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EVALUATION OF THE DCIEM 1983 DECOMPRESSION MODEL FOR COMPRESSED AIR DIVING (SERIES A-F)

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ABSTRACT

The Defence and Civil Institute of Environmental Medicine (DCIEM), Downsview, Ontario, has developed a new mathematical model for decompressing compressed air divers. This model, referred to as the **DCIEM 1983 DECOMPRESSION MODEL,** has been employed for real-time computer-controlled diving using the DCIEM XDC-2 decompression computer. This report presents the results of 391 experimental man-dives within the proposed Canadian Forces "normal" air diving limits decompressed on the new model with **Standard Air, In-Water Oxygen,** and **Surface Oxygen** decompression procedures. Both single dives and repetition dives were examined. The effectiveness of the decompression was assessed both subjectively (classical symptoms of decompression sickness) and by Doppler ultrasonic bubble detection methods.

The decompression schedules based on the DCIEM 1983 model are considerably more conservative than the equivalent United States Navy (USN) and Royal Navy (RN) schedules. However, the experimental results contained in this report indicate that this conservatism is both justified and necessary.

This report is the first of several to be published as the DCIEM 1983 Decompression Model validation process continues. These reports will be sequentially designated (Series A-F, Series G-K, etc.).

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INTRODUCTION

In early 1983, DCIEM developed a new model and procedures for decompressing compressed air divers. This model, referred to as the **DCIEM 1983 DECOMPRESSION MODEL** (1) is based on the pioneering decompression work done at DCIEM by Kidd and Stubbs (2,3,) and continued by others (4,5).

The culmination of these early efforts was the development of a microprocessor-based digital decompression computer programmed with the Kidd-Stubbs 1971 decompression model (KS-1971) - the XDC-2 (6). This instrument has since been used extensively for real-time computer-controlled diving at DCIEM (7,8,9). In 1982, XDC-2 controlled oxygen decompression procedures were developed and evaluated (10).

DCIEM has been assessing the safety of decompression profiles for compressed air diving with the Doppler ultrasonic bubble detector since 1979. Analyses of a variety of dive data indicate that there is a correlation between the number of bubbles observed in the precordial region and the safety of the decompression procedure. Although Decompression Sickness (DCS) does not necessarily accompany high bubble grades (according to grading schemes such as the Kisman-Masurel (11) or Spencer (12) bubble codes), most of the cases of DCS reported were associated with high bubble grades (grades 3 or 4). Therefore, with decompression profiles which consistently produce high bubble grades in a majority of divers, there is a definite risk of DCS, and such profiles should be avoided. Conversely, if decompression profiles consistently result in no observable bubbles, they may be overly conservative.

The extensive evaluations of the KS-1971 model using Doppler ultrasonic bubble detection (7-10) resulted in the following conclusions:

a. the KS model is overly conservative for short bottom times and therefore, it has a very restrictive no-decompression limit;

b. as bottom times are increased, the model becomes less conservative and results in increased decompression stress; and

c. at extended bottom times, the KS model again becomes excessively conservative.

The DCIEM 1983 Decompression Model was developed to overcome these shortcomings while still retaining the simplicity of the original KS model. Figure 1 presents a graphic comparison of the two models and shows that the DCIEM 1983 model does indeed remove the anomalies of KS-1971 outlined above.

For these evaluations, the XDC-2 decompression computer was reprogrammed with the DCIEM 1983 model and all dives were controlled in real-time by this computer. The dive profiles chosen for the initial evaluations are profiles previously examined with Doppler (using the KS-1971 model) where the new model reduced the decompression times maximally, and where the decompression times were increased. This provides a good comparison of the relative effectiveness of the two models. Other profiles examined here are based on the proposed Canadian Forces normal air diving limits to 54 metres of seawater (msw) or approximately 180 feet of seawater (fsw). **Standard Air, In-Water Oxygen,** and **Surface Oxygen** decompression procedures were evaluated for both single and repetitive dives. Table 1 details the dive profiles and decompression schedules used in this study and Figure 2 presents the proposed air diving limits.

This report presents the general results of the initial evaluation of the DCIEM 1983 Decompression Model. A detailed analysis of the results of these experiments will be published separately.

EXPERIMENTAL METHODS

1. DECOMPRESSION PROCEDURES

The general procedure for real-time computer controlled diving at DCIEM is as follows:

a. descend at 18 msw/min (60 fsw/min) or slower;

b. ascend at 18 msw/min or slower to the closest multiple of 3 msw (10 fsw) which is deeper than the indicated Safe Ascent Depth (SAD) of the XDC-2;

c. remain at that stop until the SAD has decreased to the next shallower 3 msw (10 fsw) multiple and then ascend to this next stop and so on; and

d. surface when the SAD = 0.

The specific decompression procedures used for these experiments were:

a. **Standard Air** Decompression

(1) The divers did a normal XDC-2 ascent at 18 msw/min to the first stop which was the closest multiple of 3 msw deeper than the indicated SAD;

(2) The divers remained at that stop until the SAD indicated the next shallower multiple of 3 msw and then ascended to that stop, and so on; and

(3) The divers surfaced from the 3 msw stop when the SAD reached "0".

b. **In-Water Oxygen** Decompression

(1) The divers did a normal XDC-2 ascent at 18 msw/min to 9 msw (30 fsw) and stopped;

(2) The divers' gas and the XDC-2 were switched to O_2. The divers remained at 9 msw until the SAD read "0"; and

(3) The divers then surfaced at 4.5 msw/min. (Note 1).

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NOTE 1: Because of vent rate limitations in the hyperbaric facility used for these experiments, almost 2 minutes were required to surface from 9 msw. Therefore, the decompression profiles presented in Table 1 show a time of 2 minutes for ascent from the 9 msw water stop.

c. **In-Water Oxygen + Surface Oxygen** Decompression

(1) The divers did a normal XDC-2 ascent at 18 msw/min to 9 msw and stopped;

(2) The divers' gas and the XDC-2 were switched to O_2. The divers remained at 9 msw until the XDC-2 SAD read "6 msw" (Note 2);

(3) The divers were then brought directly to the surface on O_2, undressed and recompressed to 12 msw (40 fsw) on O_2 in the Recompression Chamber (RCC) as rapidly as possible. The time from leaving the 9 msw in-water stop to reaching the 12 msw RCC stop, the Surface Interval (SI), was not to exceed 7 minutes (Note 3);

(4) The divers remained at 12 msw breathing O_2 until the XDC-2 SAD read "-1" msw (Note 4). No air breaks were taken; and

(5) The divers then surfaced at 6 msw/min on O_2.

Since these experiments were done, the decision has been made to modify this procedure to the more traditional method of using air only in the water and commencing O_2 breathing in the RCC on the surface. This procedure lengthens the 9 msw water stop times slightly (i.e., for a 36 msw/50 min dive, the 9 msw stop on air is 7 min vs. 4 min on O_2). Further, it was decided to introduce 5-minute air breaks after each 30-minute O_2 period in the RCC. Experiments performed with this new "SurD O_2" procedure will be reported separately.

All dives were controlled in real-time with the XDC-2 computer with printed tables available as backup. Dives were conducted in the DCIEM Diving Research Facility (DRF) which is equipped with a horizontal (isobaric) wet chamber.

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NOTE 2: Experience had shown that a diver could be surfaced safely for recompression in a chamber after completing the required 9 msw in-water stop - i.e. when SAD = 6 msw.

3: The 7-minute SI was chosen to enhance the operability of the procedure and to reduce the chances for "omitted" decompression. The full 7-minute SI was used throughout these experiments.

4: The divers remained on O_2 at 12 msw in the RCC until the indicated SAD = "-1 msw" to provide a compensatory decompression benefit for the time that they were in violation of the model during the SI. By using the computer SAD to define it, this benefit was always proportional to the severity of the dive.

The experimental dive program reported here is divided into 6 distinct phases as follows:

a. **Series A**

Standard Air decompression for selected dive profiles where decompression was reduced vs. KS-1971;

b. **Series B**

Standard Air decompression for selected profiles where decompression was increased vs. KS-1971;

c. **Series C**

In-Water O_2 decompression for four standard dive profiles;

d. **Series D**

In-Water O_2 + Surface O_2 decompression for four standard dive profiles;

e. **Series E**

Standard Air decompression for selected repetitive dive combinations; and

f. **Series F**

In-Water O_2 + Surface O_2 decompression for one repetitive dive combination.

Table 1 shows the dive/decompression profiles which were tested. For these decompression profiles, the stop times include the ascent time to the stops.

2. DIVE SUBJECTS

Each dive was planned to include a wet, working diver (on a bicycle ergometer) wearing a Viking dry suit with underwear and a Superlite SL-17B helmet; a wet, swimming diving (swimming against a barrier) and a standby diver wearing Viking dry suits with underwear and AGA Full Face Masks; and two dry, resting subjects and a team leader, all wearing coveralls. Heart rates were measured on both wet divers to control the work level as shown in Table 2.

Team leaders were DCIEM Clearance Divers. The other subjects were divers from the DCIEM Ships Diver roster, CF Reserve Divisions, the Canadian Underwater Training Centre, the Fleet Diving Units, the US Navy, the Royal Navy, and the French Navy. The subjects who participated in this study were all male. Their age, weight, and height (means and standard deviations) were 27 $\pm$ 6 yr, 76 $\pm$ 8.1 kg, and 1.77 $\pm$ 0.06 m, respectively.

All dive subjects had a minimum of 36 hours between dives and were asked not to engage in strenuous physical exercise (which was not a part of normal daily routine) for 24 hours pre-dive and for 12 hours post-dive.

3. DOPPLER ULTRASONIC MONITORING PROCEDURES

The instrument used for monitoring bubbles was the model "DUG" Bubble Detector developed by the Institut National des Sciences Appliquées de Lyon for the Centre d'Etudes et de Recherches Techniques Sous-Marines in Toulon, France, and manufactured by Sodelec SA of Marseille, France.

All divers were monitored for bubbles at the precordial site (right ventricle and/or pulmonary artery) and the subclavian sites (both left and right shoulders.) Two conditions were used at each site; in the first condition, the diver stood at rest, and in the second, the diver performed a specific movement. For the precordial site, this movement was a deep knee-bend - squatting and returning to the standing position in a continuous, smooth motion. For the subclavian sites, the movement consisted simply of clenching the fist on the side being monitored.

The Doppler ultrasonic signals, which include contributions from blood flow, cardiac motion, and bubbles, were simultaneously recorded on audio magnetic tape and assessed aurally. In cases of doubt, the tape recording was replayed and compared with the pre-dive reference recording. The bubble signals were classified according to the Kisman-Masurel code (11) which uses three criteria (each on a scale from 0 to 4):

a. the number of bubbles per cardiac cycle;

b. the percentage of cardiac cycles with bubbles; and

c. the amplitude of the bubble signals relative to the background.

The resulting 3-digit code was used to obtain a global bubble grade from 0 to 4. This bubble grade scale is similar to the other commonly used bubble grade scale developed by Spencer (12).

Monitoring was performed by two teams of experienced technicians. The reference signal was recorded before each dive, and each subject was monitored at half-hour intervals for at least two hours following the end of decompression. During this time, the divers were asked to rest in the immediate vicinity, and to refrain from excessive post-dive activity, since this is thought to contribute to decompression problems (7). If bubbles were detected, the subject was required to remain under observation until the bubbles diminished to insignificant numbers. For the repetitive diving experiments, the subjects were monitored between the dives as well as after the second dive.

The subjects were asked to report any pain or other symptoms of decompression sickness (DCS). The attending Diving Medical Officer considered subjective symptoms only, not bubble grades, in deciding whether to treat for DCS.

4. ANALYSIS PROCEDURES

The Doppler results, expressed as bubble grades, were used to assess the decompression stress experienced by each subject for a given dive profile and decompression method. A high bubble grade was considered indicative of a stressful dive for that individual. If several of the divers had high bubble grades, then this pointed to a stressful profile. These results were qualitative.

As previously stated, a much more detailed analysis of the results of these experiments (including an analysis-of-variance (ANOVA) interpretation of the Doppler data) will be published separately.

RESULTS

1. DIVE PROFILES

Table 3 (first four columns) shows the actual dives carried out with the total number of subjects in each dive and the number of wet, working divers. The water temperature for wet divers ranged from 6.8°C to 11.2°C. (Not all subjects were allowed to dive for medical or other reasons on their designated dives, and this accounts for the variation in the number of subjects in each dive.)

In Series B, one dive planned for 54 msw for 25 min had to be aborted after 21 min because of a suspected CO_2 problem. This dive has been included in this study, however, since the decompression computer was being used to control the decompression and, as a result, the decompression profile used was that calculated for exactly 21 min at 54 msw. A total of 63 man-dives using Standard Air decompression were completed in Series A and B.

A total of 93 man-dives using In-water O_2 decompression were done in Series C and 76 man-dives using In-Water O_2 + Surface O_2 decompression were completed in Series D. Three repetitive dive combinations (80 man-dive combinations) were examined in Series E and F, with Standard Air and In-Water O_2 + Surface O_2 decompression, respectively.

2. DOPPLER RESULTS

A summary of the maximum precordial bubble grades observed for all dives performed in this study is contained in Table 3 (Columns 5-14). The detailed Doppler results for two dive profiles, using different decompression methods, are presented in Table 4. A bubble grade of "0" represents no detectable bubbles. Increasing bubble grades indicate increasingly larger numbers of bubbles, with grade "1" representing only one or two bubbles per cardiac cycle, and grade "4" representing bubbles too numerous to count.

Table 5 presents the Doppler results for certain dive subjects involved in these experiments. This table highlights the differences between subjects in general. Some divers, RSD and SN for example, could be classified as high bubblers, while others, such as SMD and AR produced consistently few bubbles or none at all. For subject SP, the dives with decompression on air alone, seemed to produce more bubbles than the dives in which O_2 was used during decompression. For SN, however, the decompression method seems not to have made a difference.

In the case of RSD, although he was classed as a high bubbler during the air dives and the first series of O_2 dives, he had very few bubbles during subsequent dives. Although part of the reason for this may be the different dive profiles, it should be noted that RSD had started an exercise program and was in a much better state of physical fitness for his later dives.

Table 6 provides a summary of the percentage of man-dives which resulted in "minimal" Doppler scores ("0" or "1", precordial, after movement) for similar profiles examined with different decompression methods. In all cases, the two oxygen methods resulted in more subjects with no detectable bubbles, or only 1 or 2 bubbles per cardiac cycle, than the Standard Air method. This table tends to confirm the trend first observed during the initial O_2 decompression experiments with the KS-1971 model (10), which is that the use of O_2 during decompression enhances the "efficiency" of the decompression procedure.

Table 7 provides a comparison of Doppler results for similar dive profiles using Standard Air decompression schedules based on the KS-1971 and the DCIEM 1983 models. (Some dives included in this table were not part of these particular experiments. However, they were all computer-controlled and Doppler-monitored experimental dives performed at DCIEM.) This table shows that the DCIEM 1983 model resulted in more subjects with no detectable bubbles in the precordial region after movement and that there was a considerable reduction in subjects having grade 3 and 4 bubbles compared to the KS-1971 model. Thus, the decompression stress is lower with the DCIEM 1983 model.

3. DECOMPRESSION SICKNESS (DCS)

The number of incidents of DCS on each profile are shown in Table 3 (last column). All cases of DCS were treated using USN Treatment Tables (13).

a. **Standard Air** - Series A, and

b. **Standard Air** - Series B

For decompression on compressed air only, there were four incidents of DCS in 63 man-dives.

(1) Dry, resting subject MAP had Type I DCS (pain in his right hip) after leaving the stop at 3 msw following a dive to 36 msw for 50 minutes. Grade 0/3 (at rest/after movement) precordial bubbles were detected at 3 msw, and grade 3+ was observed when he reached the surface. Treatment commenced immediately. There was a possibility that restricted circulation may have been a contributing factor in this case.

(2) Diver BM, the standby diver in a dive to 36 msw for 50 min, had Type I DCS (pain in both shoulders) following the dive. Grade 2 bubbles were detected in the precordial site and one shoulder. Some bubbles were also detected in the other shoulder and inferior vena cava.

(3) Dry, resting subject RS had Type II DCS. He reported numbness in fingers and knee and extreme fatigue in the evening following the dive to 54 msw for 21 min. This dive had originally been planned for a 25 min bottom time. Bubbles were observed (grade 3 peak) from 66 min to 153 min following the start of decompression.

(4) Subject RSD had a skin bend after a dive to 45 msw for 30 minutes in which he was the wet, working diver. He was treated with Surface Oxygen only and was totally asymptomatic after 1 hour. His peak precordial bubble score was 3+/3+, and he had high bubble counts for over 6 hours following the dive.

c. **In-Water Oxygen** - Series C

There were two incidents of DCS in 93 man-dives.

(1) Dry, resting subject JK had Type I DCS (pain in shoulder) after a dive to 27 msw for 60 min. He was not monitored since symptoms were reported within 5 min after surfacing and he was recompressed immediately for treatment. This incident was judged to have been caused by an ill-fitting O_2 mask during the O_2 breathing phase which resulted in a serious violation of the prescribed decompression.

(2) Dry, resting subject RB had Type II DCS after a dive to 45 msw for 40 min. Bubbles were detected from 63 min to 213 min following the start of decompression, with a peak score in the precordial site of 2/3. He reported knee pain, headache and vision problems.

d. **In-Water Oxygen + Surface Oxygen** - Series D

Three incidents were associated with surface decompression dives (76 man-dives).

(1) Wet, working subject LC had Type I DCS (pain in both shoulders and hips) during the surface interval in a dive to 45 msw for 40 min. He was not monitored since he did not report any symptoms until he was recompressed to the 12 msw O_2 stop. He was then locked out and treated on a Table 5. Symptoms persisted and he was treated again (Table 6) on the following day. It was later discovered however, that the symptoms were probably not due to DCS but rather, caused by other pre-dive activities.

(2) Subject BM, who previously incurred DCS during the standard air dives, had Type I DCS following a dive to 45 msw for 40 min. He was the team leader for this dive. No bubbles were detected in the precordial region. Grade 1 bubbles were detected in the left shoulder from 76 to 139 min after the start of decompression. His symptoms were pain in the right shoulder on the day following the dive and he was treated on a Table 6 with one extension.

(3) Finally, dry, resting subject BL had Type I DCS (pain in thumb) after a dive to 54 msw for 30 min. This may have been the result of a minor injury to his thumb during the dive. Bubbles were detected from 82 min to 175 min (peak 3/3-, right subclavian). A few bubbles were also detected in the precordial region (0/1).

(4) A fourth subject, RP, was treated following a surface decompression dive to 54 msw for 30 min as a wet, working diver. It was discovered later, however, that the problem resulted from a previous dive (unrelated to the DCIEM dives) since he had similar pain in the same area before the dive. This case was, therefore, not attributed to the dive profile being tested. He was monitored only once and no bubbles were detected before he was recompressed.

e. **Standard Air** - Repetitive Dives - Series E

Four cases of DCS occured in 62 man-dives of 3 different dive combinations.

(1) Subject MC reported a vague pain in the right shoulder 15 minutes after completion of combination 3 (54 msw/30 min + 18 msw/30 min with 3 hr surface interval) as wet, working diver. Only a few bubbles were observed in the right shoulder (1/1) after the second dives. However, 3/3 bubbles were recorded in the right shoulder during the surface interval. He was treated for Type I DCS on Table 5 and complete relief was attained after 1 min at 60 fsw.

(2) Subject BB, a wet, working diver during combination 2 (45 msw/30 min + 45 msw/20 min with 2 hour surface interval) reported feeling something in his right shoulder in the evening following the dive. This feeling persisted the following morning and he was treated for Type I DCS on Table 5, 18 hrs post-dive. His discomfort disappeared during the treatment. Subject BB had 3/3 Doppler scores in his right shoulder post-dive.

(3) Subject TNB had a slight pain in his right shoulder at the 12 msw stop during ascent from the second dive of combination 2 as wet, working diver. This pain disappeared at the 3 msw stop but he had a Doppler score of 3/3 in his right shoulder at this time. The pain recurred 10 minutes after surfacing and the subject was treated for Type I DCS with total relief achieved on descent to 60 fsw.

(4) Subject GSP was a dry, resting diver for combination 2 and experienced slight discomfort in the left shoulder at the 3 msw stop following the second dive. The Doppler reading on his left shoulder was 2/3 at this time. On surfacing, subject GSP also reported discomfort in the left knee and he was treated immediately for Type I DCS with all symptoms relieved on reaching 60 fsw; and

f. **In-Water Oxygen + Surface Oxygen** -Repetitive Dives - Series F

No incidents of DCS occurred in 18 man-dives of combination 2 using In-Water O_2 + Surface O_2 decompression.

DISCUSSION

The evaluation of decompression profiles based on the DCIEM 1983 model has shown that this model is effective in reducing decompression stress and in providing safer decompression than the KS-1971 model (Table 7). Repetitive diving on the DCIEM 1983 model has also been found to be effective.

Decompression schedules for compressed air diving based on the DCIEM 1983 Decompression Model are considerably more conservative than the equivalent schedules published in the United States Navy (USN) and Royal Navy (RN) Diving Manuals (13,14). Figure 3 compares the total decompression times vs. bottom times for various depths using Standard Air decompression based on the USN, RN, and DCIEM 1983 methods. Since the DCIEM O_2 decompression procedures are derived from the same basic model, these methods are equally conservative relative to the equivalent USN and RN procedures.

Subjectively, 13 confirmed or probable incidents of DCS were encountered during these experiments in 391 man-dives for an overall DCS incidence rate of 3.3%. Out of these 13 cases of DCS, 2 were not Doppler-monitored prior to treatment, and of the remaining 11 incidents of DCS, all had some bubbles detected by Doppler. Eight of these, or 73%, had Doppler scores of 3 or greater.

In view of the apparent relationship between high Doppler scores and the incidence of DCS (15) and the summary of Doppler results for all these experimental dives (Table 3), it can be concluded that the basic conservatism of the DCIEM 1983 Decompression Model is both justified and necessary.

The results presented here also show that the application of Oxygen for decompression not only reduces the in-water decompression time, but also appears to increase the effectiveness of the decompression regimen. The application of surface decompression procedures to repetitive diving has been proven to be safe and effective.

Testing of the DCIEM 1983 model is being continued - in particular, with exceptional exposure profiles. Repetititive diving with the In-water O_2 method will also be evaluated. Further, a comparison between the In-Water O_2 + SurD O_2 procedure described here and the new SurD O_2 method (using air only in the water and taking air breaks in the RCC) will be conducted. The results of these tests will be reported separately. On completion, a comprehensive set of decompression tables and procedures based on the DCIEM 1983 model will be published.

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REFERENCES

1. **NISHI, R.Y.** and G.R. **LAUCKNER.** Development of the DCIEM 1983 Decompression Model for Compressed Air Diving. DCIEM Report No. 84-R-44. Defence and Civil Institute of Environmental Medicine, Downsview, Ontario. 1984.

2. **KIDD, D.J.** and R.A. **STUBBS.** The use of the pneumatic analog computer for divers, in P.B. Bennett and D.H. Elliott, Eds., The Physiology and Medicine of Diving and Compressed Air Work, 1st ed., pp.386-413, Bailliere, Tindall and Cassell, London. 1969

3. **KIDD, D.J., R.A. STUBBS,** and R.S. **WEAVER.** Comparative approaches to prophylactic decompression in C.J. Lambertsen, Ed., Underwater Physiology: Proceedings of the Fourth Symposium on Underwater Physiology, pp.167-177, Academic Press, New York. 1971

4. **NISHI, R.Y.** and L.A. **KUEHN.** Digital computation of decompression profiles. DCIEM Report No. 884, Defence and Civil Institute of Environmental Medicine, Downsview, Ontario. 1973

5. **KUEHN, L.A.** and R.Y. **NISHI.** The Use of Decompression Computers in Diving. pp.486-497, in W.A. Adams et al, Eds. Chemistry and Physics of Aqueous Gas Solutions. The Electrochemical Society, Inc., Princeton, N.J. 1975

6. **NISHI, R.Y.** Real-time decompression monitoring by computers. pp.25-38, in C.E. Johnson, M.L. Nuckols, and P.A. Clow, Eds. Hyperbaric Diving Systems and Thermal Protection. OED-Vol 6, The American Society of Mechanical Engineers, New York. 1978

7. **NISHI, R.Y., K.E. KISMAN, I.P. BUCKINGHAM, B.C. EATOCK,** and G. **MASUREL.** XDC-2 Digital Decompression Computer: Assessment of Decompression Profiles by Ultrasonic Monitoring, Phase I: 36-54 msw. DCIEM Report No. 80-R-32, Defence and Civil Institute of Environmental Medicine, Downsview, Ontario. 1980

8. **NISHI, R.Y., B.C. EATOCK, I.P. BUCKINGHAM,** and G. **MASUREL.** XDC-2 Digital Decompression Computer: Assessment of Profiles by Ultrasonic Monitoroing, Phase II: 30-75 msw. DCIEM Report No. 81-R-02, Defence and Civil Institute of Environmental Medicine, Downsview, Ontario. 1981

9. **NISHI, R.Y., B.C. EATOCK, I.P. BUCKINGHAM,** and B.A. **RIDGEWELL.** Assessment of Decompression Profiles by Ultrasonic Monitoring, Phase III: No-Decompression Dives. DCIEM Report No.82-R-38, Defence and Civil Institute of Environmental Medicine, Downsview, Ontario. 1982.

10. **NISHI, R.Y., G.R. LAUCKNER, B.C. EATOCK,** and J.T. **HEWITT.** Oxygen Decompression Techniques for Compressed Air Diving Using the XDC-2 Decompression Computer Programmed with the Kidd-Stubbs 1971 Model. DCIEM No. 84-R-19, Defence and Civil Institute of Environmental Medicine, Downsview, Ontario. 1984

11. **KISMAN, K.E., G. MASUREL,** and R. **GUILLERM.** Bubble evolution code for Doppler ultrasonic decompression data. Undersea Biomed. Res. 5 (1 Supplement):28 (Abstract). 1978

12. **SPENCER, M.P.** Decompression limits for compressed air determined by ultrasonically detected blood bubbles. J. Appl. Physiol. 40: 229-235. 1976

13. **U.S. NAVY.** U.S. Navy Diving Manual, Vol. 1, Air Diving. NAVSEA 0994-LP-001-9010. U.S. Navy Department, Washington, D.C. 1978

14. **ROYAL NAVY.** Diving Manual, B.R. 2806. Ministry of Defence (Navy), HMSO, London. 1972

15. **EATOCK, B.C.,** Correspondence Between Intravascular Bubbles and Symptoms of Decompression Sickness, Undersea Biomed. Res. 11(3): 326-29. 1984

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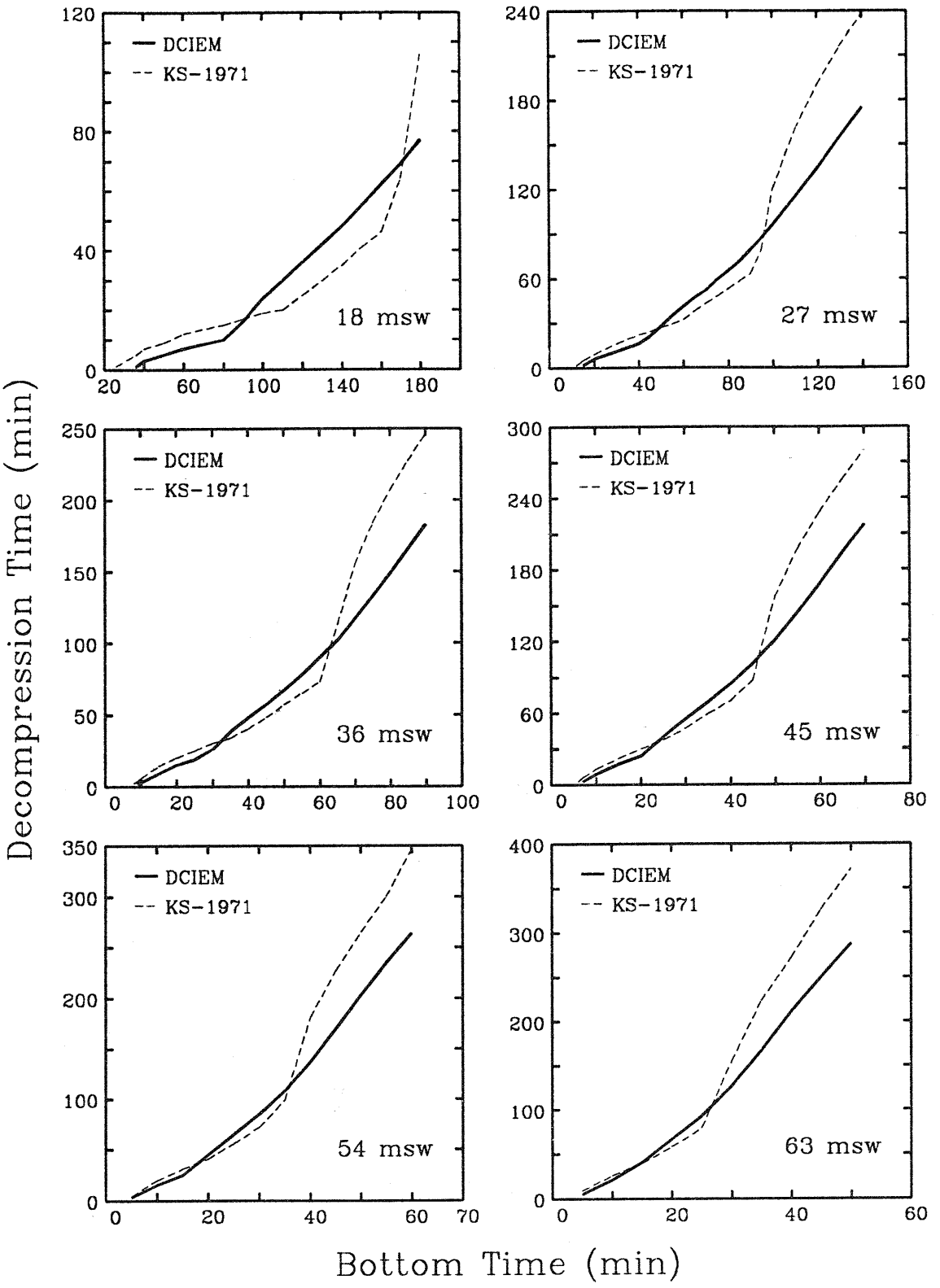

FIGURE 1

COMPARISON OF DCIEM 1983 TOTAL DECOMPRESSION TIMES FOR STANDARD AIR DIVES WITH THOSE OF THE KIDD-STUBBS (KS) 1971 MODEL FOR 18, 27, 36, 45, 54, and 63 MSW

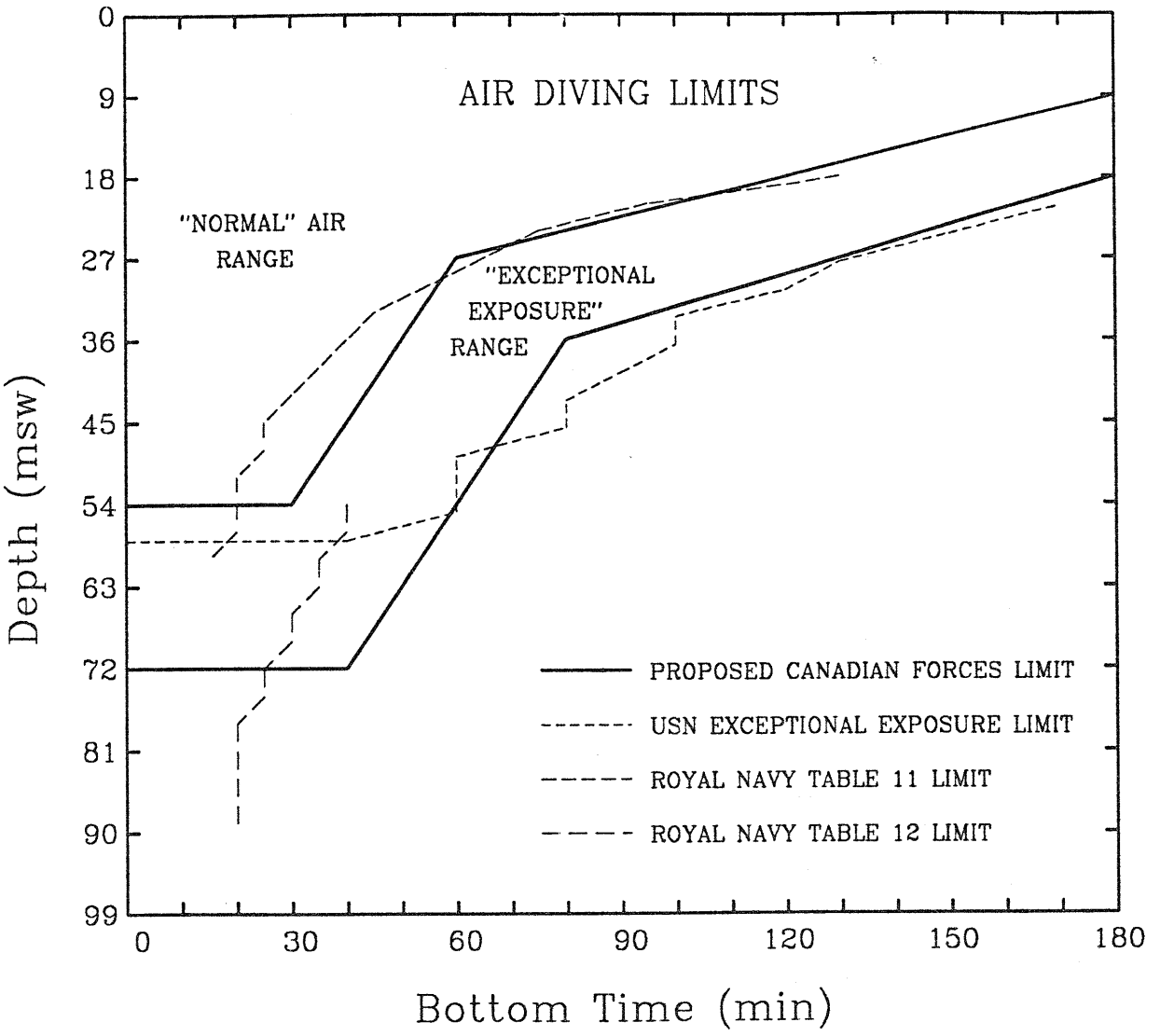

FIGURE 2

PROPOSED AIR DIVING LIMITS FOR THE CANADIAN FORCES

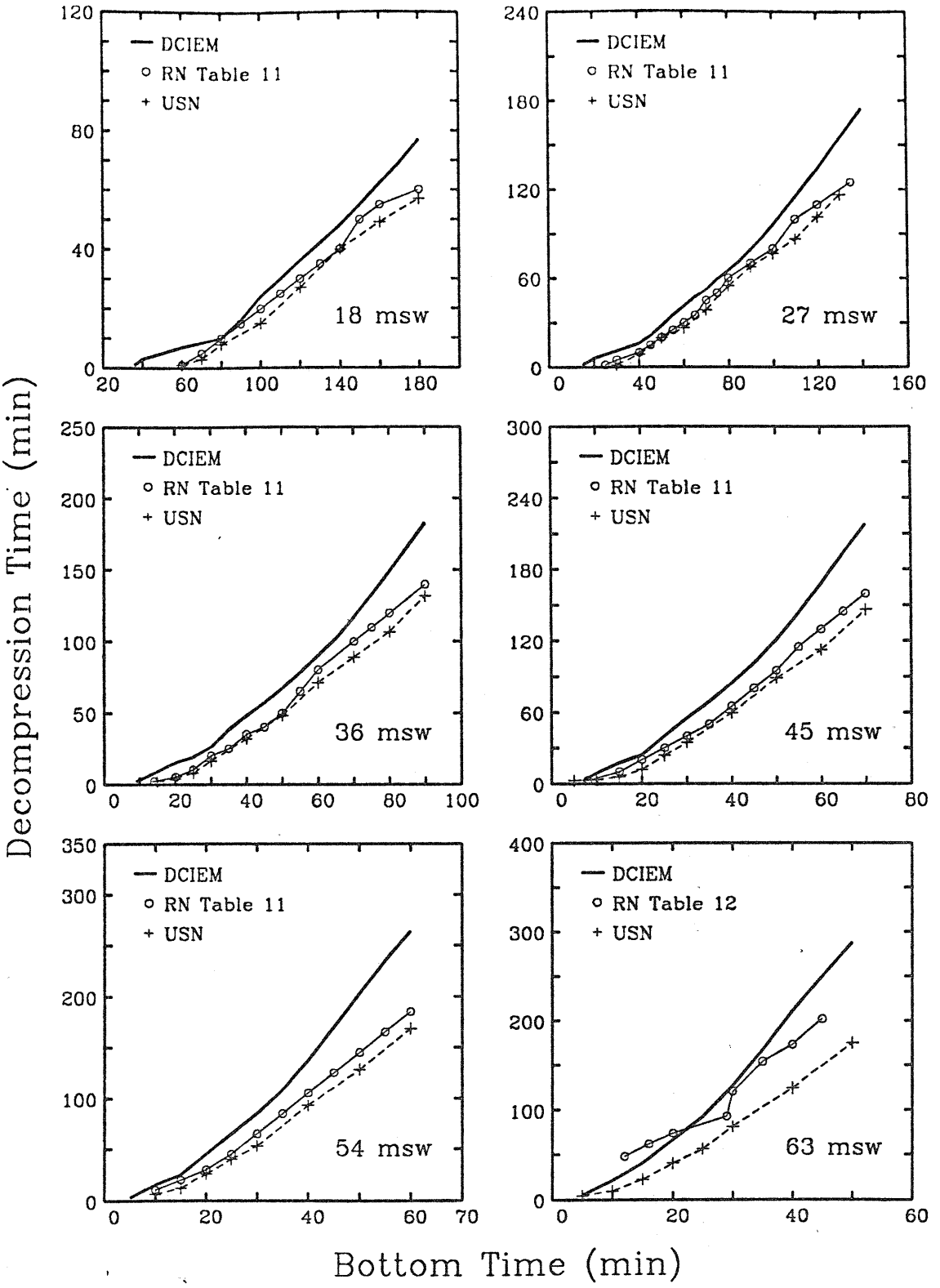

FIGURE 3

COMPARISON OF DCIEM 1983 TOTAL DECOMPRESSION TIMES FOR STANDARD AIR DIVES WITH THOSE OF THE ROYAL NAVY AND THE US NAVY AIR TABLES FOR 18, 27, 36, 45, 54, and 63 MSW

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TABLE 1

DECOMPRESSION PROFILES TESTED

SERIES A. STANDARD AIR (decompression times shorter than KS-1971)

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)						Decom. Time (min)	Decom. Time KS*
		18	15	12	9	6	3		
18	80	-	-	-	-	-	10	10	15
27	40	-	-	-	-	6	10	16	22
36	25	-	-	-	-	9	10	19	25
45	20	-	-	-	6	7	11	24	30
54	15	-	-	-	7	7	11	25	31

* Decompression time for the equivalent Kidd-Stubbs dive

SERIES B. STANDARD AIR (decompression times longer than KS-1971)

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)						Decom. Time (min)	Decom. Time KS*
		18	15	12	9	6	3		
36	50	-	-	4	7	10	46	67	57
45	30	-	-	6	6	9	34	55	47
54	25	-	5	5	7	9	39	65	56

* Decompression time for the equivalent Kidd-Stubbs dive

SERIES C. IN-WATER O_2 DECOMPRESSION

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)					Decom. Time (min)
		Air			O_2		
		18	15	12	9	Asc	
27	60	-	-	-	26	2	28
36	50	-	-	4	37	2	43
45	40	-	4	6	42	2	54
54	30	3	4	6	41	2	56

SERIES D. IN-WATER O_2 + SURFACE O_2 DECOMPRESSION

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)									Decom. Time (min)
		In-Water Stops				Surface			Chamber		
		Air			O_2	O_2	Air	O_2	O_2		
		18	15	12	9	Asc	SI	Des	12	Asc	
27	60	-	-	-	2	2	4	1	29	2	40
36	50	-	-	4	4	2	4	1	39	2	56
45	40	-	4	6	4	2	4	1	44	2	67
50	30	3	4	6	4	2	4	1	43	2	69

TABLE 1 (continued)

DECOMPRESSION PROFILES TESTED

SERIES E. REPETITIVE STANDARD AIR DECOMPRESSION

Prof.	Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)						Decom. Time (min)	Decom. Time KS*
			18	15	12	9	6	3		
1	36	40	-	-	-	8	8	32	48	40
	36	20(36)	-	-	-	-	9	27	36	28
2	45	30	-	-	6	6	9	34	55	47
	45	20(34)	-	-	-	8	9	45	62	51
3	54	30	3	4	6	7	15	50	85	72
	18	30(51)	-	-	-	-	-	4	4	10

* Decompression time for the equivalent Kidd-Stubbs dive
Note 1. Times shown in brackets are Effective Bottom times.
Note 2. Surface interval was 2 hours for profiles 1 and 2, and 3 hours for profile 3.

SERIES F. REPETITIVE IN-WATER O_2 + SURFACE O_2 DECOMPRESSION

Prof.	Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)									Decom. Time (min)
			In-Water Stops				Surface			Chamber		
			Air			O_2	O_2	Air	O_2	O_2		
			18	15	12	9	Asc	SI	Des	12	Asc	
2	45	30	-	-	6	4	2	4	1	30	2	49
	45	20(30)	-	-	-	5	2	4	1	30	2	45

TABLE 2

WORKLOAD FOR WET DIVERS

Bottom Time (min)	Workload	Percentage of Max. Heart Rate At Surface	Work/Rest Cycle
over 60 min	1	50%	Continuous
31 to 60 min	2	65%	10 min/10 min
21 to 30 min	3	70%	5 min/ 5 min
10 to 20 min	4	75%	3 min/ 2 min

TABLE 3

MAXIMUM BUBBLE GRADES OBSERVED IN THE PRECORDIAL REGION AT REST AND FOLLOWING MOVEMENT FOR ALL DIVES

SERIES A. STANDARD AIR

Depth (msw)	Bottom Time (min)	No. of Subj.	No. Man Dives†	Man-Dives with Maximum Bubble Grade										No. of DCS
				At Rest					After Movement					
				0	1	2	3	4	0	1	2	3	4	
18	80	6	6(1)	4	0	1	1	0	4	0	0	2	0	0
27	40	4	4(2)	3	1	0	0	0	2	1	1	0	0	0
36	25	6	8(2)	8	0	0	0	0	8	0	0	0	0	0
45	20	6	10(3)	6	1	1	2	0	5	1	2	1	1	0
54	15	4	4(2)	3	1	0	0	0	2	2	0	0	0	0
TOTALS			32(10)	24	3	2	3	0	21	4	3	3	1	0

SERIES B. STANDARD AIR

Depth (msw)	Bottom Time (min)	No. of Subj.	No. Man Dives†	Man-Dives with Maximum Bubble Grade										No. of DCS
				At Rest					After Movement					
				0	1	2	3	4	0	1	2	3	4	
36	50	6	11(3)	1	0	6	4	0	1	1	1	7	1	2
45	30	7	10(2)	5	1	0	4	0	3	0	2	5	0	1
54	21	5	5(1)	4	0	0	1	0	4	0	0	1	0	1
54	25	5	5(1)	1	0	3	1	0	1	0	1	2	1	0
TOTALS			31(7)	11	1	9	10	0	9	1	4	15	2	4

SERIES C. IN-WATER O_2 DECOMPRESSION

Depth (msw)	Bottom Time (min)	No. of Subj.	No. Man Dives†	Man-Dives with Maximum Bubble Grade										No. of DCS
				At Rest					After Movement					
				0	1	2	3	4	0	1	2	3	4	
27	60	13	23(7)	20	1	0	1	0	19	0	2	1	0	1*
36	50	13	24(8)	12	2	4	6	0	9	1	1	9	4	0
45	40	12	22(5)	19	0	1	2	0	18	1	0	3	0	1
54	30	12	24(7)	19	1	3	1	0	19	0	1	4	0	0
TOTALS			93(27)	70	4	8	10	0	65	2	4	17	4	2

* Subject with DCS not monitored.

† Numbers in () indicate number of wet divers.

TABLE 3 (continued)

MAXIMUM BUBBLE GRADES OBSERVED IN THE PRECORDIAL REGION AT REST AND FOLLOWING MOVEMENT FOR ALL DIVES

SERIES D. IN-WATER O_2 + SURFACE O_2

Depth (msw)	Bottom Time (min)	No. of Subj.	No. Man Dives†	Man-Dives with Maximum Bubble Grade										No. of DCS
				At Rest					After Movement					
				0	1	2	3	4	0	1	2	3	4	
27	60	13	19(6)	18	0	0	1	0	17	0	1	1	0	0
36	50	11	21(6)	15	1	3	2	0	11	2	2	5	1	0
45	40	11	22(9)	19	0	1	1	0	19	0	0	2	0	2*
54	30	10	14(4)	13	0	0	1	0	10	1	0	2	1	1
TOTALS			76(25)	65	1	4	5	0	57	3	3	10	2	3

* One subject with DCS not monitored.

SERIES E. REPETITIVE STANDARD AIR

Depth (msw)	Bottom Time (min)	No. of Subj.	No. Man Dives†	Man-Dives with Maximum Bubble Grade										No. of DCS
				At Rest					After Movement					
				0	1	2	3	4	0	1	2	3	4	
36	40	13	20(4)	15	3	2	0	0	11	2	6	1	0	0
36	20(36)	13	20(4)	18	1	1	0	0	15	4	0	1	0	1
45	30	13	21(4)	15	2	0	4	0	10	5	2	4	0	0
45	20(34)	13	20(4)	17	0	1	2	0	16	1	0	3	0	2
54	30	13	21(4)	14	0	5	2	0	13	2	2	4	0	0
18	30(51)	13	21(4)	20	1	0	0	0	19	2	0	0	0	1
TOTALS			123(24)	99	7	9	8	0	84	16	10	13	0	4

Bottom time in () is "Effective Bottom Time" of the second dive.

SERIES F. REPETITIVE IN-WATER O_2 + SURFACE O_2

Depth (msw)	Bottom Time (min)	No. of Subj.	No. Man Dives†	Man-Dives with Maximum Bubble Grade										No. of DCS
				At Rest					After Movement					
				0	1	2	3	4	0	1	2	3	4	
45	30	12	18(4)	17	1	0	0	0	17	0	0	1	0	0
45	20(30)	12	18(4)	18	0	0	0	0	18	0	0	0	0	0
TOTALS			36(8)	35	1	0	0	0	35	0	0	1	0	0

Bottom time in () is "Effective Bottom Time" of the second dive.

† Numbers in () indicate number of wet divers.

TABLE 4

MAXIMUM BUBBLE GRADES FROM THE PRECORDIAL AND SUBCLAVIAN SITES

DIVE (msw/min)	DIVER	ROLE	P	T (min)	LS	T (min)	RS	T (min)	DCS
Series B	DB	WW	3/4	207	2/3-	116	2/2	207	
36/50	DB	DR	3/3	170	3/3+	140	0	-	
Std Air	GD	WW	3-/3	80	0/2	80	0	-	
	GD	DR	2/3	212	0	-	0	-	
	YDR	DR	0	-	3/3-	93	0	-	
	YDR	WW	2/3	142	3-/3-	175	3/3	77	
	MAP	DR	3+/3	100	NM	-	NM	-	Type 1
	DVE	L	2/3	199	2/1	140	0	-	
	DVE	L	2/3	150	0	-	2/1	189	
	BM	S	2/1	87	3/2	87	3-/1	87	
	BM	S	2/2	85	1/1	95	2/2	95	Type 1
Series D	BPC	DR	2/3	124	0	-	0	-	
36/50	BPC	WW	0/3-	122	0/1	92	3-/3-	122	
In-Water O_2	RK	WW	0/2	101	0/1	71	0/1	130	
+	RK	DR	0	-	0/1	129	0	-	
Surface O_2	CS	DR	0	-	0	-	0	-	
	CS	WW	0/1	92	1/1	151	0/1	151	
	CA	DR	0/3-	130	0	-	0	-	
	GBB	WW	0	-	0	-	0	-	
	GBB	DR	0	-	0	-	0	-	
	PD	WW	0	-	0	-	0	-	
	PD	DR	0	-	0	-	0	-	
	PP	DR	0	-	0	-	0	-	
	PP	WW	0	-	0	-	0	-	
	RSD	L	3+/4	132	0	-	0	-	
	RSD	L	2/1	95	0/1	95	1/0	185	
	SN	L	3-/3	64	0	-	0	-	
	SN	L	1/2	70	0	-	0	-	
	SS	S	0	-	0	-	0	-	
	SS	S	0	-	0	-	0	-	
	DW	S	2/3	124	2/1+	185	0	-	
	DW	S	0	-	0	-	0	-	

Explanation of Symbols

Role		Code	
WW	- wet-working diver	P	- precordial site
DR	- dry-resting subject	LS	- left shoulder
S	- standby diver	RS	- right shoulder
L	- team leader, dry	a/b	a bubble grade for rest b bubble grade for movement
		T	- time from the start of decompression
		NM	- not monitored

TABLE 4 (continued)

MAXIMUM BUBBLE GRADES FROM THE PRECORDIAL AND SUBCLAVIAN SITES

DIVE (msw/min)	DIVER	ROLE	P	T (min)	LS	T (min)	RS	T (min)	DCS
Series C 45/40 In-Water O_2	LC	DR	0	-	0	-	0	-	
	DH	DR	0	-	0	-	0	-	
	IS	WW	0	-	0	-	0	-	
	IS	DR	0	-	0	-	0	-	
	RB	WW	0	-	3-/2+	131	2/2	71	
	RB	DR	2/3	95	2/2+	124	3/2	154	Type 2
	GTD	WW	0	-	0	-	0	-	
	GTD	DR	0	-	0	-	0	-	
	ME	DR	3-/3+	95	0	-	0	-	
	ME	DR	0/1	119	0	-	0	-	
	KM	DR	0	-	0	-	0	-	
	KM	WW	0	-	0	-	0	-	
	DTS	DR	0	-	0	-	0	-	
	DTS	WW	0	-	0	-	0	-	
	SGG	L	0	-	0	-	2/3-	130	
	SGG	L	0	-	0/1	90	0	-	
	BM	L	0	-	3-/3	107	1/0	77	
	BM	L	0	-	2/1	160	0	-	
	GWB	S	0	-	0	-	0	-	
	GWB	S	0	-	0	-	0	-	
	LW	S	3-/3	134	0/2	105	2/1	225	
	LW	S	0	-	0	-	0/1	95	
Series D 45/40 In-Water O_2 + Surface O_2	SN	WW	3-/3-	144	0	-	0	-	
	LC	DR	0	-	0	-	0/1	167	
	LC	WW	NM	-	NM	-	NM	-	Type 1
	DH	WW	0	-	0	-	0	-	
	DP	DR	0	-	0/1	76	0/1	136	
	IS	WW	0	-	0	-	0	-	
	IS	DR	0	-	0	-	0	-	
	GTD	WW	0	-	0	-	0	-	
	GTD	DR	0	-	0	-	0	-	
	ME	WW	0	-	0	-	0	-	
	KM	WW	0	-	0	-	0	-	
	KM	WW	0	-	0	-	1/0	172	
	DTS	DR	0	-	0	-	0	-	
	DTS	WW	2/3-	191	0	-	0	-	
	SGG	L	0	-	0	-	0/1+	134	
	SGG	L	0	-	0	-	0	-	
	BM	L	0	-	0/1	131	0	-	
	BM	L	0	-	1/1	76	0	-	Type 1
	GWB	S	0	-	2/1	161	0	-	
	GWB	S	0	-	1/1	100	0	-	
	LW	S	0	-	0	-	0	-	
	LW	S	0	-	0	-	0	-	

TABLE 5

MAXIMUM BUBBLE GRADES FROM THE PRECORDIAL AND SUBCLAVIAN SITES
SAMPLE SUBJECTS, PROFILE, AND DECOMPRESSION METHOD

DIVER	DIVE (msw/min)	METHOD	ROLE	P	T (min)	LS	T (min)	RS	T (min)	DCS
RSD	45/20	AIR	WW	3/4	73	0/1	73	2/1	73	
RSD	45/20	AIR	DR	3-/2	130	0	-	0	-	
RSD	45/30	AIR	WW	3+/3+	97	2/2	97	3-/3	97	Skin
RSD	45/30	AIR	DR	3/3	105	0	-	2/0	171	
RSD	36/50	IW	L	3/4	122	2/2	179	3/3-	238	
RSD	36/50	IW	L	3/4	120	1/1	215	3-/3	215	
RSD	36/50	SD	L	3+/4	132	0	-	0	-	
RSD	36/50	SD	L	2/1	95	0/1	95	1/0	185	
RSD	54/30	IW	L	0	-	0	-	0	-	
RSD	54/30	IW	L	0	-	0	-	2/2	127	
RSD	54/30	SD	L	0/3-	140	0	-	0	-	
RSD	54/30	SD	L	0	-	0	-	0	-	
SN	45/30	AIR	DR	0/2	94	0	-	0	-	
SN	54/25	AIR	DR	2/3-	120	0	-	0	-	
SN	36/50	IW	WW	3/3+	154	0	-	0	-	
SN	36/50	IW	L	2+/3+	74	0	-	0	-	
SN	36/50	IW	DR	3/3+	94	0	-	0	-	
SN	36/50	SD	L	3-/3	64	0	-	0	-	
SN	36/50	SD	L	1/2	70	0	-	0	-	
SN	45/40	SD	WW	3-/3-	144	0	-	0	-	
SN	36/40	RA	L	0/1	97	0	-	0	-	
	36/20	RA	L	0	-	0	-	0	-	
SN	54/30	RA	L	3/3	108	0	-	0	-	
	18/30	RA	L	0	-	0	-	0	-	
SMD	36/25	AIR	WW	0	-	0	-	0	-	
SMD	36/25	AIR	DR	0	-	0	-	0	-	
SMD	45/30	RA	L	0	-	0	-	0	-	
	45/20	RA	L	0	-	0	-	0	-	
SMD	45/30	RSD	L	0	-	0	-	0	-	
	45/20	RSD	L	0	-	0	-	0	-	

Explanation of Symbols

Method
- AIR - Standard air
- SD - In-Water O_2 + Surface O_2
- IW - In-Water O_2
- RA - Repetitive-standard air
- RSD - Repetitive In-Water O_2 + Surface O_2

Role
- WW - wet-working diver
- DR - dry-resting subject
- S - standby diver, dry
- L - team leader, dry

Code
- P - precordial site
- LS - left shoulder
- RS - right shoulder
- T - time from start of decompression
- a/b - a bubble grade, rest
  - b bubble grade, movement
- NM - not monitored

TABLE 5 (continued)

MAXIMUM BUBBLE GRADES FROM THE PRECORDIAL AND SUBCLAVIAN SITES
SAMPLE SUBJECTS, PROFILE, AND DECOMPRESSION METHOD

DIVER	DIVE (msw/min)	METHOD	ROLE	P	T (min)	LS	T (min)	RS	T (min)	DCS
AR	45/20	AIR	L	0	-	0	-	0	-	
AR	45/20	AIR	L	0	-	0	-	0	-	
AR	45/30	AIR	L	0/3-	197	0	-	0	-	
AR	45/30	AIR	DR	0	-	0	-	0	-	
AR	45/30	RA	L	0	-	0	-	0	-	
	45/20	RA	L	0	-	0	-	0	-	
AR	45/30	RSD	L	0	-	0	-	0	-	
	45/20	RSD	L	0	-	0	-	0	-	
SP	45/30	RA	WW	1/2	123	0	-	0	-	
	45/20	RA	WW	2/3	117	0	-	1/0	117	
SP	45/30	RA	DR	0/1	100	0	-	0	-	
	45/20	RA	DR	0	-	0	-	0	-	
SP	45/30	RSD	DR	0	-	0	-	0	-	
	45/20	RSD	DR	0	-	0	-	0	-	
SP	45/30	RSD	WW	0	-	0	-	0	-	
	45/20	RSD	WW	0	-	0	-	0	-	

TABLE 6

COMPARISON OF MAN-DIVES USING THE DCIEM 1983 DECOMPRESSION MODEL WHICH RESULTED IN "MINIMAL" DOPPLER SCORES (GRADES "0" OR "1", PRECORDIAL, AFTER MOVEMENT)

Profile (msw/min)	Percentage of Man-Dives Decompression Method		
	Standard Air	In-Water O_2	In-Water O_2 + Surface O_2
27/60	-	83(23C)†	89(19D)
36/50	18(11B)	42(24C)	62(21D)
45/30	58(31B,E*)	-	94(18F*)
45/40	-	86(22C)	86(22D)
54/30	71(21E*)	79(24C)	79(14D)
45/30+45/20**	85(20E)	-	100(18F)

* Includes first dives of repetitive dives
** After second dive of repetitive dives
† Figures and letters in () are number of man-dives and dive series

TABLE 7

COMPARISON OF DOPPLER SCORES (PRECORDIAL, AFTER MOVEMENT) OF SIMILAR DIVES USING 'STANDARD AIR' DECOMPRESSION BASED ON THE KS-1971 AND DCIEM 1983 DECOMPRESSION MODELS

Doppler Scores	Percentage of Man-Dives	
	KS - 1971 (124 man-dives)	DCIEM 1983 (133 man-dives)
0	25.0%	51.9%
1	10.5	10.5
2	12.9	12.8
3	37.1	22.6
4	14.5	2.2