred during November 1998 at an operational base. The author supported implementation of the procedure and assisted the pilot performing the dual-cycle ergometer exercise prior to both operational high flights that week. He assisted with equipment set-up, training 9th PSPTS personnel on the procedure, and pilot practice of the procedure in preparation for the high flights.

The 9th PSPTS personnel were instructed on how to adjust the ergometer resistance and monitor/adjust heart rate. They practiced the procedure on two subsequent prebreathe and suit-up trials with success and required no additional input during the second practice session. Coordination with the Health and Wellness Center civilian-in-charge of USAF fitness testing included his monitoring of an exercise session.

After 6 proficiency high flights using EDP at Beale, the pilot's first 2 operational high flight missions using EDP involved no DCS symptoms (Table 3). Both high flights lasted longer than either of the earlier high flights, without EDP, that resulted in DCS. The procedure worked well and no break in prebreathe was observed. It was emphasized to obtain a flow of 100% oxygen through the face cavity prior to taking a breath following any opening of the visor to adjust glasses, etc.. [Additional information on a break in prebreathe on page 11-12 under Increasing Prebreathe Effectiveness]

Because of the need for adjustments of the pilot's glasses, 9th PSPTS personnel anticipated that opening of the helmet visor during the preoxygenation might be necessary in future procedures. Considerable discussion ensued about breaks in prebreathe and the "chart" used previously at Beale AFB. The 9th PSPTS requested AFRL/HEPR to provide an updated procedure for this contingency. A new procedure was outlined by AFRL/HEPR and forwarded to Beale AFB. Research supporting either the old or new "chart" was not documented in the literature and a new research protocol was initiated to determine the effects of a break in the middle of a 60-min prebreathe (Pilmanis et al., 2010; see page 11-12).

Support for Transition of the Procedure

The pilot using the EDP procedure beginning in 1998 eventually decided he would prefer a different total-body exercise device. To determine the exercise level corresponding to 75% of maximal exercise intensity, thus matching the dual-cycle ergometry procedure, a method developed by Karvonen et al., (1957) was used to provide a heart rate (HR) goal during the exercise. HR can be monitored easily and accurately with most off-the-shelf exercise HR monitors; e.g. Polar Favor, Model 77048 as used during several operational trials.

Calculation of heart rate corresponding to 75% of maximal exercise intensity:

1. Estimate maximal heart rate (MaxHR) in beats X min^{-1} based on subject age using the following equation (Fox et al., 1972):

   MaxHR = 220 - (age in years)

2. Calculate target heart rate (THR; beats X min^{-1}) at 75% of maximal exercise intensity using the following equation:

   THR = (0.75 X MaxHR)

It is worth noting that the calculated values for THR are a general reference point and may not represent the true oxygen uptake during the exercise period. Well trained athletes may attain high oxygen uptakes without a well-correlated increase in heart rate. The variance in thermal loading is considerable, although reviewers of the EDP research did not suggest that core temperature would be affected. The increase in peripheral temperature resulting from peripheral vasodilation is significant and indicates the success at producing peripheral vasodilation. Minimizing the clothing worn during the exercise to that worn during aerobic workouts should help to minimize heat retention. If the pilots could recline comfortably for a few minutes following the 10-min exercise period, much of that peripheral heat should dissipate, particularly if moist, cool towels could be used to remove excess sweat. Using very cold, wet towels may inhibit the blood flow to the peripheral muscles and joints, thereby reducing the effectiveness of EDP. There is no research to support this during EDP trials, only subjective reasoning. If the 2-min warm up is kept to a non-taxing level and the environmental temperature of the EDP kept reasonably cool, less than 75^{o}F, the thermal loading following EDP should be minimized.

Additional exercise equipment was funded by the ACC Surgeon General's Office to allow employment of the procedure at all overseas detachments. TABLE 2 shows a comparison of upper/lower body exercise devices, most of which have been used in USAF fitness centers. Any of these exercise devices could be used in the event a dual-cycle ergometer is unavailable or is not the preferred device. All of them should result in sufficient upper arm exercise to emulate the dual-cycle ergometer and, therefore, be effective in producing total body increases in perfusion and denitrogenation assuming the target heart rate is maintained for at least 5 min of the 10-min exercise (including 2-min warm-up). The total exercise period of 10 min should not be altered. Cool-down exercise can vary as necessary.

Integration and Compatibility

Whether or not EDP is acceptable must, of course, be determined by the commanders who set operational policy. The exercise proposed here would be performed prior to donning the pressure suit and would have no impact on suit design or operation. The procedure can be varied to be compatible with crew procedures and does not require modification of any other personal equipment. Since the exercise is accomplished prior to arrival at the aircraft, aircraft equipment compatibility is not an issue.

TABLE 2. Comparison of Total-Body Exercise Devices

Characteristic	Dual-Cycle Ergometer[B]	Nordic Track	Life Fitness 9500 Cross Trainer™	Versa-Climber CL108P	Step Exerciser with Arm Weights
Cost[A]	$2000	$1000	$3500	$3600	$40
Heart rate monitor incorporated	No	No	Yes	Yes	No
Computerized exercise timing	No	No	Yes	Yes	No
Quantifies upper vs. lower-body exercise	Yes	No	No	No	No
Ease of learning; 1=easy 10=difficult	5	8	1	1	6
Footprint in ft^2	15[C]	16[D]	15-20[E]	8	8
9th PSPTS Assistance Req.; 1=none 10=much	4	4	2	2	6
Device Weight	130	100	420	210	15
Reproducibility; 1=excellent 10=not	1	4	3	3	9
Injury Chance; 1=none & 10=high	1	3	1	1	3
Maintenance; 1=easy 10=difficult	4	4	3	3	1

[A] The cost of a metronome to help establish cadence and cost of a heart rate monitor are not compared because they are included with some of the options. 1999 cost estimates.

[B] Necessary only for research purposes.

[C] 65” long, 30” wide, 72” high (allow additional 12” for headspace)

[D] 84” long, 27” wide, 62” high (allow additional 28” for headspace)

[E] 76” long, 28” wide, 70” high (allow additional 12” for headspace)

Operational Challenges and Solutions

The following guidelines may assist in providing the optimal solution for operational challenges of EDP:

- Ensure a WBGT measurement is available and provide a means of maintaining temperature, 65-75°F
- Monitor pilots engaged with EDP and assess physiological condition (e.g. excessive sweating, labored respiration)
- Provide standard nutrition and fluids prior to and immediately following activity
- Emphasize the goal of EDP during pilot training sessions or targeted forums.

RESULTS

U-2 Operational DCS History without and with EDP

During his first 7 U-2 operational high flights (without EDP), the pilot reported 2 episodes of DCS (TABLE 3, Flights 19 & 25) which were treated with hyperbaric oxygen therapy resulting in complete resolution of all symptoms. After instituting EDP, the same pilot flew 36 U-2 high flights without any reports of DCS (TABLE 3; Webb et al., 1999; Hankins et al., 2000; Flights 26-61). Subsequent to the Hankins report (Hankins et al., 2000), the pilot flew another 61 high flights without DCS (TABLE 3, Flights 62-122). Use of EDP was beneficial for this pilot and served as the model for other pilots, some of whom continue to benefit from the procedure.

TABLE 3. One Pilot's Self-Reported History of High Flights

Flt #	Preoxygenation Minutes Activity	High Flight Type/ Duration*, min	Time to Symptom, min	Presenting Symptom	Disposition
1	60 Rest	Training/170			
2	60 Rest	Training/20			
3	60 Rest	Training/220			
4	60 Rest	Training/220			
5	60 Rest	Training/220			
6	60 Rest	Training/220			
7	60 Rest	Training/110			
8	60 Rest	Training/120			
9	60 Rest	Training/90			
10	60 Rest	Training/210			
11	60 Rest	Training/210			
12	60 Rest	Training/220			
13	60 Rest	Training/230			
14	60 Rest	Training/90			
15	60 Rest	Training/110			
16	60 Rest	Training/110			
17	60 Rest	Training/290			
18	60 Rest	Training/180			
19	60 Rest	Mission DCS Abort/410	300	Mottling, "chokes"	HBO
20	60 Rest	Mission/440			

Flt #	Preoxygenation Minutes Activity	High Flight Type/ Duration*, min	Time to Symptom, min	Presenting Symptom	Disposition
21	60 Rest	Mission/440			
22	90 Rest	Mission/440			
23	90 Rest	Mission/440			
24	90 Rest	Mission/440			
25	90 Rest	Mission DCS Abort/260	300	Mottling, "chokes", Pain	HBO
26	10 Exercise + 80 Rest	Proficiency/260			
27	10 Exercise + 80 Rest	Proficiency/230			
28	10 Exercise + 80 Rest	Proficiency/440			
29	10 Exercise + 80 Rest	Proficiency/260			
30	10 Exercise + 80 Rest	Proficiency/260			
31	10 Exercise + 80 Rest	Mission/440			
32	10 Exercise + 80 Rest	Mission/440			
33	10 Exercise + 80 Rest	Mission/440			
34	10 Exercise + 80 Rest	Mission/440			
35	10 Exercise + 80 Rest	Mission/440			
36	10 Exercise + 80 Rest	Mission/320			
37	10 Exercise + 80 Rest	Mission/320			
38	10 Exercise + 80 Rest	Mission/320			
39	10 Exercise + 80 Rest	Maint. Abort/110			
40	10 Exercise + 80 Rest	Mission/110			
41	10 Exercise + 80 Rest	Mission/440			
42	10 Exercise + 80 Rest	Mission/320			
43	10 Exercise + 80 Rest	Mission/320			
44	10 Exercise + 80 Rest	Mission/320			
45	10 Exercise + 80 Rest	Proficiency/85			
46	10 Exercise + 80 Rest	Proficiency/90			
47	10 Exercise + 80 Rest[†]	Proficiency/85			
48	10 Exercise + 80 Rest[‡]	Mission/290			
49	10 Exercise + 80 Rest[‡]	Mission/190			
50	10 Exercise + 80 Rest[‡]	Mission/440			
51	10 Exercise + 80 Rest[‡]	Mission/440			
52	10 Exercise + 80 Rest[‡]	Mission/440			
53	10 Exercise + 80 Rest[†]	Proficiency/80			
54	10 Exercise + 80 Rest[†]	Mission/255			
55	10 Exercise + 80 Rest[†]	Mission/260			
56	10 Exercise + 80 Rest[†]	Mission/260			
57	10 Exercise + 80 Rest[†]	Mission/260			
58	10 Exercise + 80 Rest[†]	Mission/260			
59	10 Exercise + 80 Rest[†]	Mission/260			
60	10 Exercise + 80 Rest[†]	Mission/270			
61	10 Exercise + 80 Rest[†]	Mission/215			
62	10 Exercise + 80 Rest[†]	Mission/265			
63	10 Exercise + 80 Rest[†]	Mission/215			
64	10 Exercise + 80 Rest[†]	Mission/290			
65	10 Exercise + 80 Rest[†]	Proficiency/110			
66	10 Exercise + 80 Rest[†]	Mission/440			
67	10 Exercise + 80 Rest[†]	Mission/320			
68	10 Exercise + 80 Rest[†]	Mission/440			
69	10 Exercise + 80 Rest[†]	Mission/170			
70	10 Exercise + 80 Rest[†]	Mission/270			

Flt #	Preoxygenation Minutes Activity	High Flight Type/ Duration*, min	Time to Symptom, min	Presenting Symptom	Disposition
71	5 min Mild Exercise in suit + 55 Rest	Mission/235§	200/230§	Shoulder joint pain and slight creeps	Applied suit pressure intermittently; resolution on descent
72	10 Exercise + 80 Rest†	Mission/260			
73	10 Exercise + 80 Rest†	Mission/255			
74	10 Exercise + 80 Rest†	Mission/255			
75	10 Exercise + 80 Rest†	Mission/245			
76	10 Exercise + 80 Rest†	Mission/260			
77	10 Exercise + 80 Rest†	Mission/260			
78	10 Exercise + 80 Rest†	Mission/260			
79	10 Exercise + 80 Rest†	Mission/245			
80	10 Exercise + 80 Rest†	Mission/260			
81	10 Exercise + 80 Rest†	FCF chk/110			
82	10 Exercise + 80 Rest†	Chk ride/235			
83	10 Exercise + 80 Rest†	Mission/260			
84	10 Exercise + 80 Rest†	Mission/260			
85	10 Exercise + 80 Rest†	Mission/260			
86	10 Exercise + 80 Rest†	Mission/255			
87	10 Exercise + 80 Rest†	Mission/265			
88	10 Exercise + 80 Rest†	Mission/260			
89	0 Exercise + 60 Rest	FCF chk/100λ			
90	10 Exercise + 80 Rest†	Mission/265			
91	10 Exercise + 80 Rest†	Mission/260			
92	0 Exercise + 60 Rest	FCF chk/130			
93	10 Exercise + 80 Rest†	Mission/500			
94	0 Exercise + 60 Rest	FCF chk/88			
95	10 Exercise + 80 Rest†	Mission/260			
96	10 Exercise + 80 Rest†	Mission/260			
97	10 Exercise + 80 Rest†	Mission/260			
98	0 Exercise + 60 Rest	FCF chk/68			
99	10 Exercise + 80 Rest†	Mission/260			
100	0 Exercise + 60 Rest	Proficiency/85			
101	0 Exercise + 60 Rest	IP tng/85			
102	0 Exercise + 60 Rest	IP tng/110			
103	0 Exercise + 60 Rest	IP chk ride/82			
104	0 Exercise + 60 Rest	Student tng/235	180	Slight wrist, knee, & shoulder pain	Resolved with suit inflation
105	10 Exercise + 80 Rest†	Mission qual/195			
106	0 Exercise + 60 Rest	FCF chk/115			
107	0 Exercise + 60 Rest	Student tng/50			
108	0 Exercise + 60 Rest	Student tng/75			
109	10 Exercise + 80 Rest†	Student tng/176			
110	10 Exercise + 80 Rest†	Student tng/240			
111	0 Exercise + 60 Rest	FCF chk/80			
112	0 Exercise + 60 Rest	Proficiency/80			
113	0 Exercise + 60 Rest	Proficiency/110			
114	0 Exercise + 60 Rest	Student tng/75			
115	10 Exercise + 80 Rest†	Mission/610			

Flt #	Preoxygenation Minutes Activity	High Flight Type/ Duration*, min	Time to Symptom, min	Presenting Symptom	Disposition
116	10 Exercise + 80 Rest†	Mission/490			
117	10 Exercise + 80 Rest†	Mission/240			
118	10 Exercise + 80 Rest†	Student tng/180			
119	0 Exercise + 60 Rest	Student tng/105			
120	0 Exercise + 60 Rest	FCF chk/145			
121	0 Exercise + 60 Rest	Proficiency/95			
122	0 Exercise + 60 Rest	FCF chk/85			

* Duration is time at high altitude. Training high flights were required to qualify in the U-2. EDP employed a dual-cycle ergometer unless noted.
† = Exercised with a Life Fitness Cross Trainer™ during preoxygenation.
‡ = Exercised with a VersaClimber™ during preoxygenation.
§ = Short-notice flight to finish a relatively short mission w/o abort. Symptoms began at 200 min and suit pressure reduced symptoms. The flight was continued at altitude for another 30 min with intermittent suit deflation to activate controls.
λ = Short-notice flight with no symptoms or pilot experimented with deleting EDP for flights of less than 160 min at high altitude.

Other EDP Successes

An early use of EDP was reported in Berg's "Lindbergh" (1998). He described the efforts of Charles Lindbergh to help the war effort after being told by President Roosevelt that he could not put on a uniform and fight with the troops in Europe (Page 446, paragraph 4) because he was too valuable to lose. Lindbergh decided he could help by volunteering to be a human test subject for experiments designed to develop procedures and equipment for use by WWII pilots. "For the next ten days, he became a human guinea pig. The experiments in which he partook at the aeromedical laboratory required intense physical activity and mental acuity. Before entering the chamber he had to "desaturate" for half an hour--riding an exercise bicycle or walking on a treadmill while breathing pure oxygen through a rubber face mask--to wash the nitrogen out of his body and prevent the formation of nitrogen bubbles under decreased pressure."

When we published the 1996 article (Webb et al., 1996), this effort of Lindbergh was unknown to me. The introduction to that 1996 paper cited papers published in the 1940s and 1950s which inspired that research effort. Later, NASA tested EDP for possible use on the Space Shuttle and eventually used it there and on the International Space Station (ISS).

In July 2001, NASA Mission Specialists performed an extravehicular activity (EVA) from the ISS using an EDP procedure based on the one discussed in Webb et al. (1996) and Webb and Pilmanis (1998). They exercised at the same level of effort for the same period of time followed by some mild exercise (Gernhardt et al., 2000; Appendix E). The EVA was successful and NASA continued to use the EDP procedure during 21, two-member EVAs (42 individual EVAs) from ISS (personal communication; NASA Flight Surgeon Dr. Joe Dervay, 12 Jul 07) with complete success. In January 2007, they started what they call a "campout" procedure involving an overnight "campout" in the ISS lock which was depressurized to about 10,000 ft (about 10.1 psia). The "campout" procedure shortens the time from the beginning of the EVA checklist after the overnight rest until exiting the ISS because some of the procedures are incorporated into the overnight “campout” procedure. Thus, “campout” procedure shortens the EVA day for those participating. However, the EDP procedure remains the most effective prebreathe procedure used to date and remains a current option for use by ISS personnel. It was used during a late 2009 ISS EVA preparation when the “campout” procedure was aborted before completion (personal communication; NASA Flight Surgeon Dr. Joe Dervay, 24Dec09).

Appendix F contains part of an interview with Mission Specialist Mike Gernhardt before STS-104 in July 2001 regarding the EDP procedure he was planning to use prior to the flight. Some specifics on the procedure he used were published in an abstract he wrote (Gernhardt et al. 2000, reprinted in Appendix E). Mission Specialist Sunita Williams kept a journal about her EVA from ISS following EDP in December, 2006, also quoted in Appendix G.

Survey of U-2 Pilots who used EDP

A survey was sent to U-2 pilots who used EDP in an effort to quantify the effectiveness of the procedure (Appendix E). Responses of the 2 pilots who responded indicated moderate to considerable success in reducing DCS incidence and/or severity. They did indicate very little to moderate increase in fatigue as a result of doing the EDP procedure. Thermal issues were also present, partially due to inadequate air conditioning at remote sites.

DISCUSSION

There are several potential ways of reducing DCS risk in U-2 operations. Although increasing cabin pressure differential is not feasible, it should be considered for any future high-altitude, piloted aircraft. Using partial pressure suit inflation could provide some additional useful effective prebreathe time during climb, albeit of short duration. Using differential suit pressure to maintain a lower physiologic altitude could be of value if that pressure does not adversely reduce mobility and/or comfort. Some additional prebreathe time provides a small amount of additional protection which may impact fatigue on long missions. However, enhancing the effectiveness of the standard 60-min prebreathe time with EDP appears to offer a better way to DCS risk (Webb et al., 1996).

The use of EDP was of assistance in greatly reducing DCS risk for the first pilot who used the procedure. If the level of effort, as measured by oxygen consumption, of pilots during high altitude cruise was measured, it could allow a better estimate of DCS risk. This estimate could be derived from study of a small cadre of pressure-suited pilots doing typical in-cruise activities in a ground-level simulator. Integrating that data with information from a proposed study of DCS risk during seated, resting exposures, would allow correlation with the recently acquired information on oxygen consumption vs. DCS incidence in research chamber operations (Webb et al., 2010). Part of this data acquisition effort would help clarify aspects of pilot activity necessary to alleviate effects of long-duration flights with very limited mobility.

Current Guidelines Regarding Return To Flying Status (RTFS)

Since EDP is not the absolute solution to better prebreathe, DCS will continue to occur. Since that is the case, it is pertinent to address return of the pilot to flying status following a case of DCS. AFI 48-123, Medical Examinations and Standards (24 Sep 09), guides that any episode of DCS or arterial gas embolism (AGE), which produces residual symptoms after completion of all indicated treatment or persists for greater than 2 weeks, requires a waiver (6.44.30.1.1.). The instruction also specifies that all episodes of DCS/AGE require a minimum of 72 hours DNIF after completion of treatment, and that DCS without neurological involvement that resolves completely within two weeks may be returned to flying status by the local flight surgeon after consultation with base SGP and USAFSAM Hyperbarics and MAJCOM/SGPA. Earlier guidance in the 1980's was much more restrictive and, in fact, permanently grounded the pilot if symptoms were reported. The change largely resulted from the analyses of three anonymous surveys of U-2 pilots, both active and retired (Bendrick et al., 1996). These surveys documented what was well known among the high altitude reconnaissance community. There was a high incidence of DCS, but it was not reported for fear of being grounded. Although fear of grounding is now largely a non-issue, DCS symptoms continue to induce additional stress during U-2 operational missions and occasionally result in mission degradation, including early descent, treatment, and increased preoxygenation time for some pilots who choose that option.

CONCLUSIONS AND RECOMMENDATIONS

EDP is more effective than resting prebreathe for most people susceptible to DCS. At least 3 U-2 pilots have used the procedure and NASA has employed it successfully. Crewmembers routinely exposed to cockpit altitudes above 20,000 ft with a history of DCS should be given the option of using an EDP procedure in an attempt to reduce the risk of developing symptoms. EDP should involve both upper- and lower-body exercise to ensure that major muscle groups experience the need for more oxygen and receive additional blood flow to enhance denitrogenation rate. EDP should involve approximately 2 min of warm-up exercise with the remaining 8 minutes at an intensity sufficient to induce a HR increase to about 75% of maximum for the individual. The total exercise should involve no more than 10 min of total exercise. This exercise should not be attempted in-suit as it could result in abrasion and/or overheating. U-2 pilots who have never reported DCS should not be required to do EDP unless they so choose. This conclusion is based on the Webb et al. (1996) paper which indicated that 2 of the 26 subjects in the EDP test of EDP vs. Resting prebreathe developed DCS after EDP but not after resting prebreathe. It also indicated that 9 of the 26 subjects developed DCS following both prebreathe procedures and 4 did not develop DC after either procedure. It was only the 11 of 26 who did not develop DCS following EDP and did develop DCS following the resting prebreathe who provided the evidence for the effectiveness of EDP.

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APPENDIX A

The four factors used to develop ADRAC, altitude, time at altitude, prebreathe time, and level of activity while decompressed, account for the vast majority of DCS risk with the first three able to alter the risk from zero to 100% of a subject population. The level of activity may increase a low to medium (10-50%) risk to 100%. None of the other factors listed in TABLE A1 appear to have the capability to increase a subject population's incidence by more than about 30% (Female BMI) and the rest each increase risk by no more than about 10%.

Two of the references listed, Webb et al. (2003) and (2005), indicate variable effects of the anthropometric and physiologic parameters due to the purpose and data used as their source. The analysis of the effect of gender required that all data emanate from exposures experienced by both males and females and that 5-95% DCS was reported. As a result of those restrictions, those analyses only used 809 subject-exposures from the AFRL DCS Research Database of over 3000 exposures. The analyses of susceptibility to DCS required that each subject had at least four subject-exposures, that there were at least 10 subject-exposures in each profile, and 5-95% DCS was reported. Those restrictions limited the total sample size to 859 subject-exposures. For the purpose of evaluating the effects of the anthropometric and physiologic parameters, a more diverse sample of subject-exposures was possible. However, since it was important to compare a range of DCS incidence to allow its variation, the limit of 20-80% DCS was imposed on each of the profiles used and each having at least 10 subject-exposures. As an example, it would provide little information about how the variation in weight affected DCS risk if the DCS incidence in a profile was 90% since nearly everyone, regardless of weight, developed DCS. Even with those restrictions, further analyses with an additional 280 subject-exposures completed after the 2003 report allowed use of 1919 subject-exposures by 313 males and 80 females. Although the previous studies' designs (Webb et al., 2003, 2005) required use of each subject's response to each profile, the current analyses had a different limitation. The average incidence of DCS reported by each subject was used in the current analyses since the anthropometric and physiologic parameters were of interest and those changed little throughout their involvement in the protocols. The total sample size of available information was divided into four groups of average parameter value. This allowed linear regression lines to be presented based on a relatively equal number of observations. The differences between what is shown in TABLE A1 and the previous reports cited above come from differences in sample size, profile selection based on purpose of the analyses, and the averaging of each subject's DCS reporting.

Several of the parameters shown in TABLE A1 indicate a high correlation ($R \geq 0.80$) between the parameter value and the DCS incidence. <u>However, this relationship is insufficient to have any value in predicting the DCS susceptibility of any one individual</u> (Webb et al., 2005), <u>only in showing that it is a factor in a population study</u>. Even as a factor, all but one of the anthropometric and physiologic parameters listed has less than about a 10% influence on DCS risk from the lowest to the highest average group value of that parameter. TABLE A2 and A3 show ORM individual and mission assessments of DCS risk factors based on the footnoted references for Table A1.

TABLE A1. Factors Which Contribute (or not) to DCS Risk

Factor	Higher Values	Lower Values	Relationship
Casual Factors Influencing DCS Incidence			
Altitude	More DCS	Less DCS	Sigmoidal[1]
Time at Altitude	More DCS	Less DCS	Sigmoidal[2]
Prebreathe Time	Less DCS	More DCS	Exponential[3]
Activity while at Altitude	More DCS	Less DCS	Linear[4]
Contributing Factors Influencing DCS Incidence			
Physical Fitness, $\mathbf{V}O_{2max}$	Slightly Less DCS	Slightly More DCS	[5]
Body Mass Index (BMI)	More DCS	Less DCS	[5]
Weight, Males	Slightly More DCS	Slightly Less DCS	Linear[5]
Height, Males	Slightly More DCS	Slightly Less DCS	Linear[5]
Age, Males	Slightly More DCS	Slightly Less DCS	Linear[6]
Age, Females	Slightly Less DCS	Slightly More DCS	Linear[6]
Female Menstrual Cycle	Influenced by hormonal contraception		Variable[7]
Body Fat, Females	Slightly More DCS	Slightly Less DCS	[8]
Suspected Factors Which May Influence DCS Incidence			
Level of Hydration	Slightly Less DCS	Slightly More DCS	Unproven
Fatigue	Slightly Less DCS	Slightly More DCS	Unproven
Environmental Temperature	Slightly Less DCS	Slightly More DCS	Unproven
Factors Which Do Not Influence DCS Incidence			
Gender			N.S.[9]
Height, Females			N.S.[5]
Weight, Females			N.S.[5]
Rate of Climb			N.S.[10]
Post-Flight Exercise			N.S.[11]

N.S. = Not Significant at $P < 0.05$; applicable only to groups of individuals with the same physiologic and anthropometric norms as the volunteer subjects tested at Brooks.

1 Webb & Pilmanis, 1995, Webb et al., 2003.
2 Webb & Pilmanis, 1995.
3 Webb & Pilmanis, 1995; Webb et al., 1996, 2002b; Webb & Pilmanis, 1999. Exercise During Prebreathe may provide additional protection if accomplished for 10 min (not longer) with a 2-min warm-up and 8 min at 75% of Heart Rate Reserve plus Resting Heart Rate (see Support for Transition of the Procedure) using both upper and lower-body exercise.
4 Webb et al., 2010. Repeated, levels of increased activity appear to result in more DCS. Typical activities during the Brooks AFB protocols were: Seated rest with occasional mild movement of arms and legs equivalent to a pilot hovering a helicopter and a KC-135 experienced pilot flying during an emergency. The high levels of DCS reported during exposures to 30,000 ft were well beyond pilot activities; between slow walking and recreational volleyball (Woodrow & Webb, 2010; Nutrition section)
5 Webb et al., 2003, 2005.
6 Webb et al., 2003, 2005. See Webb et al., 2003 for explanation.
7 Webb et al., 2003. Variable depending on stage of cycle.
8 Webb et al., 2003. Significant (P<0.05) only in 2003 report on females.
9 Webb et al., 2003. Females are less susceptible to development of venous gas emboli.
10 Pilmanis et al., 2004. Non-significant increase in neurologic DCS with 80,000 fpm rate of climb.
11 Webb et al., 2002a. Although there was no effect of post-exposure exercise on DCS incidence, it is not recommended since a minor injury could confound diagnosis of DCS.

TABLE A2. ORM Individual Assessment of DCS Risk Factors

99 ERS Individual DCS Risk Assessment

Name: **Date:**

Age, years	Points	Score
Females > 34	0.0	
Females 27-34	0.1	
Females < 27	0.2	
Males < 34	0.1	
Males No effect	0.0	
	Sub-Total	
Body Mass Index, Wt[#]/(Ht[inches])^2*703.08		
Females < 22	0.0	
Females 22-24	0.1	
Females > 24	0.3	
Males < 26	0.0	
Males > 26	0.1	
	Sub-Total	
Weight, pounds		
Males < 176	0.0	
Males > 176	0.1	
Females no effect	0.0	
	Sub-Total	
Height, inches		
Males < 70	0.0	
Males > 70	0.1	
Females no effect	0.0	
	Sub-Total	
Previous DCS events		
No prior DCS events	0.0	
One prior DCS event	0.5	
More than one prior DCS event	1.0	
	Sub-Total	
	Total Individual DCS Assessment	

Low DCS Risk:	0.0 to 0.2
Moderate DCS Risk	0.3 to 0.5
Increased DCS Risk:	>0.5

The Individual DCS Assessment is a one time evaluation of the pilots baseline susceptibly to DCS
The score will be calculated at the beginning of the pilots deployment and updated if required
The score will be added to the ORM score each flight
The scores above emphasize the negligible effect of individual factors

TABLE A3. ORM Mission Assessment of DCS Risk Factors

99 ERS Mission DCS Assessment

Name: **Date:**

Flight duration	Points	Score
< 8 h	0	
8-10 h	1	
> 10 h	2	
	Sub-Total	
Prebreathe		
Standard 60 min at rest	0.0	
90 min at rest	-0.2	
10-min exercise during prebreathe, total 60 min	-2.0	
	Sub-Total	
	Total Individual DCS Assessment	

Low DCS Risk:	0.0 to 0.8
Moderate DCS Risk:	0.9 to 1.0
Increased DCS Risk:	>1.0

Assumes consistent exposure pressure
Does not include any advantage from partial inflation of the pressure suit
Assumes consistent level of activity during exposure (unknown)
Emphasizes the effect of increased exposure duration & EDP

APPENDIX B

RESULTS FROM SURVEYS COMPLETED BY TWO U-2 PILOTS

SURVEY OF EFFECTIVENESS OF EXERCISE-ENHANCED PREBREATHE TO REDUCE OR ELIMINATE DCS SYMPTOMS DURING U-2 HIGH FLIGHTS
Survey Control Number (SCN): USAF SCN 08-028, valid through 2 October 2009
This is a non-retribution, anonymous survey.
This information will only be released as group averages.

<u>BEFORE</u> YOU STARTED USING EXERCISE-ENHANCED PREBREATHE:

1. How many high flights did you have? **<u>25, ~50</u>**

2. For what length of time did you pre-breathe prior to those high flights? Please make sure these add to 100%.

<65 minutes **<u>100%</u>** (all were approximately 60 minutes); 65-75 minutes **<u>0%</u>**; >75 minutes **<u>0%</u>**

3. During how many of those high flights did you experience DCS symptoms? 1+, 2 (if zero, skip to item 6.)
   Multiple times after flights, I would experience numbness on the top of my thighs the morning after. This may or may not be attributed to DCS or just sitting still for hours at a time causing nerve compression issues later.

4. Prior to those high flights where you experienced DCS symptoms, please identify the percent of flights where you prebreathed for the length of time specified. Please make sure these add to 100%. See above.

   Percent of fights where I experienced DCS symptoms when I prebreathed for <65 minutes: **<u>100, 100</u>**
   Percent of fights where I experienced DCS symptoms when I prebreathed for 65-75 minutes: **<u>0%</u>**
   Percent of fights where I experienced DCS symptoms when I prebreathed for >75 minutes: **<u>0%</u>**

5. How many of those high flights where you experienced DCS symptoms resulted in a degradation in mission effectiveness (early abort, change in mission parameters, etc.) due to these symptoms: **<u>2, 1</u>**

<u>AFTER</u> YOU STARTED USING EXERCISE-ENHANCED PREBREATHE:

6. How many high flights have you had? **<u>~20, 96</u>**

7. Before how many of those high flights did you use exercise-enhanced prebreathe? **<u>76, all</u>**

8. On how many high flights following use of exercise-enhanced prebreathe did you experience DCS symptoms? **1, 0**

9. Prior to those high flights where you used exercise-enhanced prebreathe AND experienced DCS symptoms, please identify the percent of flights where you experienced DCS symptoms when you did pre-breathe for the length of time specified. Please ensure these add to 100%.

   Percent of fights where I experienced DCS symptoms when I did exercise-enhanced prebreathe for <65 minutes: **0%**
   Percent of fights where I experienced DCS symptoms when I did exercise-enhanced prebreathe for 65-75 minutes:**100%**
   Percent of fights where I experienced DCS symptoms when I did exercise-enhanced prebreathe for >75 minutes: **0%**

10. On how many high flights following use of exercise-enhanced prebreathe did you experience DCS symptoms that caused degradation in mission effectiveness (early abort, change in mission parameters, etc.)? **0, 0**

11. What effect did the prebreathe with exercise have in preventing DCS symptoms or in significantly reducing incidence and/or severity of DCS symptoms relative to not using prebreathe with exercise (circle one)?
    None Very Little **Moderate** **Considerable**

12. To what extent did exercise-enhanced prebreathe increase your level of fatigue throughout your high flights relative to not using it? (circle one)
    None **Very Little** **Moderate** Considerable

Other negative effects of exercise-enhanced prebreathe:

Discomfort due to being hot and sometimes sweaty before even getting into suit, sweat on glasses, and no way to clean them for remainder of missions (sometimes over 11 hours), inconvenient or impractical for short-notice contingency missions, threw off timing when flying with student, threw off timing with maintainers when flying FCF sorties. I preferred not to do the exercise-enhanced prebreathe whenever possible, and found that I could successfully do that with no symptoms for flights up to 200 minute duration. All of the sorties in which I experienced DCS symptoms occurred when not pre-exercising and sortie durations of more than 200 minutes. The exception to that was approximately 10 years earlier when flying an unpressurized T-37 at FL250 for approximately 90 minutes, on one occasion I experienced joint pain.

The suit up facilities at Osan are marginal in the summer time. The air conditioner can cool the area down some but with the high humidity, any exertion in the summer time makes you sweat. Then, because of mission timing, you only get about 5-10 minutes to cool down again before you

have to start integrating. So I spent the first hour or two hours with cooling set to maximum in an effort to stop sweating.

Optional Information

Average age, **35.5**; BMI, **32.4**; personal estimate of physical fitness, **Moderate**

13. Remarks about prebreathe with exercise for some U-2 pilots:

The exercise prebreathe is a fix to a symptom. The real problem is the long exposure to high altitudes. An engineering study to try to drop cabin altitude to 18,000 feet would solve/address the real problem.

The pre-breathe with exercise allowed me to continue flying the U-2 after two mission aborts early in my U-2 career requiring treatment in a hyperbaric chamber. Although it was somewhat of a "pain in the neck," it did allow me to keep flying. Later in my U-2 career, I did some "experimenting" with high flights without the pre-exercise, and found I could safely fly up to 200 minute durations with no problems. Beyond that, I was taking my chances, and so wound up doing the pre-exercise on all of the long-duration operational missions.

APPENDIX C

Figure C1. Monarch 818E Leg Ergometer and Monarch 881E Arm Ergometer

If the dual-cycle ergometer does not need to be mobile, as shown above, the arm ergometer may be positioned via a wall mount[12] or table so it will be in the same relative position above the leg ergometer flywheel so that both can be appropriately adjusted and operated.

These ergometers have the appropriate resistance and rpm indications and otherwise meet the required measurements to ensure that the appropriate level of leg ergometry (0-7 kp) can be established and maintained by appropriately trained physiology technicians in support of high altitude reconnaissance efforts of Air Combat Command. The Monarch 818E Leg Ergometer has the appropriate resistance and rpm indications with the appropriate adjustability for arm length (4 feet and 7 feet tall) and arm length (20" to 40"). This is to ensure that the appropriate level of arm ergometry (0-4 kp) can be established and maintained by appropriately trained physiology technicians in support of high altitude reconnaissance efforts.

[12] The wall mount is not available thru Monarch and must be constructed locally. One suitable and reasonably versatile mount consists of Superstrut® A1400 metal framing channels (1, 10-ft channel cut into 5-ft lengths) fastened vertically to a wall at about 3-8 ft high and approximately 18" apart. Superstrut® S-236 brackets are held to the framing channels with CM 100-1/2 Nylon Cone Nuts and E-142 ½ X 15/16" hex head cap screws to provide the basis of a movable platform. A ¾" plywood platform about 20 ½ X 27" will ensure adequate size to allow the channels to be fastened to wall studs or into concrete block with molly screws or lag bolts.

APPENDIX D

CHECKLIST FOR INCORPORATION OF DUAL-CYCLE ERGOMETRY DURING PREOYXGENATION[13]

Time	Activity
0-15	The leg and arm ergometers are adjusted to the height and spacing appropriate for the pilot[14]
0+00	The pilot will begin preoxygenating (100% oxygen) with three, slow, deep ventilation cycles to help clear respiratory dead space of high nitrogen concentration. After completing the first three breaths, the pilot will mount the cycle ergometer and begin to pedal
0+00	The pilot will maintain leg ergometry at 60 rpm and 1 kp for 1 min to warm up
0+01	After 1 min at 1 kp on the leg ergometer, the resistance will be increased to 2 kp for the second min as a continued warm-up
0+02	After 1 min at 2 kp on the leg ergometer, the resistance will be changed to the target leg kp and the arm ergometry will begin at 60 rpm and target arm kp/Watts
0+02	If the pilot's HR exceeds the target HR (220 - age) the resistance should be reduced on the arms by 0.1-0.2 kp for 30 sec while observing the change in HR. If the HR continues to climb, reduce the leg resistance by 0.2 kp and continue observation. This cycle should be continued to smoothly adjust the pilot's HR to the desired level.
0+10	After 10 min of ergometry (2 min of warm-up and 8 min of dual-ergometry), the pilot will discontinue arm ergometry and begin cool-down leg ergometry at 60 rpm and 1 kp for at least 1 min
0+11	Following the cool-down period, the pilot will dismount the ergometer and continue donning personal equipment and the pressure suit without breaking preoxygenation.

The 10-min exercise at approximately 75% of peak oxygen uptake is accomplished by the pilot at the beginning of preoxygenation. Estimated peak oxygen uptake ($\mathbf{VO}_{2peak}$) for the pilot in ml/kg/min can be obtained from the Health and Wellness Center (HAWC) US Air Force Cycle Ergometry Test results. They provide the basis for calculating the initial resistance to be set on the dual-cycle ergometer during EDP. The estimated $\mathbf{VO}_{2peak}$ was multiplied by the pilot's wt in kg/1000 to obtain $\mathbf{VO}_{2peak}$ in l/min for the pilot. The resistance for leg and arm exercise at 60 rpm can then be derived from Appendix H.

[13] Alternative exercise devices should ensure both upper- and lower-body exercise is accomplished at a level which ensures increased blood flow while not resulting in muscle fatigue or injury.
[14] Figure C1 shows relative placement of the arm/leg ergometers to allow comfortable exercise without excessive strain.

APPENDIX E

CHECKLIST FOR INCORPORATION OF GENERIC UPPER AND LOWER BODY EXERCISE DURING PREOYXGENATION[15]

Time	**Activity**
0-15	The exercise device is adjusted to the height and spacing appropriate for the pilot.
0+00	The pilot will begin preoxygenating (100% oxygen) with three, slow, deep ventilation cycles to help clear respiratory dead space of high nitrogen concentration. After completing the first three breaths, the pilot will mount the exercise device and begin a warm-up
0+00	The pilot will establish a comfortable level of exercise which involves arm and leg movement with resistance.
0+01	After 1 min, the resistance or rate will be increased to for the second min as a continued warm-up.
0+02	After the 2-min warm-up, the resistance and/or rate will be increased to a level the pilot can easily sustain for 8 min and results in a significant increase in HR and ventilation without causing excessive thermal load or fatigue.
0+02	If the pilot's HR exceeds the target HR (75% of [220 - age]) the resistance and/or rate should be reduced slightly to ensure it remains no higher than this level.
0+10	After 10 min of exercise, the pilot will considerably reduce resistance and/or rate for at least 1 min as a cool-down.
0+11	Following the cool-down period, the pilot will dismount the exercise device and relax for a few minutes, possibly using cool, moist towels to wipe down, trying to reduce any continued thermal loading.

[15] Alternative exercise devices should ensure both upper- and lower-body exercise is accomplished at a level which ensures increased blood flow while not resulting in muscle fatigue or injury.

APPENDIX F

GERNHARDT, ET AL. 2000 ABSTRACT

Gernhardt ML, Conkin J, Foster PP, et al. Design of a 2-hour prebreathe protocol for space walks from the international space station. Aviat Space Environ Med 2000; 71:277-8.

> "Purpose. The majority of extravehicular activities (EVAs) performed from [the] shuttle use a 10.2 psi staged decompression. The International Space Station (ISS) will operate at 14.7 psi, requiring crews to "campout" in the airlock at 10.2 psi. The constraints associated with campout (crew isolation, oxygen usage and waste management), provided the rationale to develop a 2-hour prebreathe protocol from 14.7 psi. Previous studies on the affect of microgravity and EDP suggested the feasibility of this approach. Methods. Various combinations of adynamia (non-walking subjects), prebreathe exercise doses, and space suit donning options (10.2 vs. 14.7 psi) were analyzed against timeline and consumable constraints. Prospective DCS and venous gas emboli (VGE) accept/reject criteria were defined from statistical analysis of historical DCS data, combined with risk management of DCS under ISS mission circumstances. Maximum operational DCS levels were defined based on protecting for EVA capability with two crewmembers at 95% confidence, throughout ISS lifetime (within the constraints of NASA DCS disposition policy JPG 1800.3). The accept/reject limits were adjusted for greater safety (including Grade IV VGE criteria) based on analysis of related medical factors. Monte-Carlo simulation was performed to design a closed sequential, multi-center laboratory trial, including the capability of rejecting the primary protocol and testing at least one alternate exercise dose, within the 2-hour prebreathe. Results. The 2-hour protocol incorporates O_2 breathing for 50 min at 14.7 psi, including 10 min dual-cycle ergometry at 75% of $\dot{V}O_{2peak}$. It requires an additional 30 min O_2 breathing during depress from 14.7 to 10.2 psi, followed by a 30-60 min suit donning break at 10.2 psi/26.5% O_2. It concludes with a 40-min in-suit O_2 prebreathe. The protocol would be accepted for operations if the incidence of DCS was less than 15% and Grade IV VGE less than 20%, both at 95% confidence. Conclusion. The above protocol and accept/reject limits were implemented in a multi-center study."

APPENDIX G

EXCERPT FROM INTERVIEW WITH DR. MIKE GERNHARDT PRIOR TO HIS STS-104 (12 to 24 JULY 2001) FLIGHT

http://spaceflight.nasa.gov/shuttle/archives/sts-104/crew/intgernhardt.html

Q: “Will there be any appreciable difference in, say, prebreathing procedures beforehand?”

A: “Yes. Actually, we're working, and we hope to use on this flight, a new prebreathe protocol, and that's a great question. On the shuttle, we typically go down to 10.2 psi, so we depress the whole cabin of the shuttle from 14.7 psi to 10.2 psi with 26½% oxygen. And on the vast majority of the shuttle flights we stay there thirty hours or more -- actually, the average has been forty hours. And that allows us to re-equilibrate at the lower pressure and lose nitrogen. Then, before we go EVA we get into the suits and we breathe another forty minutes of oxygen, to purge the nitrogen so we don't get bubbles that can give us "the bends." Well, on space station we can't drop the whole space station down to 10.2 psi because it wasn't designed to work that way, partially because some of the life science experiments they do they want to have it the same pressure as ground controls, and so for that reason none of the hardware was certified to operate at the lower pressure, and at lower pressures the cooling is not as good and so forth. So the whole station has to stay at 14.7 psi. So the two options that we have are, first, campout, which was the baseline procedure, where would we have to go into the airlock, this Joint Airlock, the night before we did a space walk, depressurize to 10.2 psi, and sleep there. And keep in mind, you're isolated and there's no bathroom or food or anything, you know, none of the things that you would like to have as far as comfort features. So, we would campout in the airlock, and then in the morning we'd put on these oxygen masks so we didn't interrupt the prebreathe and re-saturate with nitrogen, we'd have to re-compress the airlock, exit on a long hose to go use the bathroom, and then on the way back grab some food, get back into the airlock, depressurize that to 10.2 psi, eat your breakfast, and then prepare to do your space walk. And there's a lot of overhead in that -- in fact, it really wasn't going to work out that well in the sense that you couldn't do back-to-back EVAs, and still meet our scheduling constraints, because you'd of had to get one crew back in and out and the other crew in to campout, and so, you know, it was workable but certainly not an optimal approach. Back in 1997, we started a project called the Prebreathe Reduction Program, which was based on a lot of enabling research that had gone on here at NASA and at the Air Force, and Duke University over several years looking at how to cut back on the prebreathe while maintaining the same degree of safety. And one of the things we jumped on was the use of exercise during prebreathe to speed up your blood flow and your nitrogen elimination, and that was based on the experiments that the U.S. Air Force had done with Drs. Pilmanis and Webb, some of the basic research done here by Dr. Michael Powell, and some work at Duke. So, I joined that team and actually functioned as the project manager and then Principal Investigator to develop this protocol, that we hope to use on our flight; it's in the final stages of approval now, but it's the two-hour exercise prebreathe protocol. And what we do is we get up and we don't have to campout so we sleep at the station, you know, 14.7 psi, we get up in the morning and we have an hour where we don't have to do anything other than our regular crew, post-sleep activities. And then we put on oxygen masks and we go and we ride the station bicycle against a very specific exercise prescription that's based on our maximum aerobic capacity that we've already had a test on, and we ride the bike for just ten minutes -- there's basically a five-minute warm-up, and then there's five minutes at what's called 75% $\mathbf{VO}_{2peak}$, which is basically like a nice jog. So we ride the bike and we're pulling on surgical tubes to keep our upper body moving, and what's happening is you're increasing your cardiac output and your blood flow, and the more blood flow you have to the tissues the more nitrogen is carried back to your lungs. And so we do that, and then we do the balance of eighty minutes on the mask, preparing to get in our suits. So at that point, we end up getting in the airlock, we start putting on our liquid cooling garment, our biomed, we do some power-ups and suit checks on the suits; once we arrive at 10.2 psi then we can come off the masks and take our time to get in the suit, and, you know, once we get in the suit it's just like what we do on the shuttle -- we do another forty minutes prebreathe and go out the door. And we worked with a very world-class team of decompression researchers at the Canadian Defense and Civil Institute for Environmental Medicine, Duke University, and Hermann-UT. We did a whole bunch of tests of this trial, or of this protocol -- we actually looked at four different exercise levels, and what we found is that the ten minutes of heavy exercise by itself was not sufficient to provide adequate protection, then we looked at light exercise and light exercise by itself, associated with the EVA prep, wasn't enough; but when we coupled the heavy and the light, we didn't have any decompression sickness. Actually, it's the safest trial that we've had to date, and, like I said, it's going through the final approval process, and we hope to use it for this flight; if not for this flight, then in the very near future.”

APPENDIX H

EXCERPT FROM MISSION LOG OF MISSION SPECIALIST SUNITA WILLIAMS ABOUT HER EVA FROM ISS DURING STS-116 ON 16 DEC 2006 DESCRIBING NASA EVA PREBREATHE PROCEDURES

(http://www.nasa.gov/mission_pages/station/expeditions/expedition15/journal_sunita_williams_10.html):

> "There are 3 methods we use to purge the nitrogen out of our blood to prevent "the bends." The methods are pretty complicated in reality and a ton of research and data were needed to establish these "protocols." But, in general they are:
>
> 1. Pre-breathe - Get in the space suit 4 hours early and hang out breathing 100% O_2 before opening the hatch and going outside.
> 2. Exercise - Wearing a mask breathing 100% O_2, exercise on the bike for about 15 minutes doing an interval workout using both arms and legs to accelerate exchange of O_2 for air in the blood.
> 3. Camp-out - Sleep overnight in the airlock at a decreased pressure with an increased O_2 concentration so that the O_2 level in the blood increases as you sleep. Get up in the morning, get on a mask of 100% O_2 to re-pressurize to ambient - to use the bathroom one last time before the EVA - and to let 3rd crewperson into the airlock to help us get in the suit."

Dr. Williams' account, above, of the use of EDP on the ISS did not exactly follow what was shown to be effective during NASA trials as reported in the abstract by Gernhardt et al. (2000) and his interview in 2001; i.e. using a 10-min strenuous EDP. ISS mission specialists may have used a 15-min exercise as stated above, and some additional exercise later in prebreathe according to Dr. Gernhardt's interview. If 15 min of exercise was performed, it may have been because they did not have the information presented in a later paper resulting from additional research on EDP (Webb et al., 2002b). That research indicated a 15-min EDP was no better than the 10-min EDP and perhaps not as effective. Survey results from 2 U-2 pilots indicated improvement in DCS protection, albeit with some issues with fatigue and heat stress.

APPENDIX I

DETERMINATION OF LEG AND ARM WORKLOAD (KP) AT 60 RPM TO OBTAIN 75% OF VO2PEAK ENTERING WITH VO2PEAK IN L/MIN

TABLE E1. VO_{2peak} vs. Workload

VO_{2peak}	Leg kp[16]	Arm W[17]	Arm kp[19]
2.10	1.4	21	0.9
2.20	1.5	22	0.9
2.30	1.6	23	1.0
2.40	1.7	25	1.0
2.50	1.8	26	1.1
2.60	1.8	27	1.1
2.70	1.9	28	1.2
2.80	2.0	29	1.3
2.90	2.1	31	1.3
3.00	2.2	32	1.4
3.10	2.3	33	1.4
3.20	2.3	34	1.5
3.30	2.4	36	1.5
3.40	2.5	37	1.6
3.50	2.6	38	1.6
3.60	2.7	39	1.7
3.70	2.8	40	1.7
3.80	2.8	42	1.8
3.90	2.9	43	1.8
4.00	3.0	44	1.9
4.10	3.1	45	1.9

[16] Extrapolation is necessary when applying derived resistances to the Monarch leg ergometer because it is only marked in 0.5kp increments.
[17] W = watts as marked on the arm ergometer; kp as marked on vernier applied after delivery.