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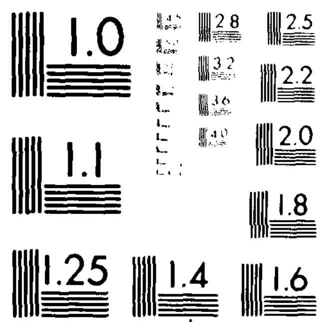

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DCIEM REPORT NO. 80-R-32

XDC-2 DIGITAL DECOMPRESSION COMPUTER: ASSESSMENT OF DECOMPRESSION PROFILES BY ULTRASONIC MONITORING, PHASE I: 36 - 54 MSW

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ABSTRACT

Decompression from experimental, operational, and training dives at the Defence and Civil Institute of Environmental Medicine (DCIEM) has been carried out for many years under control of decompression computers rather than by means of published decompression tables. The XDC-2 digital decompression computer and dive monitor is presently in use at DCIEM. An evaluation program for determining and defining the operational limiting bottom times for different depths and the safety of using the computer by following exactly the displayed safe ascent during decompression has been started. In this report, the results of Phase I of the evaluation program, covering the depth range 36 to 54 meters of seawater (msw), are presented. Seventeen chamber dives, consisting of 102 man-dives, were conducted using 9 different profiles. In order to assist in the evaluation of the XDC-2 profiles, two Doppler ultrasonic bubble detectors were used to monitor bubbles in the diving subjects for at least 3 hours and, in some cases, up to 7 hours after the start of decompression. Seven incidences of decompression sickness occurred and were treated. Two others may have been probable cases of decompression sickness. The severity of the different profiles was assessed on the basis of bubbles detected in the subjects and, as a result of this assessment, a bottom time vs. depth limit line for safe exposures was determined. Additionally, the effect of using oxygen decompression for reducing decompression stress in a severe dive was investigated. Diving subjects were also assessed as to whether they were high, moderate or low "bubblers", i.e., bubble producers.

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INTRODUCTION

Decompression from experimental, operational, and training dives at the Defence and Civil Institute of Environmental Medicine (DCIEM) has been carried out for a considerable number of years under control of decompression computers rather than by means of published decompression tables. Decompression computers take into account the actual depth-time profile of a dive and can provide a more efficient decompression in cases of non-standard dives or repetitive dives. The DCIEM decompression computer was originally designed and developed by R.A. Stubbs and D.J. Kidd as a pneumatic-mechanical analogue computer and was used successfully in this form with a very low incidence of decompression sickness for over a decade with hyperbaric chamber dives at DCIEM and on field trials in the ocean (1).

With the advent of microprocessors, it has become possible to replace the pneumatic analogue computers with an electronic real-time digital computer which samples the diver's actual depth and calculates his safe ascent depth. The XDC-2 digital decompression monitor (2) incorporates the Kidd-Stubbs mathematical model and displays, among other things, the actual depth and the computed safe depth for dives within a hyperbaric chamber or for surface-supported dives. Although the XDC-2 was expected to have the same safety record as the pneumatic analogue decompression computers, it was necessary to evaluate the performance of this computer since it allowed the mathematical model to be followed exactly during decompression. In addition, it was necessary to determine and define the bottom time limits at various depths for operational diving before the computer could be issued to the Canadian Forces Fleet Diving Units.

The operational evaluation of the XDC-2 was carried out in several phases. In this report, the results of Phase I, consisting of 17 dives (102 man-dives), covering the depth range 36 to 54 meters of seawater (msw) are presented. Instead of relying purely on the incidence of bends or on subjective comments from the divers, judgement of the severity of the dive profiles generated by the XDC-2 was also made using the Doppler ultrasonic bubble detector. Doppler monitoring was conducted on the divers periodically at depth and on the surface after decompression. Most divers were monitored for at least 3 hours from the start of decompression and, in some cases, for up to 7 hours.

EXPERIMENTAL DIVE PROGRAM

1. XDC-2 Digital Decompression Monitor

The XDC-2 digital decompression monitor was designed and developed by CTF Systems Inc., Port Coquitlam, British Columbia, on a contract from DCIEM. It is microprocessor-controlled and is contained in a splash-proof case, 12.7 cm high by 20.3 cm wide and 25.4 cm deep.

It includes a built-in pressure transducer so that the only input required is a pneumatic line from the hyperbaric chamber or from a surface-supported diver. On the front face are four digital displays showing the actual depth, the computed safe depth, the elapsed time, and the rate of ascent or descent. The rate display can be switched to show the no-decompression time remaining or the optimum ascent time back to surface. The depth can be displayed in either feet of seawater (fsw) or msw. There are several other features included in the XDC-2 which make the instrument extremely versatile (2).

The Kidd-Stubbs decompression computer model incorporated in the XDC-2 is the same mathematical model which defined the pneumatic analogue decompression computer and consists of four tissue compartments in series (3,4). In the XDC-2, all compartment pressures are calculated numerically from the actual dive pressure and the safe ascent depth is selected from the largest compartment pressure. Because the safe ascent depth is displayed digitally, it is possible to follow the safe ascent depth exactly as calculated during the decompression.

This was not always possible with the pneumatic-mechanical analogue decompression computers because of mechanical constraints which limited the resolution of the actual depth and safe depth displays, and operational considerations which generally resulted in the actual depth being deeper by several feet than the calculated safe depth. Only under controlled conditions with critically calibrated instruments was it possible to follow the safe depth exactly. The small errors introduced by the calibration constraints and the operational considerations provided an additional safety factor which may have contributed to the large number of successful decompressions recorded with the pneumatic computers. Over 5000 experimental man-dives were conducted to develop and validate this computer model (primarily with resting dry subjects). Most of the subsequent dives with decompression computers have also been done with dry subjects.

In recent years, more and more dives have involved wet working divers as well as dry divers. All of the dives conducted since the introduction of the XDC-2 were conducted by staying a foot or more deeper than the safe depth, following operational procedures which had been developed in the past when the pneumatic computers had been in use, and to compensate for the fact that the digital depth displays were truncated rather than rounded to the nearest foot of seawater. (This has since been corrected.) In the DCIEM 340 fsw hyperbaric chamber, the wet divers were also under an additional 3 to 5 fsw pressure more than the dry subjects because of the water pressure. In spite of these assumed safety factors, it was found that a number of unexpected decompression incidents were encountered, specifically at 150 fsw for 45 minutes and 200 fsw for 30 minutes, throwing some doubt on the safety aspects of the XDC-2 computer. A check of the CANDID diving data bank (5) (which includes details on all decompression computer controlled dives at DCIEM) indicated that there was little information as to the safety of profiles at depths from around 150 to 200 fsw and bottom times in the 30 to 45 minute time range.

As a result, an evaluation of the XDC-2 performance and operational capabilities was found to be necessary to determine if safe decompression could be accomplished by following the safe ascent depth exactly as calculated during the decompression, and to determine and define the operational limiting bottom times at various depths for both dry and wet diving subjects.

2. Dive Profiles

The Phase I dive program consisted of 9 bounce dive profiles conducted in the transfer sphere and the dive chamber of the DCIEM Diving Research Facility (DRF) at depths of 36, 45, and 54 msw. In order to determine the limiting bottom times for these depths, three bottom times were selected for each depth. Initially, the dive profiles were 36 msw at 40, 50, and 60 minutes, 45 msw at 25, 30, and 35 minutes, and 54 msw at 20, 25, and 30 minutes. (The maximum bottom times at each depth were determined by the point at which the third compartment in the mathematical model became the controlling compartment for determining the safe ascent depth during decompression.) However, after the first dive (36 msw for 50 minutes), 3 out of the 6 divers suffered from decompression sickness and it was decided to reduce the maximum bottom times for the remaining planned profiles. Table 1 shows the final dive profiles selected and the decompression times expected. The three bottom times at each depth are centered on the bottom times for the Royal Navy Limit Line for air dives at these depths (6).

A comparison with the U.S. Navy Standard Air Tables (7) and the Royal Navy Air Tables (6) showed that the final XDC-2 profiles selected were more conservative than the corresponding tables and this helped to lessen any apprehension or reluctance on the part of the dive subjects because of the deleterious psychological effects of the results of the first dive.

The ideal bounce dive profile to be tested required descent at 18 msw/min to the bottom depth, the stay at the bottom depth, ascent at 18 msw/min until the safe ascent depth was reached, continuous ascent following the safe ascent depth displayed on the computer until 3 msw, a hold at 3 msw until the computer indicated that surfacing was possible and, finally, the ascent to surface. Unfortunately, this procedure could not be followed exactly for the transfer sphere and dive chamber combination because of the restrictions imposed by the valves and the gas-inlet and gas-outlet pipe sizes. For the descent, the pressurization rate varied from 18 msw/min at the start to 8.8 msw/min at 54 msw. For the initial ascent to surface, a rate of 18 msw/min could be maintained to approximately 35 msw, after which the ascent rate was controlled by the maximum venting rate of the transfer sphere and dive chamber combination. As a result, ascent from 3 msw to the surface required 2.3 minutes.

Figure 1 shows the actual descent and ascent profiles that were possible for Phase I dives. The dive profiles as generated on a digital computer using the actual descent and ascent rates showed that the total decompression times, excluding the ascent from 3 msw to surface, were different by about one minute from the ideal bounce dive profiles and, thus, were not considered to be significantly different from the ideal profiles. Figures 2 to 10 show the dive profiles plotted as a function of time. Also shown for comparison are the U.S. Navy and Royal Navy profiles for the same bottom depth and bottom times.

Each dive was monitored with four XDC-2 computers - one monitoring the transfer sphere, one monitoring the dry portion of the dive chamber, and two monitoring the divers in the horizontal wet pot of the dive chamber by way of the umbilical lines to the divers. The output of the four computers was recorded on a digital data logger and was also printed out on a teletype. The decompression was generally controlled by following the computer showing the deepest safe ascent depth since there could be some differences among the four computers, particularly, those monitoring the wet divers in the horizontal wet pot who could be subjected to a slightly lower or higher pressure than the dry subjects because of the water pressure.

3. Dive Subjects

Each dive had six subjects - two working wet divers wearing KMB-9 breathing apparatus and standard foam neoprene wet suits in the wet pot of the dive chamber, two dry attendants performing a light workload in order to support the wet divers in the dry part of the dive chamber, and two dry non-working subjects in the transfer sphere. The two wet divers took turns performing a workload estimated to be about 100 watts on a submerged exercise ergometer set for 50 watts in normobaric air, each diver working for a six-minute period.

Two teams of divers were used, with each team diving on alternate dive days. Team A consisted of 6 divers divided into 3 pairs who were rotated among the three dive positions. Team B came from a pool of 18 divers from which 6 were selected each dive day according to availability. Divers were all qualified Ship's Divers or Clearance Divers and included both military and civilian personnel. Table 2 shows the age, weight, percent body fat determined from skin-fold measurements (8), and the calculated recommended weight range for each subject. The subjects were instructed to limit their consumption of alcoholic beverages and drugs and to obtain adequate sleep during the trial period. Each diver was required to fill out a questionnaire after the dive indicating his activities before the dive and whether or not he was fatigued after the dive.

4. Doppler Monitoring of Divers

All divers were monitored with the Doppler Precordial Bubble Detector*. Two monitoring teams were used, each team being responsible for monitoring 3 divers. The blood flow and bubble signals were assessed aurally through headphones at the time of monitoring and recorded on audio cassette tape for later reference or verification. Bubbles were assessed according to a code developed by Kisman and Masurel (9) which breaks up the bubble signal into three parameters - frequency, duration, and amplitude. The resulting bubble grades, on a scale from 0 to 4, are similar to those developed by Spencer (10) but include finer steps.

Both the precordial (right ventricle and/or pulmonary artery) and subclavian (left and right shoulders) sites were monitored. The precordial site provided whole-body monitoring since the entire venous system drains through this site. Monitoring was obtained for two conditions; first, at rest with the diver standing at ease, and then after a specified movement consisting of the diver performing a deep knee bend by slowly squatting down and then standing up again. The purpose of the movement was to help identify the bubbles, confirm the bubble signals obtained at rest, and predict when bubbles would appear at rest, since bubbles were often detected first following movement rather than at rest.

The subclavian veins were also monitored for two conditions; with the diver standing at rest, and again after a movement consisting of the diver clenching his fist on the side being monitored. Although the subclavian vein drains only one arm and shoulder, it was valuable because of the ease of monitoring and because distinct, unambiguous bubble signals could be obtained. The subclavian sites were only monitored on the surface after decompression, and were not done consistently until after the first few dives had taken place.

A reference signal was recorded for each diver one-half hour before the dive began. The four dry subjects were monitored (precordial site) at the bottom depth and at approximately 15 minute intervals during decompression in the chamber. All divers had been previously instructed on how to place the Doppler probe over the precordial region of the chest, since monitoring was required inside the chamber. After the surface was reached, the wet divers and then the dry divers were monitored (precordial and subclavian sites) while still in the vicinity of the DRF. All divers were subsequently monitored periodically while relaxing in a nearby resting area for at least 3 hours and, in some cases, up to 7 hours after the start of decompression. A cassette tape was assigned to each diver so that on replay of the

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*The instruments used were developed by the Institut National des Sciences Appliquées, Lyon in co-operation with the Centre d'Etudes et de Recherches Techniques Sous-Marines, Toulon under a contract with the French Direction des Recherches et Moyens d'Essais, and are manufactured by SODELEC S.A. of Marseille, France.

cassette, the evolution of each diver's bubble signatures throughout the decompression and post-decompression periods could be easily followed to assist in later verifications or analyses.

The divers were instructed to report all symptoms of pain or possible decompression sickness. Initiation of treatment was not based on bubble-grade results, although these results were used by the diving medical officer to help decide whether or not reported symptoms required recompression. During the first 7 dives, the divers were allowed to listen to the blood and bubble signals while being monitored. However, this practice was stopped because of a possible adverse psychological influence on the divers in reporting bends or pain symptoms.

RESULTS AND DISCUSSION

1. Dive Profiles

It was originally intended that both teams dive each profile shown in Table 1 which would have resulted in 18 dives. However, because of the high incidence of bends on the first profile tested (36 msw for 50 minutes), only one dive was done for this profile on compressed air. The next dive day was lost due to the treatment required for the divers incurring decompression sickness on this profile. Only one dive was conducted to 45 msw for 20 minutes. Since this dive appeared to be a low stress dive, it was decided to use the day allocated for the second dive to repeat the profile to 36 msw for 50 minutes but with oxygen being used during decompression from 10 msw to the surface to determine what effect it would have on the severity of the profile. As a result, only 17 dives were conducted.

The actual dive profiles as executed followed closely the theoretically derived profiles shown in Figures 2 to 10. Of the four computers monitoring the divers, the safe ascent depths were usually within 0.1 msw.

The water temperature in the dive chamber was constant for each dive and was between 18 to 23° C during this dive period. The air temperature varied during the profile, reaching approximately 30° C several minutes after bottom depth was reached in the dive chamber and decreasing by about 5° C before the start of ascent. In the transfer sphere, the maximum air temperature was a few degrees higher even though the connecting door to the dive chamber was open. The final bottom temperature was approximately the same as in the dive chamber. During the ascent phase of the profile, the temperature decreased to a minimum of about 17° C and then stabilized at between 18 to 21° C at the 3 msw decompression stop.

The relative humidity in the dive chamber was generally high at the beginning of the dive because of the air-water interface of the wet pot. During the descent phase, the relative humidity rose to approximately 90 to 98% before the chamber environmental control loop became effective. During the bottom phase, the relative humidity decreased to as low as approximately 40% and then slowly increased to values between 50 and 85% in the dive chamber, depending on the day. During the initial ascent phase, the relative humidity in the dive chamber dropped to about 40 to 50%, and then increased slowly to about 50 to 85% as the ascent rate slowed and the 3 msw stop was reached. The relative humidity then increased by about 5% before ascent to the surface was started. In the transfer sphere, the relative humidity was considerably lower and the minimum values attained were about 20%.

2. Precordial Bubble Results

Figures 11 and 12 show examples of the bubble grades detected as a function of time in the precordial region for both rest and movement conditions for a severe stress dive and a mild stress dive. Zero time denotes the start of decompression and the time at which surface was reached is marked with an "S". The bubble grades have been divided into finer steps than in the Spencer code by using + or - signs according to the Kisman-Masurel code (9). In general, when bubbles were detected, they were observed initially following the movement condition. In severe stress dives, bubbles were detected at depth before surface was reached in the dry subjects. This information was not available for the wet subjects since they were not monitored at depth. Bubble evolution usually reached a maximum between one and two hours after the start of decompression for divers at rest and remained at this level for some time before disappearing four or five hours after the start of decompression. Bubble grades observed following movement were usually higher than those at rest, but this was not always the case. Bubbles observed following movement also generally persisted for a longer time than at rest.

Table 3 shows the maximum precordial bubble grades observed for both rest and movement for each dive profile by subject. The date of each dive is also shown to indicate the frequency of diving for each subject. The minimum time between dives for any given subject was two days to try to avoid any interdive effects on bubble formation. The diver role is indicated by W for wet working, D for dry non-working, and A for dry attendant. Seven cases of decompression sickness were incurred and these are indicated by asterisks. These will be discussed in more detail later. The dive to 36 msw for 50 minutes with oxygen decompression is not shown. In this dive, done by subjects in Team A except for RLe who was replaced by DJ from Team B, bubbles were detected in only one subject, WM, at the grade 1 level.

Table 4 presents a summary of all the dives showing the number of man-dives for each profile, the maximum bubble grades detected in the precordial region at rest, the number of bends incurred, and the maximum bubble grades associated with these bends. No distinction has been made for diver role in this table. Table 5 shows the same information as Table 4 for bubbles detected following movement.

Maximum bubble grades detected as shown in Tables 3 to 5, although convenient indicators, are misleading to some extent in indicating the severity of the dives since they do not indicate the duration of bubbling at the maximum bubble grade or the time distribution of the bubble grades observed. For example, a maximum of grade 2 does not indicate whether this was a momentary indication observed at only one monitoring session or whether the grade 2 bubbles were observed over several monitoring sessions.

An index of severity, S, has been devised which is an attempt to integrate the total amount of bubbles detected over a period of time (11). This index is defined by

$$S = \{100/4^{\alpha}(t_j - t_0)\} \sum_{i=1}^{j} [(t_i - t_{i-1})(d_i^{\alpha} + d_{i-1}^{\alpha})/2],$$

where d_i is the bubble grade observed at time t_i, ($d_0 = 0$),
j is the number of observations,
t_j is the time of the last observation, ($t_0 = 0$), and
α is a parameter which takes into account the fact that the bubble grade, d, is not a linear measure of bubble quantity. (A value, $\alpha = 3$, has been assumed by Kisman et al (11).) The index of severity is normalized to a value for grade 4 bubbles over the entire monitoring period.

For comparative purposes for these dives, t_j, the time of the last measurement, was taken to be 300 minutes since, except for 4 man-dives, bubbles were no longer detectable by this time or were considered insignificant for the calculations. For three man-dives in which decompression sickness occurred within 300 minutes, t_j was selected as the time of the last actual measurement and this probably resulted in a lower value of S for these man-dives.

Table 6 shows the index of severity calculated for each diver for the subjects at rest, with the corresponding maximum bubble grades observed as a comparison. Also shown are the diver roles. It was found that the subjects in each dive could be conveniently divided into low bubblers, moderate bubblers and high bubblers according to the index of severity. The results also show the variability in the tendency to bubble in certain individuals. For example, subjects who were normally low bubblers (compared to the rest of the divers) could become a moderate or high bubbler in one or two of the dives. Conversely, normally high bubblers could occasionally become non-bubblers or low bubblers in some dives. A good example is the subject RLe who participated twice in the dive to 54 msw for 15 minutes, once as a dry subject producing grade 3 bubbles and the second time as a wet diver with no bubbles being produced. No obvious correlations could be made between diver role and diver stress from these data.

Table 7 shows the mean and standard deviation of the index of severity for each dive profile. The means do not include values which were exceptionally different from the rest of the values in the high bubbler category, these being listed separately. In addition, non-bubblers were separated from the low bubblers.

The index of severity does not strictly apply to bubbles detected following movement since the detected bubbles are transient events which decay to the rest values after a few cardiac cycles. The index of severity, however, is convenient to use for comparative purposes only, and can perhaps give some indication of the store of bubbles or the potential for bubbling. Unlike the bubbles detected at rest, bubbles detected after movement could not be considered insignificant by 300 minutes after the start of decompression for 25 man-dives. Monitoring was terminated between about 300 minutes and 460 minutes after the start of decompression for most of these man-dives with bubble grades of 1 to 3 still being observed. However, for convenience, the time of the last measurement was taken to be 300 minutes for these calculations.

Table 8 shows the index of severity for movement for each subject and dive profile. Once again, the divers could be conveniently divided into the three distinct groupings of high, moderate, and low bubblers. Some individuals who were moderate bubblers at rest did not bubble significantly more following movement, and as a result, became low bubblers in this comparison. Others bubbled considerably on movement, and in some cases, moved from low or moderate bubblers at rest to high bubblers following movement.

Table 9 shows the means and standard deviations of the index of severity for the different dive profiles. Exceptionally high values have again been omitted from the means shown. There is more variability between individuals following movement and as a result the standard deviations are higher.

3. Subclavian Bubble Results

Doppler monitoring of the subclavian region was not done consistently at the beginning of the dive series and not all individuals were monitored. Table 10 shows the maximum bubble grades observed for both the left and right shoulders for the last five dive profiles. Figure 13 shows two examples of bubbles detected in the subclavian region with the results of the precordial measurements for comparison.

Bubbles present in the subclavian region are generally easy to detect because the background blood flow signal is low. In many cases, although considerable bubbling may have been detected in the precordial region, no bubbles were detected in the subclavian veins. This indicated that bubbles detected in the precordial region originated elsewhere in the body than from the arms or shoulders. In other cases, bubbles were detected in the subclavian veins, either the left or right shoulder or both, but not in the precordial region. Although one would expect that these bubbles should be detected in the precordial region, the most likely explanation of why they are not detected is that these bubbles do not grow sufficiently by the time they reach the heart to be detectable over the threshold imposed by the background noise. It has been estimated that, to be detectable, bubbles in the precordial region must be around 100 micrometers in diameter (10,12). Because the background blood flow signal is not as high as it is in the precordial region, bubbles detected in the subclavian veins can be considerably smaller than those detected in the precordial region. It is also possible that these small bubbles could be resorbed into solution in the trunk before reaching the heart.

These results showed that the failure to detect bubbles in the precordial region does not mean that bubbles do not exist. Bubbles do exist but they are too small to be detectable with the Doppler instruments being used. In several man-dives, bubbling in the subclavian region persisted well after bubbles were no longer detectable in the precordial region.

In the dive to 36 msw for 50 minutes with oxygen decompression, where 5 subjects had no precordial bubbles and one subject had grade 1 bubbles only at rest, the subclavian results showed that bubbles existed in 3 subjects. The subject who had precordial bubbles developed grade 3 bubbles at rest and grade 4- bubbles after movement in the right shoulder.

Subclavian monitoring on divers who incurred decompression sickness and who reported pain in the arm or shoulder generally showed at least grade 3 bubbles at rest.

4. Assessment of Divers

Bubbles were detected in all subjects in either the precordial or subclavian region without exception. Some individuals, such as subject DF, showed no bubbles in the precordial region but showed bubbles in the subclavian region. It is difficult to categorize individuals as high, moderate or low bubblers just from the bubble grades observed since the decompression stress would depend upon the dive profile as well. On a severe dive profile, even low bubblers could have grade 2 or grade 3 bubble scores. Hence it is necessary to compare each diver with the others in a particular dive. In addition, divers vary in their tendency to bubble from dive to dive occasionally, so that in some dives, a diver could be a low bubbler, for example, and in other dives, could be a moderate bubbler. As a result, it is important to look at all the dives performed.

The classification of divers into high, moderate and low bubblers, as shown in Tables 6 and 8, permitted a good method for assessing the divers. The number of times each diver fell into the high, moderate or low categories was rated and an assessment was made as to which category he generally belonged. Divers who had dives which were about equally divided between two or more categories were generally classified into the higher category. In some cases, the decision was made by taking into consideration the results for movement if they differed from the results at rest.

The final classification of the divers into high, moderate or low bubblers is shown in Table 11. The number of dives listed is the total number of dives considered for the rating and not the number of dives in which the subject was a high, moderate or low bubbler. In one individual, DJ, only one dive was considered, and his rating as a high bubbler may be incorrect.

The mean and standard deviation of the ages of all subjects (except RMe for whom no data were available) was 33 ± 7 years. For high bubblers, the mean age was 36 ± 7 years, and for moderate bubblers, the mean age was 33 ± 8 years. The mean age for the low bubblers was 27 ± 1.5 years. A test of the differences in the mean ages of the high and moderate bubblers showed that there was little difference in the two means (probability of the two means being the same was greater than 0.2). However, a test of the differences in the mean ages of the low bubblers and the combined grouping of high and moderate bubblers (mean age 35 ± 7.5 years) showed that the means were significant at a probability level of less than 0.02. This would suggest that older divers are probably more susceptible to bubbling and should avoid high stress dives.

The effect of body build on how much individuals bubbled was not as clear. Skin-fold measurements showed that the high bubblers consisted of 4 individuals who were slightly heavier than or at the top end of their recommended weight range, 3 individuals who were within their recommended weight range, and 4 who were below. The leanest individual, RLe, with only 11.2% body fat, was among the high bubblers. Of the moderate bubblers, one was overweight and 6 of the other 7 were either within or at the low end of their recommended weight range. No information was available on the other individual (RMe). Of the low bubblers, 2 were heavier than or near the top of the recommended weight range and 3 were lower than or at the low end of the recommended weight range.

Although subjects were instructed to limit their alcohol consumption and to obtain adequate sleep during the trial period, a check of the post-dive questionnaires showed that these instructions were not followed by many of the individuals. Some individuals also participated in physical exercise which they normally did not do, and others ran the day before the dive. However, no conclusions could be made about the influence of variables such as these on bubbling.

5. Incidences of Decompression Sickness

Seven incidences of decompression sickness occurred during this dive series and were treated by recompression therapy. Two other cases may have been probable incidences of decompression sickness but were not treated. These 9 incidences involved 6 divers and are shown in Table 12. The two probable cases were individuals who had incurred decompression sickness in previous dives. Six of the 7 cases treated were associated with a maximum of grade 3 bubbles detected at rest in the precordial region and one was associated with grade 2 at rest. One of the probable cases had grade 3 bubbles and the other had grade 4 bubbles. The total man-dives for bubbles observed at rest were 22 man-dives resulting in grade 2 bubbles, 24 man-dives resulting in grade 3 bubbles, and 2 man-dives resulting in grade 4 bubbles. The Doppler results for bubbles following movement showed that 4 of these bends incidences had grade 3 bubbles and the other 3 had grade 4 bubbles. Both probable cases had grade 4 bubbles following movement. The total for all the divers for bubbles following movement were 36 man-dives showing grade 3 and 17 man-dives showing grade 4 bubbles.

It is difficult to select a criterion for indicating the probability of bends from these figures. The best criterion appears to be grade 3 bubbles at rest. It is obvious that not all grades 3 or 4 bubbles at rest are associated with decompression sickness. However, it appears likely that most cases of decompression sickness are associated with grade 3 or grade 4 bubbles at rest and that there is some risk involved in dive profiles that produce these levels of bubbling.

Treatment by recompression was only given in the 7 incidences where symptoms were reported and not for high bubble grades observed. Spencer (10), in his work on direct decompression dives, used a more conservative approach and used recompression therapy if bubbles occurred in more than grade 3 quantities, or if bends pain developed. In many instances, when grade 1 bubbles were detected early and progressed to grade 2 quantities, his subjects breathed 100% oxygen at one atmosphere until the bubble signals diminished or disappeared. This approach was not used for these XDC-2 dive profiles.

Because one subject (MK) incurred decompression sickness with grade 2 bubbles, it would appear that there may be a small probability that grade 2 bubbles could result in decompression sickness. The symptoms in this case were a vague feeling of discomfort in the right shoulder and vague feelings of malaise. The subject was given a trial recompression to 18 msw on oxygen and felt better. A full U.S. Navy Table 5 treatment (7) was then given. The subject had been involved in moving his home for a week prior to the dive and had many late nights and was not feeling his usual self before the dive. The subject was a high bubbler, 32 years old, and slightly above his recommended weight range based on skin-fold measurements.

It is worthwhile to look at the other cases of decompression sickness to see whether there were any contributing or predisposing factors. Of the remaining 5 divers, 3 were high bubblers, 1 was a moderate bubbler, and 1 was a low bubbler.

The low bubbler, YL, was a dry non-working diver on the dive to 45 msw for 30 minutes. Prior to this dive, he had registered only a maximum of grade 1 bubbles. On exiting from the chamber after the dive, this subject was extremely active, coiling the diving umbilical lines and stowing away the KMB-9 masks. Eight minutes after surfacing, the subject had pain in his shoulder, with bubble grade 3 on rest and bubble grade 4 on movement, and fainted for several seconds. The subject was recompressed and experienced full relief soon after reaching the treatment depth of 18 msw. This subject was 28 years old and was slightly above his recommended weight range as based on his skinfold measurements. The increased activity after surfacing could have been a contributing factor, since on subsequent dives in which he did not exercise after decompression, he reverted back to grade 0 bubbles on two dives, had a maximum of grade 1 on another dive, and grade 2 on a fourth dive. After this decompression incident, all subjects were cautioned against excessive movement after surfacing because it was felt that movement could contribute to bubble formation.

The moderate bubbler, GP, reported symptoms approximately 18 hours after surfacing from the dive to 36 msw for 50 minutes. He had pain in his right elbow, felt tired and dizzy and required treatment. During the post-decompression monitoring, this subject had grade 3 bubbles for both rest and after movement. At the termination of the monitoring period 6 hours after the start of decompression, bubbles at rest had disappeared but bubbles on movement were still at the grade 3 level. This diver was 37 years old and was on the low side of his recommended weight range.

Diver EN reported a "crick" in his right shoulder approximately one hour after surfacing from the dive to 36 msw for 50 minute. He had grade 3- bubbles at rest and 3+ following movement at that time. He experienced full relief on being treated. This diver was 37 years old and was below his recommended weight range.

Diver AK dived twice and incurred decompression sickness on both occasions. In both cases, he had pain in the left leg and other symptoms of Type II decompression sickness. In his first dive (36 msw for 50 minute), symptoms occurred 18 hours after the dive. On his second dive (45 msw for 30 minutes), symptoms occurred approximately 13 hours after the dive. This subject had apparently injured his left leg many years previously and this previous injury may have been a contributing factor. He was also the oldest diver and was slightly over his recommended weight range.

Diver RLe felt a slight discomfort in his left calf about 4 hours after the dive to 36 msw for 40 minutes, which was alleviated on treatment. This diver ran for 5 miles the day before the dive. However, he also ran for 3 or 4 miles before three of his other dives. There appeared to be no influence on the degree of bubbling whether he ran or not the day before. This diver was 25 years old and his weight was well below his recommended weight range.

Several divers reported feeling extremely tired after their dives but did not have any symptoms of decompression sickness. In these cases, the bubble scores were generally high, usually grades 3 or 4 at rest and grade 4 on movement. Hence, there appears to be some evidence that excessive bubbling could contribute to extreme fatigue.

6. Assessment of Decompression Profiles

Doppler monitoring of all divers during this dive series provided a convenient method for assessing the safety or severity of the decompression profiles. With the normal method of assessing decompression profiles by using the bends incidence as the essential criterion, a large number of dives must be conducted (13) to validate the dive as safe depending on the acceptable incidence of decompression sickness, the variability around this incidence level and the confidence limits desired.

For example, in this dive series, 3 out of 6 divers suffered from decompression sickness on the dive to 36 msw for 50 minutes, 1 out of 12 on the dive to 36 msw for 40 minutes, 2 out of 12 on the dive to 45 msw for 30 minutes, and 1 out of 12 on the dive to 54 msw for 15 minutes. This information, however, is insufficient to determine the relative decompression stress associated with these profiles, or to determine the probability of decompression sickness. It is not possible to conclude, for example, that the dive to 36 msw for 40 minutes has the same degree of decompression stress as the dive to 54 msw for 15 minutes because both dives resulted in 1 bend each. Many more dives must be done to make any statistical comparisons that are based on the incidence of bends.

The maximum bubble grades detected for each dive profile can give more useful information than the incidence of decompression sickness. Dives which produce many bubbles are more severe than those which do not produce as many bubbles and there is an element of risk associated with grade 3 bubbles at rest. In Tables 4 and 5, which show the maximum bubble grades observed for rest and movement, it can be seen that for each depth, as the bottom time increases, the number of divers with higher bubble grades increase and those with lower bubble grades decrease, indicating a trend toward more severe dives. These numbers could be misleading, however, since they are population dependent. A severe dive done with low bubblers could look less stressful than a less severe dive done with only high bubblers. Maximum bubble grades could also be misleading (as stated previously) because they do not give the duration of bubbling at the maximum grade or the temporal distribution of bubbles.

The index of severity provides a more objective method of rating the severity of dive profiles. Tables 7 and 9 show the mean values of the index for rest and movement for all profiles. In Table 7, for precordial bubbles at rest, it can be observed that the dives to 36 msw for 30 minutes, 45 msw for 25 minutes, and 54 msw for 15 minutes all have approximately the same values of S for high bubblers and approximately the same values for moderate bubblers, indicating that these three dives produce about the same decompression stress. Similarly, the dives to 36 msw for 40 minutes and 54 msw for 20 minutes have approximately the same values of S for high and moderate bubblers at rest, showing that these dives produce the same decompression stress. Similar conclusions can be reached from the dives to 36 msw for 50 minutes and 54 msw for 25 minutes. The index of severity for movement gives similar results but there is more variability in the values between the comparable dive profiles since in many dives, bubbles had not terminated at the maximum time used in the calculations.

Figure 14 shows the profiles tested as depth vs. bottom time on a log-log plot. A line joining the dives to 36 msw for 40 minutes and 54 msw for 20 minutes shows the depth and bottom times which will produce grade 3 bubbles at rest in high bubblers and grade 2 bubbles in moderate bubblers. There will be some risk of decompression sickness for high bubblers on this line. Above this line, high bubblers will probably have grade 3 or grade 4 bubbles at rest and there will be a definite risk of decompression sickness for depths and times in this range. Five of the 7 incidences occured in this range. For depths and times below this line, high bubblers would typically show grade 2 bubbles at rest and moderate bubblers would show a maximum of grade 1 bubbles at rest.

This line presents reasonably good limiting bottom times for operating with the XDC-2 decompression computer. It is interesting to note that this line is almost identical to the Royal Navy limiting line in their Table 11 air dives (6). Dives with bottom times beyond this limit line also have a higher risk of decompression sickness in the Royal Navy tables. In fact, the Royal Navy air tables were used to assist in the selection of the bottom times to be selected for this dive trial.

Comparisons with the Royal Navy and U.S. Navy air tables for the same depth and bottom times show that the XDC-2 profiles are more conservative (Figures 2 to 10). The decompression times for the longer bottom times at each depth are only slightly longer than the Royal Navy tables. For the shorter bottom times, the decompression times are considerably more conservative and probably contribute to the lower stress of these dives. Because considerable bubble activity was observed in the XDC-2 dives despite the conservative nature of these profiles, dives based on the U.S. Navy and Royal Navy Tables should be monitored with the Doppler bubble detector in order to determine the decompression stress produced by these tables and to determine whether there is any difference between continuous decompression and staged decompression.

SUMMARY

The bubble results from the precordial region obtained during these dives showed that bubbles often did not occur during or immediately after decompression but some time after surfacing, reaching a maximum between one and two hours after the start of decompression and remaining at this level for some time. Bubbles at rest generally disappeared by about 4 or 5 hours after the start of decompression. Bubble grades observed following movement were generally greater and persisted for a longer period. In some instances, after 6 hours of monitoring, bubbles were still at the grade 3 level following movement.

It should be noted that bubbles observed in the precordial region are just the detectable bubbles. No bubbles being detected in the precordial region does not conclusively imply that bubbles do not exist. Bubbles must be sufficiently large in the precordial region to be detectable above the background signals by Doppler units operating at 5 MHz frequency. The results of monitoring the subclavian veins have shown that numerous bubbles could be detected in this region in some individuals and not be detected in the precordial region. This likely happened because these bubbles did not grow sufficiently large to be detectable by the time the precordial region was reached. Because of the lower background signal in the subclavian region, bubbles can be considerably smaller than in the precordial region and still be detected. Another possibility is that these bubbles could have been resorbed and not been detected in the precordial region. Bubbles too small to be detected could persist for much longer periods than those detectable and may explain why symptoms of decompression sickness can occur many hours later as in subjects AK and GP. The fact that bubbles persist for so long after a dive can have severe consequences, particularly for individuals who fly after diving.

The maximum bubble grade observed is convenient for characterizing the severity of a dive. However, this value does not indicate the duration of bubbling at this maximum grade nor does it reflect the temporal distribution of the bubble evolution. An index of severity has been defined to give a more accurate comparison between dives and divers. For routine use, however, the maximum bubble grade observed in the precordial region at rest would appear to be the most convenient parameter to use for comparing and judging dives. Grade 3 bubbles observed at rest in the precordial region has been found to present some hazards in terms of decompression sickness.

Bubbles were detected in all divers in the precordial region and/or the subclavian sites. Divers could also be divided into high, moderate, or low bubblers based on the Doppler results. No obvious differences could be determined between the different diver roles, i.e., wet working, dry attendant, and dry non-working.

For the XDC-2 decompression computer in the depth range from 36 to 54 msw, a bottom time limiting line was determined. All divers should be able to dive for bottom times less than the limiting values. Bubbles produced in high bubblers should be at the grade 2 level. Only moderate and low bubblers should be diving at bottom times approaching the limiting values and only low bubblers should dive beyond the limiting values. However, there may always be the exception to the rule, since divers sometimes varied considerably in their tendency to bubble from dive to dive.

Decompression with oxygen showed a dramatic decrease in observable bubbles. In a stressful dive beyond the limiting line, where 3 out of 6 individuals incurred decompression sickness without oxygen, the same profile with oxygen decompression resulted in only one individual in 6 having bubbles in the precordial region, and only at the grade 1 level. However, three individuals showed subclavian bubbles. Hence oxygen decompression does not eliminate bubbles entirely but it does reduce the stress of the dive.

The results of this investigation show that, if decompression testing is to conducted, diving subjects should be tested beforehand and be divided into teams consisting of the same type of bubblers, i.e., all high bubblers, or all low bubblers. Any decompression profiles found to be safe for high bubblers within some acceptable level of risk should be safe for moderate or low bubblers with little risk. Attempting to develop safe profiles with low bubblers could result in decompression tables or profiles which could be hazardous for high bubblers.

In summary, the results of this investigation have shown that the use of the Doppler ultrasonic bubble detector, together with a good bubble coding scheme, provides a convenient and valuable method for assessing the safety or severity of decompression profiles and for assessing divers as to their susceptibility to bubbling after diving.

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TABLE I

DIVE TIMES FOR XDC-2 DECOMPRESSION COMPUTER PROFILES

DEPTH (msw)	BOTTOM TIME (min)	ASCENT TIME TO 3 MSW (min)	STOP TIME AT 3 MSW (min)	TOTAL ASCENT TIME (min)	TOTAL TIME OF DIVE (min)
36	30	14	15	31	61
36	40	18	20	40	80
36	50	22	31	55	105
45	20	15	14	31	51
45	25	19	16	37	62
45	30	22	21	45	75
54	15	16	13	31	46
54	20	22	16	40	60
54	25	27	24	53	78

NOTES:

1. Bottom time includes the descent time from surface to bottom depth. The descent rate for the transfer sphere and dive chamber combination varies from 18 msw/min at surface to 8.8 msw/min at 54 msw in accordance with Figure 1.
2. Ascent time to 3 msw consists of an initial ascent at 18 msw/min to about 35 msw, followed by ascent at a decreasing rate determined by the maximum venting capability of the transfer sphere/dive chamber combination until the safe ascent depth is reached. The safe ascent depth is then followed until 3 msw is reached.

TABLE 2

SUBJECT STATISTICS

SUBJECT	AGE	WEIGHT (kg)	SUM OF SKINFOLDS (mm)	PERCENT BODY FAT	RECOMMENDED WEIGHT RANGE (kg)	NUMBER OF DIVES
TEAM A						
GF	25	77.1	33.4	17.5	77-82	8
DS	21	88.5	42.8	20.9	85-90	8
YL	28	90.7	50.2	23.2	85-90	8
JO	29	77.1	45.2	21.7	74-78	8
RLe	25	74.1	21.4	11.2	80-85	8
WM	43	86.2	32.1	16.9	88-92	8
TEAM B						
RL	46	79.4	45.2	21.7	76-80	4
RMc	25	73.5	36.8	18.7	73-77	4
GM	37	79.4	27.6	14.7	82-87	4
EN	37	74.8	30.8	16.2	76-81	4
MP	32	72.0	37.4	19.0	71-75	4
NR	33	74.8	43.8	21.2	72-76	4
KS	32	73.0	41.0	20.3	71-75	4
RC	27	70.5	38.0	19.2	69-73	3
MK	32	75.3	51.1	23.3	70-75	3
RM	34	95.7	36.6	18.7	95-100	3
GP	37	73.9	32.3	17.0	74-78	3
CC	44	81.2	38.0	19.2	80-85	2
DE	27	64.0	28.2	15.1	65-69	2
DF	27	72.8	37.2	19.0	72-76	2
DJ	33	93.7	52.8	24.7	86-90	2
AK	47	81.6	51.1	23.3	76-81	2
RMe	--	----	----	----	-----	2
BR	40	93.9	51.2	23.3	86-91	2

TABLE 3

MAXIMUM BUBBLE GRADES IN THE PRECORDIAL REGION BY SUBJECT AND ROLE

SUBJ.	DIVES - DEPTH (msw)/BOTTOM TIME (min)								
	36/30	36/40	36/50	45/20	45/25	45/30	54/15	54/20	54/25
TEAM A									
Date	26-06	22-06			03-07	28-06	13-07	09-07	11-07
GF	W 1/3-	W 2/4			A 0/2-	A 1/3-	W 0/1	D 1/1	W 2/3+
DS	W 0/0	W 3/4			A 0/1	A 1/3	W 1/2+	D 0/0	W1+/3
YL	A 0/0	A 0/1			D 1/1	D 3/4*	A 0/0	W 0/0	A 2/2
JO	A 0/0	A 1/3-			D 0/0	D 0/0	A 0/0	W 2/3	A 0/0
WM	D 0/0	D 2/3+			W 1/2	W 3/3+	D 2/3	A 3/3+	D 3/3
RLe	D3-/2+	D3+/4*			W 2/3-	W 2/3	D3-/3 W 0/0	A 3/3-	D 3/3
TEAM B									
Date	25-06	21-06	19-06	27-06	29-06	04-07	06-07	10-07	12-07
RL	W2+/4		A 3/4		W 2/3+			W 2/3	
RMc			D 1/3		D 0/0	D 0/2-	W 0/0		
GM		A 3/4		W 1/3		A 1/2		D 0/0	
EN			A3-/3+*	W 0/0			D 0/0		A3+/3+**
MP	D2+/3				W 2/2			W 3/4	D 3/4
NR	D 0/0		W 3/4		A1+/2+				W3-/3
KS		D 0/0			A 1/1		D1-/0		D2+/2+
RC	W 1/3					D 1/1+		A3+/4-	
MK		W2+/4					A 2/3*		A 4/4**
RM	A 2/3	A 3/4						D 4/4	
GP	A 1/1		W3-/3*	D 2/3					
CC								A 2/3	W 2/3+
DE					D 0/0		A 0/1		
DF				D 0/0		A 0/0			
AK			D3+/4*			W 3/3+*			
RMe		D 1/4-		A 1/3					
BR				A 1/0		W 2/3			
DJ		W 3/3							

NOTES:

1. Explanation of code X a/b:
   X - diver role: W = wet diver
   D = dry non-working subject
   A = dry attendant for wet diver
   a - bubble grade for rest, b - bubble grade for movement
   * - indicates bend (treated), ** - probable bend (untreated)
   Date - day-month

2. The dive to 36 msw for 50 minutes with oxygen decompression (Date 05-07-79) was done with Team A except for subject RLe who was replaced by DJ from Team B. Bubbles were detected on only subject, WM, who had grade 1 bubbles at rest.

TABLE 4

MAXIMUM BUBBLE GRADES IN THE PRECORDIAL REGION AT REST

DEPTH (msw)	BOTTOM TIME (min)	NO. MAN DIVES /TEAM	NO. OF DIVERS WITH MAXIMUM BUBBLE GRADE 0	1	2	3	4	NO. OF BENDS	BUBBLE GRADE FOR BENDS
36	30	6/A	4	1	0	1	0	0	
		6/B	1	2	3	0	0	0	
36	40	6/A	1	1	2	2	0	1	3
		6/B	1	1	1	3	0	0	
36	50	6/B	0	1	0	5	0	3	3
	50+02	6/A	5	1	0	0	0	0	
45	20	6/B	2	3	1	0	0	0	
45	25	6/A	3	2	1	0	0	0	
		6/B	2	2	2	0	0	0	
45	30	6/A	1	2	1	2	0	1	3
		6/B	2	2	1	1	0	1	3
54	15	6/A	4	1	1	0	0	0	
		6/B	3	1	1	1	0	1	2
54	20	6/A	2	1	1	2	0	0	
		6/B	1	0	2	2	1	0	
54	25	6/A	1	1	2	2	0	0	
		6/B	0	0	2	3	1	*	
TOTALS		102	33	22	21	24	2	7	

NOTE:
No distinction has been made for diver role (i.e., whether dry, wet, or attendant).

* Two probable cases, untreated, maximum bubble grades 3, 4.

TABLE 5

MAXIMUM BUBBLE GRADES IN THE PRECORDIAL REGION AFTER MOVEMENT

DEPTH (msw)	BOTTOM TIME (min)	NO. MAN DIVES /TEAM	NO. OF DIVERS WITH MAXIMUM BUBBLE GRADE 0	1	2	3	4	NO. OF BENDS	BUBBLE GRADE FOR BENDS
36	30	6/A	4	0	1	1	0	0	
		6/B	1	1	0	3	1	0	
36	40	6/A	0	1	0	2	3	1	4
		6/B	1	0	0	1	4	0	
36	50	6/B	0	0	0	3	3	3	3,4
	50+02	6/A	6	0	0	0	0	0	
45	20	6/B	3	0	0	3	0	0	
45	25	6/A	1	2	2	1	0	0	
		6/B	2	1	2	1	0	0	
45	30	6/A	1	0	0	4	1	1	4
		6/B	1	1	2	2	0	1	3
54	15	6/A	3	1	1	1	0	0	
		6/B	3	1	0	2	0	1	3
54	20	6/A	2	1	0	3	0	0	
		6/B	1	0	0	2	3	0	
54	25	6/A	1	0	1	4	0	0	
		6/B	0	0	1	3	2	*	
TOTALS		102	30	9	10	36	17	7	

NOTE:
No distinction has been made for diver role (i.e., whether dry, wet, or attendant).

* Two probable cases, untreated, maximum bubble grade 4.

TABLE 6

SUBJECT ROLE, BUBBLE GRADE, AND INDEX OF SEVERITY, S, FOR HIGH, MODERATE, AND LOW BUBBLERS - PRECORDIAL AT REST

PROFILE	HIGH BUBBLERS				MODERATE BUBBLERS				LOW BUBBLERS			
msw/min	SUBJ	ROLE	BC	S	SUBJ	ROLE	BC	S	SUBJ	ROLE	BC	S
36/30	RLe	D	3-	3.6	GF	W	1	0.2	DS	W	0	0
	RL	W	2+	5.0	RC	W	1	0.4	YL	A	0	0
	MP	D	2+	3.8	GP	A	1	0.2	JO	A	0	0
	RM	A	2	1.5					WM	D	0	0
									NR	D	0	0
36/40	DS	W	3	15.6	GF	W	2	5.8	YL	A	0	0
	RLe*	D	3+	11.7	WM	D	2	2.6	KS	D	0	0
	GM	A	3	20.0					RMe	D	1	0.5
	MK	W	2+	9.1					JO	A	1	0.2
	RM	A	3	14.5								
	DJ	W	3	15.3								
36/50	RL	A	3	14.6	GP*	W	3-	6.8	RMc	D	1	0.5
	EN*	A	3-	36.6								
	NR	W	3	15.8								
	AK*	D	3+	20.5								
45/20	GP	D	2	1.6	GM	W	1	0.6	EN	W	0	0
					RMe	A	1	0.6	DF	D	0	0
					BR	A	1	0.2				
45/25	RLe	W	2	1.8	YL	D	1	0.6	GF	A	0	0
	RL	W	2	5.8	WM	W	1	0.2	DS	A	0	0
	MP	W	2	1.5	NR	A	1+	0.3	JO	D	0	0
					KS	A	1	0.3	RMc	D	0	0
									DE	D	0	0
45/30	YL*	D	3	13.8	RLe	W	2	2.2	JO	D	0	0
	WM	W	3	8.0	GM	A	1	0.8	RMc	D	0	0
	AK*	W	3	13.2	DS	A	1	1.1	DF	A	0	0
					BR	W	2	2.6	GF	A	1	0.1
									RC	D	1	0.1

TABLE 6 (continued)

SUBJECT ROLE, BUBBLE GRADE, AND INDEX OF SEVERITY, S, FOR HIGH, MODERATE, AND LOW BUBBLERS - PRECORDIAL AT REST

PROFILE	HIGH BUBBLERS				MODERATE BUBBLERS				LOW BUBBLERS			
msw/min	SUBJ	ROLE	BC	S	SUBJ	ROLE	BC	S	SUBJ	ROLE	BC	S
54/15	RLe	D	3-	4.7	DS	W	1	0.2	GF	W	0	0
	WM	D	2	2.0	KS	D	1-	0.1	YL	A	0	0
	MK*	A	2	5.9					JO	A	0	0
									RLe	W	0	0
									RMc	W	0	0
									EN	D	0	0
									DE	A	0	0
54/20	WM	A	3	11.6	JO	W	2	3.5	DS	D	0	0
	MP	W	3	16.8	RLe	A	3	4.9	YL	W	0	0
	RC	A	3+	19.5	RL	W	2	5.8	GM	D	0	0
	RM	D	4	34.3	CC	A	2	2.2	GF	D	1	0.6
54/25	RLe	D	3	17.4	GF	W	2	5.6	JO	A	0	0
	WM	D	3	13.2	YL	A	2	3.9	DS	W	1+	0.5
	EN**	A	3+	14.1	NR	W	3-	7.3				
	MP	D	3	24.2	KS	D	2+	3.6				
	MK**	A	4	45.3	CC	W	2	3.2				

NOTES:

BC = bubble code, maximum grade observed
S = index of severity

Diver role - W = wet diver
D = dry non-working subject
A = dry attendant
S = dry supervisor.

* Bend, treated
** Probable bend, untreated

TABLE 7

INDEX OF SEVERITY, S, FOR HIGH, MODERATE, AND LOW BUBBLERS BASED ON 5 HOURS OF MONITORING THE PRECORDIAL REGION AT REST

PROFILE msw/min	HIGH BUBBLERS NO. OF DIVERS	HIGH BUBBLERS S MEAN S.D.	MODERATE BUBBLERS NO. OF DIVERS	MODERATE BUBBLERS S MEAN S.D.	LOW BUBBLERS NO. OF DIVERS	LOW BUBBLERS S MEAN S.D.
36/30	4	3.5 ± 1.4	3	0.3 ± 0.1	5	0
36/40	6	14.4 ± 3.7	2	4.2 ± 2.3	2 2	0 0.3 ± 0.2
36/50	3 1	17.0 ± 3.1 36.6	1	6.8	1	0.5
45/20	1	1.6	3	0.5 ± 0.2	2	0
45/25	3	3.0 ± 2.4	4	0.4 ± 0.2	5	0
45/30	3	11.7 ± 3.2	4	1.7 ± 0.9	3 2	0 0.1
54/15	3	4.2 ± 2.0	2	0.2 ± 0.1	7	0
54/20	3 1	16.0 ± 4.0 34.3	4	4.1 ± 1.6	3 1	0 0.6
54/25	4 1	17.2 ± 5.0 45.3	5	4.7 ± 1.7	1 1	0 0.5

TABLE 8

SUBJECT ROLE, BUBBLE GRADE, AND INDEX OF SEVERITY, S, FOR HIGH, MODERATE, AND LOW BUBBLERS - PRECORDIAL AFTER MOVEMENT

PROFILE	HIGH BUBBLERS				MODERATE BUBBLERS				LOW BUBBLERS			
msw/min	SUBJ	ROLE	BC	S	SUBJ	ROLE	BC	S	SUBJ	ROLE	BC	S
36/30	RL	W	4	44.1	GP	A	1	0.7	DS	W	0	0
	GF	W	3-	4.9	RLe	D	2+	2.3	YL	A	0	0
	MP	D	3	5.6					JO	A	0	0
	RC	W	3	9.8					WM	D	0	0
	RM	A	3	8.1					NR	D	0	0
36/40	GF	W	4	41.6	JO	A	3-	12.3	YL	A	1	0.1
	DS	W	4	48.8					KS	D	0	0
	RLe*	D	4	44.9								
	WM	D	3+	30.9								
	GM	A	4	51.0								
	MK	W	4	44.7								
	RM	A	4	34.5								
	RMe	D	4-	38.5								
	DJ	W	3	30.2								
36/50	RL	A	4	56.6	GP*	W	3	31.5	RMc	D	3	13.7
	EN*	A	3+	57.1								
	NR	W	4	64.1								
	AK*	D	4	63.5								
45/20	GM	W	3	16.2	GP	D	3	5.7	EN	W	0	0
	RMe	A	3	10.6					DF	D	0	0
									BR	A	0	0
45/25	RLe	W	3-	13.0	WM	W	2	3.2	JO	D	0	0
	RL	W	3+	32.3	MP	W	2	1.9	RMc	D	0	0
					NR	A	2+	2.4	DE	D	0	0
									GF	A	2-	0.9
									DS	A	1	0.5
									YL	D	1	0.3
									KS	A	1	0.2

TABLE 8 (continued)

SUBJECT ROLE, BUBBLE GRADE, AND INDEX OF SEVERITY, S, FOR HIGH, MODERATE, AND LOW BUBBLERS - PRECORDIAL AFTER MOVEMENT

PROFILE	HIGH BUBBLERS				MODERATE BUBBLERS				LOW BUBBLERS			
msw/min	SUBJ	ROLE	BC	S	SUBJ	ROLE	BC	S	SUBJ	ROLE	BC	S
45/30	YL*	D	4	?	GF	A	3-	13.3	JO	D	0	0
	DS	A	3	29.1	RLe	W	3	15.9	DF	A	0	0
	WM	W	3+	27.8	BR	W	3	15.1	RC	D	1+	0.7
	AK*	W	3+	30.8					GM	A	2	2.5
									RMc	D	2-	2.3
54/15	MK*	A	3	18.9	DS	W	2+	5.6	YL	A	0	0
	WM	D	3	11.5					JO	A	0	0
	RLe	D	3	9.6					RLe	W	0	0
									RMc	W	0	0
									EN	D	0	0
									KS	D	0	0
									DE	A	1	0.3
									GF	W	1	0.2
54/20	RL	W	3	31.1	JO	W	3	14.6	DS	D	0	0
	MP	W	4	51.1	RLe	A	3-	9.6	YL	W	0	0
	RC	A	4-	32.9	WM	A	3+	13.7	GM	D	0	0
	RM	D	4	45.9					GF	D	1	0.6
	CC	A	3	26.1								
54/25	RLe	D	3	30.3	NR	W	3	12.2	JO	A	0	0
	EN**	A	3+	35.2	WM	D	3	14.3	YL	A	2	6.8
	MP	D	4	58.7	DS	W	3	13.5	KS	D	2+	3.2
	MK**	A	4	75.5	CC	W	3+	23.7				
					GF	W	3+	24.6				

NOTES:

BC = bubble code, maximum grade observed
S = index of severity

Diver role - W = wet diver
D = dry non-working subject
A = dry attendant
S = dry supervisor.

* Bend, treated
** Probable bend, untreated

TABLE 9

INDEX OF SEVERITY, S, FOR HIGH, MODERATE, AND LOW BUBBLERS BASED ON 5 HOURS OF MONITORING THE PRECORDIAL REGION AFTER MOVEMENT

PROFILE msw/min	HIGH BUBBLERS NO. OF DIVERS	HIGH BUBBLERS S MEAN S.D.	MODERATE BUBBLERS NO. OF DIVERS	MODERATE BUBBLERS S MEAN S.D.	LOW BUBBLERS NO. OF DIVERS	LOW BUBBLERS S MEAN S.D.
36/30	4 1	7.1 ± 2.3 44.1	2	1.5 ± 1.1	5	0
36/40	9	40.6 ± 7.6	1	12.3	1 1	0 0.1
36/50	4	60.3 ± 4.0	1	31.5	1	13.7
45/20	2	13.4 ± 4.0	1	5.7	3	0
45/25	2	22.6 ±13.6	3	2.5 ± 0.7	3 4	0 0.5 ± 0.3
45/30	3 1	29.2 ± 1.5 unknown	3	14.8 ± 1.3	2 3	0 1.8 ± 1.0
54/15	3	13.3 ± 4.9	1	5.6	6 2	0 0.2 ± 0.1
54/20	5	37.4 ±10.6	3	12.6 ± 2.7	3 1	0 0.6
54/25	3 1	41.4 ±15.2 75.5	5	17.7 ± 6.0	1 2	0 5.0 ± 2.6

TABLE 10

MAXIMUM BUBBLE GRADES IN THE SUBCLAVIAN SITES BY SUBJECT AND ROLE

SUBJ.	DIVES - DEPTH (MSW)/BOTTOM TIME (MIN)									
	45/25		45/30		54/15		54/20		54/25	
TEAM A	LS	RS	LS	RS	LS	RS	LS	RS	LS	RS
GF	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
DS	0/0	0/0	0/0	0/0	3/3	0/0	0/0	0/0	0/0	0/0
YL	0/0	1/2	*	*	0/1	0/0	1/1	0/1	2/2	2/2
JO	0/0	0/0	0/1	0/0	0/0	0/0	1/2	0/1	0/0	0/0
WM	0/0	0/0	3/3+	3+/4	1/2+	0/0	4-/4	0/0	4-/4	2/3-
RLe	2/3	0/0	3/3	0/1	3+/3	3/3	3+/4	0/0	4-/4	0/0
					1/1	0/0				
TEAM B										
RL	3-/3	1+/3-					3-/3	3+/3-		
RMc	0/0	0/0	0/0	0/0	0/0	0/0				
GM			0/0	1/0			0/0	0/0		
EN					0/0	0/0			0/0**	3+/3+**
MP	0/0	2+/3-					0/0	3+/4-	0/0	3/3+
NR	0/0	0/0							0/0	3/4
KS	0/0	0/0			1-/1	0/0			3-/3+	0/0
RC			0/0	0/0			0/0	1/2		
MK					3-/2*	3/3-*			3+/3+**	4-/3+**
RM							3+/3-	3+/3+		
CC							3/3+	3-/3+	0/1	0/1
DE	0/0	0/0			0/0	0/1				
DF			0/0	1/2+						
AK			0/3-*	0/2+*						
BR			2/3-	2/2						

NOTES:

Explanation of code: LS - left shoulder, RS - right shoulder
* - indicates bend, treated
** - indicates probable bend, not treated
a/b: a - bubble grade for rest
b - bubble grade for movement

TABLE 11

ASSESSMENT OF DIVERS AS HIGH, MODERATE, AND LOW BUBBLERS

HIGH BUBBLERS	NO. OF DIVES	MODERATE BUBBLERS	NO. OF DIVES	LOW BUBBLERS	NO. OF DIVES
RLe	8	GF	7	YL	7
WM	7	DS	7	JO	7
RL	4	NR	4	RMc	4
GM	4	KS	4	DE	2
MP	4	GP	3	DF	2
EN	4	CC	2		
RC	3	RMe	2		
MK	3	BR	2		
RM	3				
AK	2				
DJ	1				

NOTE: The dive to 36 msw for 50 minute with oxygen decompression has not been counted.

TABLE 12

DECOMPRESSION SICKNESS INCIDENCES

SUBJECT	PROFILE msw/min	MAX. BUBBLE GRADE PRECORDIAL AT REST/AFTER MOVEMENT	TYPE DCS
RLe	36/40	3+/4	I
EN	36/50	3-/3+	I
AK	36/50	3+/4	II
GP	36/50	3-/3	I
YL	45/30	3 /4	I
AK	45/30	3 /3+	II
MK	54/15	2 /3	I
EN	54/25	3+/3+	*
MK	54/25	4 /4	*

* Probable case of decompression sickness, not treated.

LIST OF FIGURES

Figure 14. Limiting bottom time line for XDC-2 decompression computer profiles. The data points show the dive profiles tested. Numbers to the left of the data points give the mean index of severity, S, for high bubblers (precordial, at rest). Numbers in parentheses to the right of the data points give the value of S for moderate bubblers. Dives with bottom times less than the limiting values are low or mild stress dives. Dives above the limiting values are high stress dives.

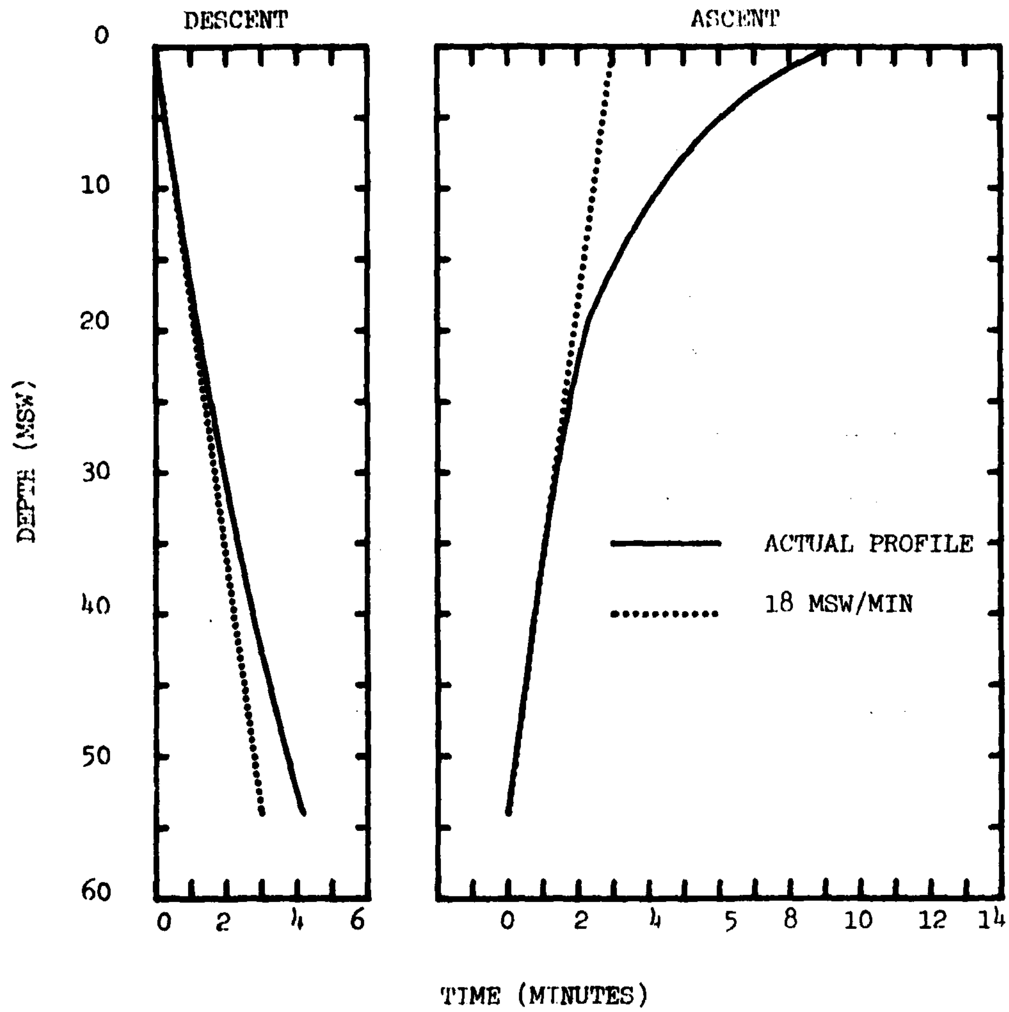

FIGURE 1: Descent and ascent profiles for dive chamber and transfer sphere combinations.

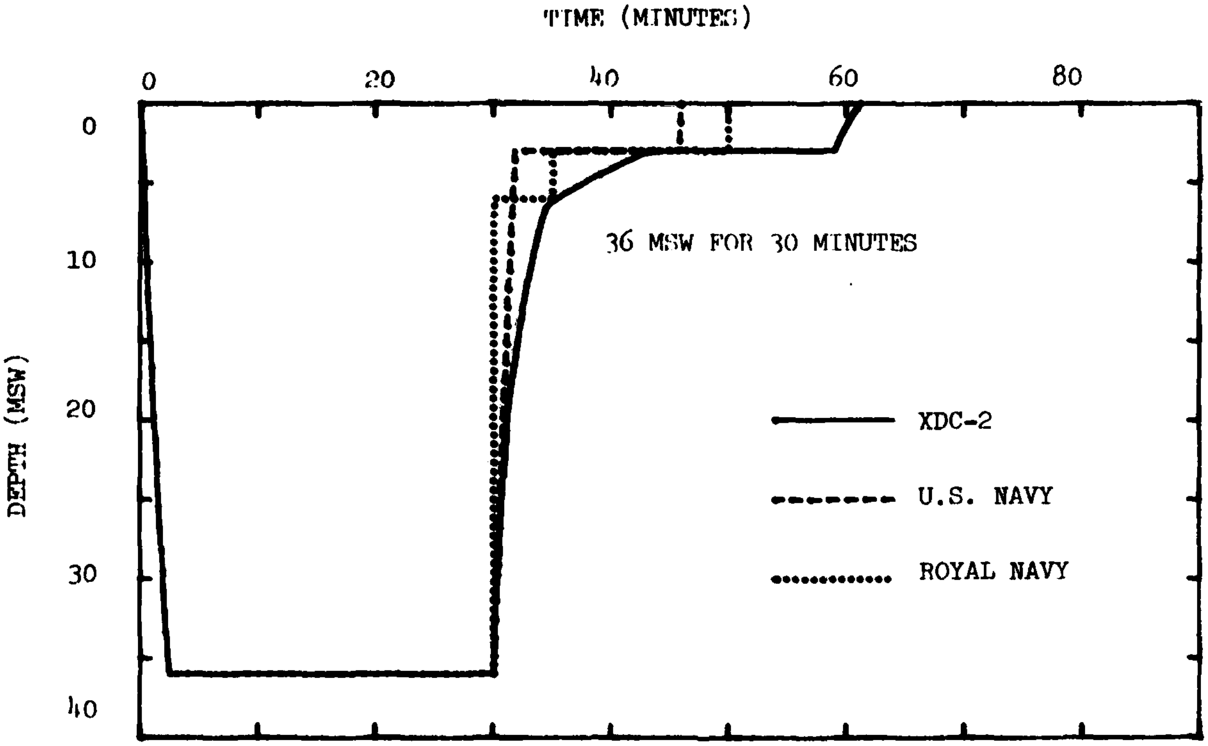

FIGURE 2 : XDC-2 dive profile for 36 msw for 30 minutes with comparison to the U.S. Navy and Royal Navy tables.

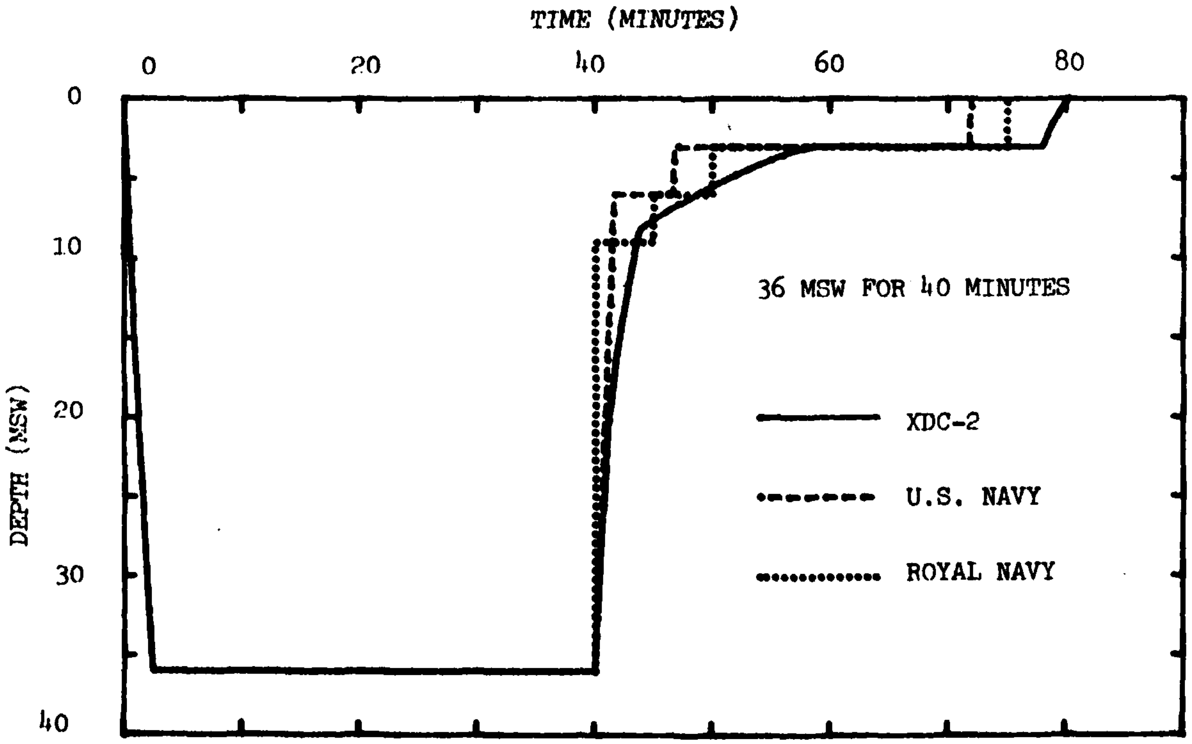

FIGURE 3: XDC-2 dive profile for 36 msw for 40 minutes with comparison to the U.S. Navy and Royal Navy tables.

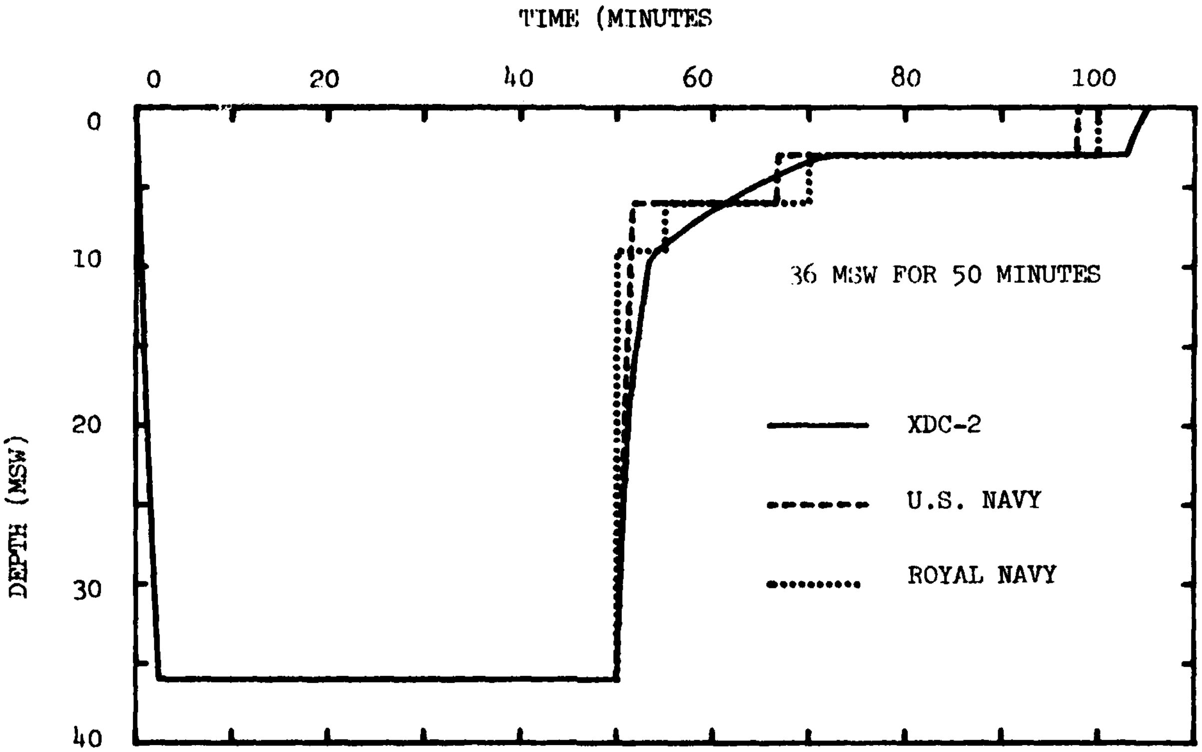

FIGURE 4: XDC-2 dive profile for 36 msw for 50 minutes with comparison to the U.S. Navy and Royal Navy tables.

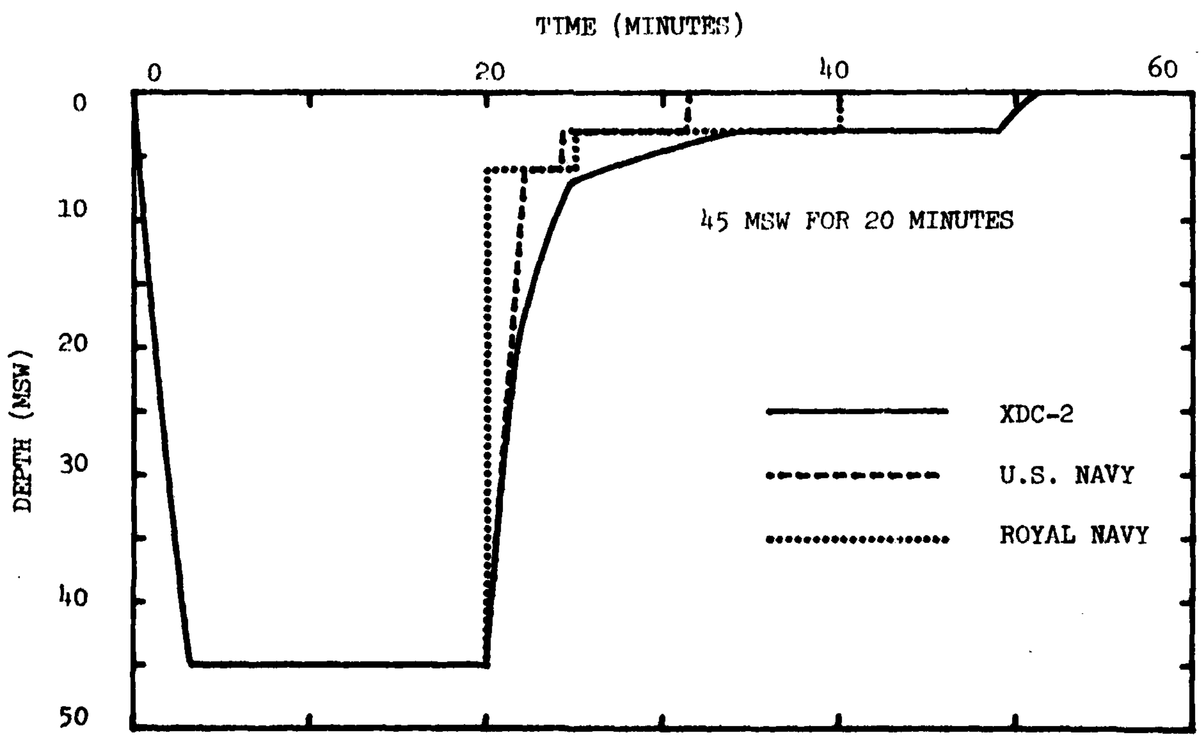

FIGURE 5: XDC-2 dive profile for 45 msw for 20 minutes with comparison to the U.S. Navy and Royal Navy tables.

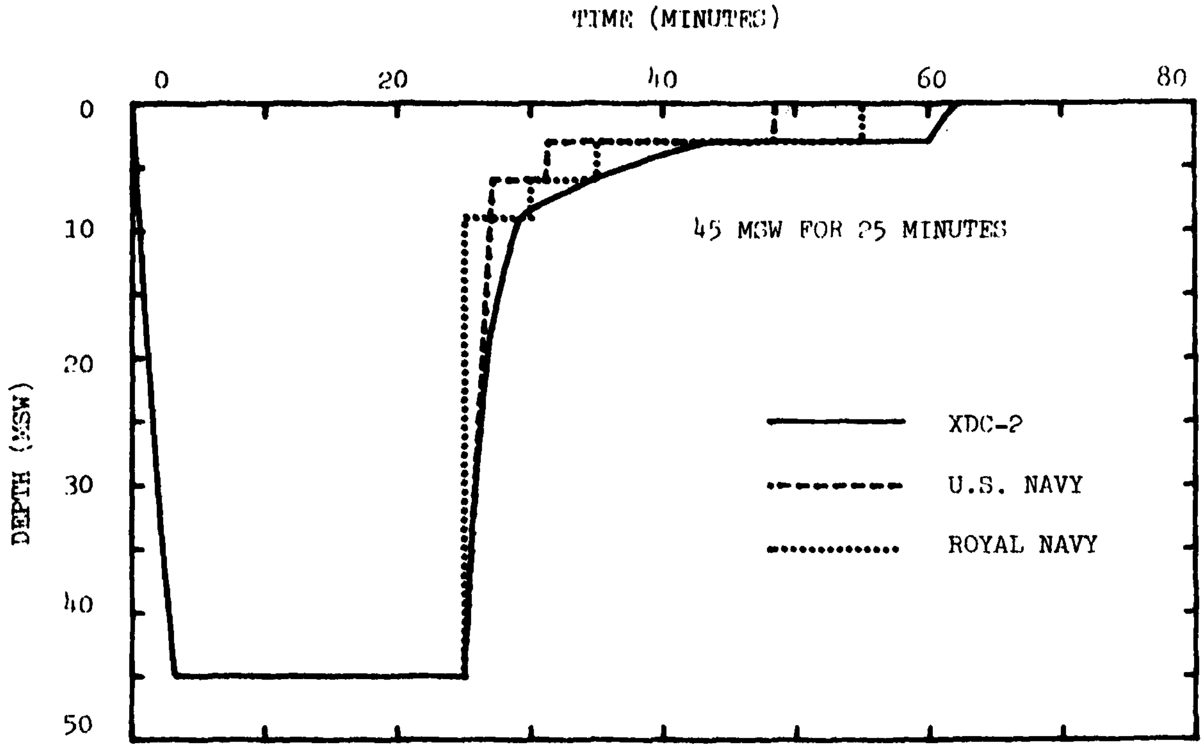

FIGURE 6: XDC-2 dive profile for 45 msw for 25 minutes with comparison to the U.S. Navy and Royal Navy tables.

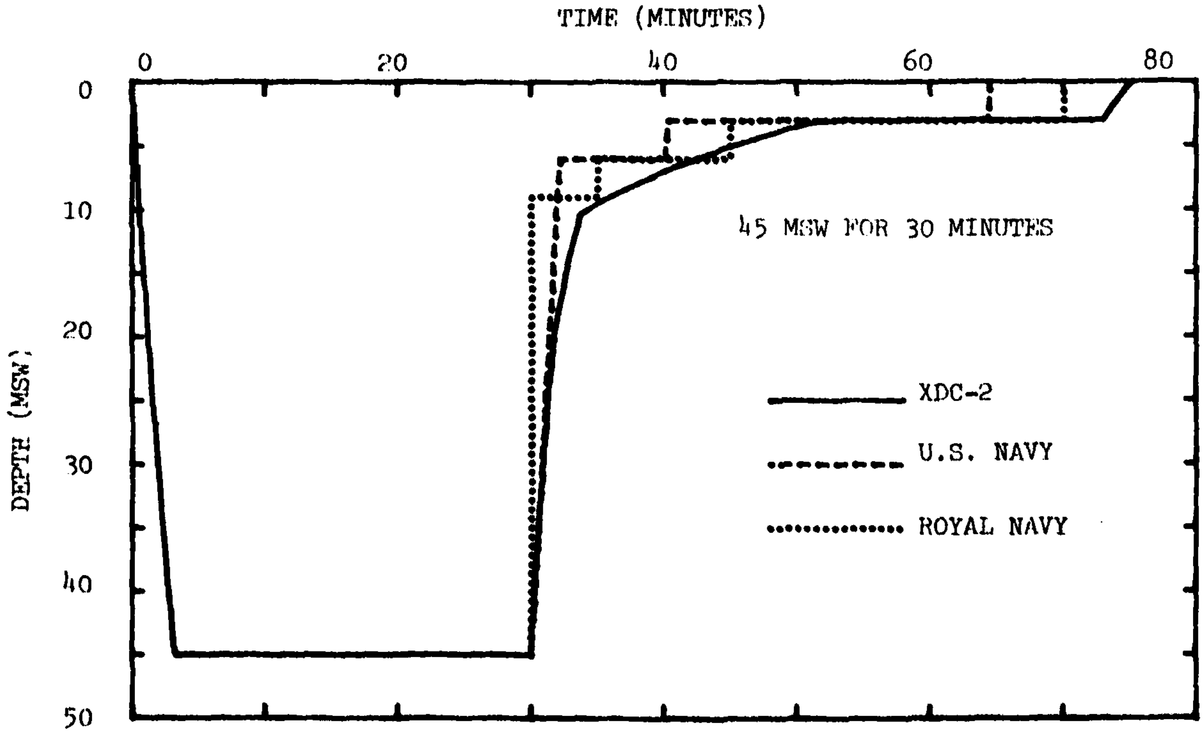

FIGURE 7: XDC-2 dive profile for 45 msw for 30 minutes with comparison to the U.S. Navy and Royal Navy tables.

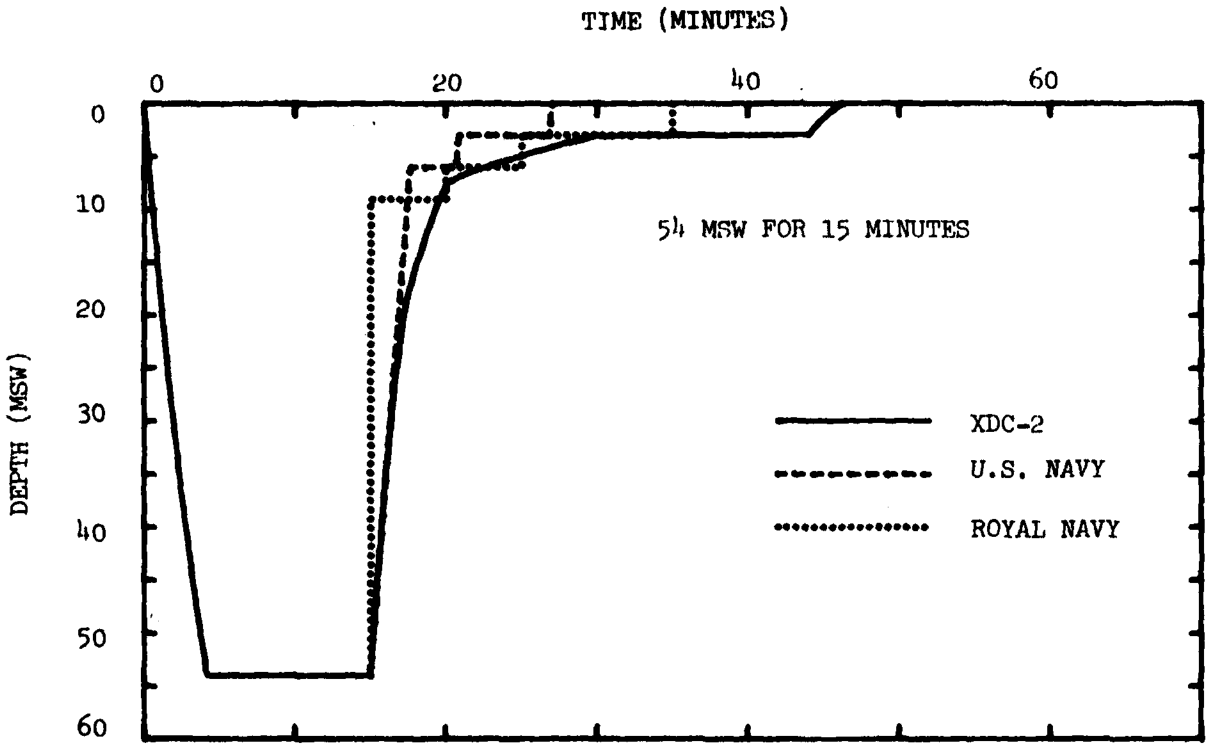

FIGURE 8: XDC-2 dive profile for 54 msw for 15 minutes with comparison to the U.S. Navy and Royal Navy tables.

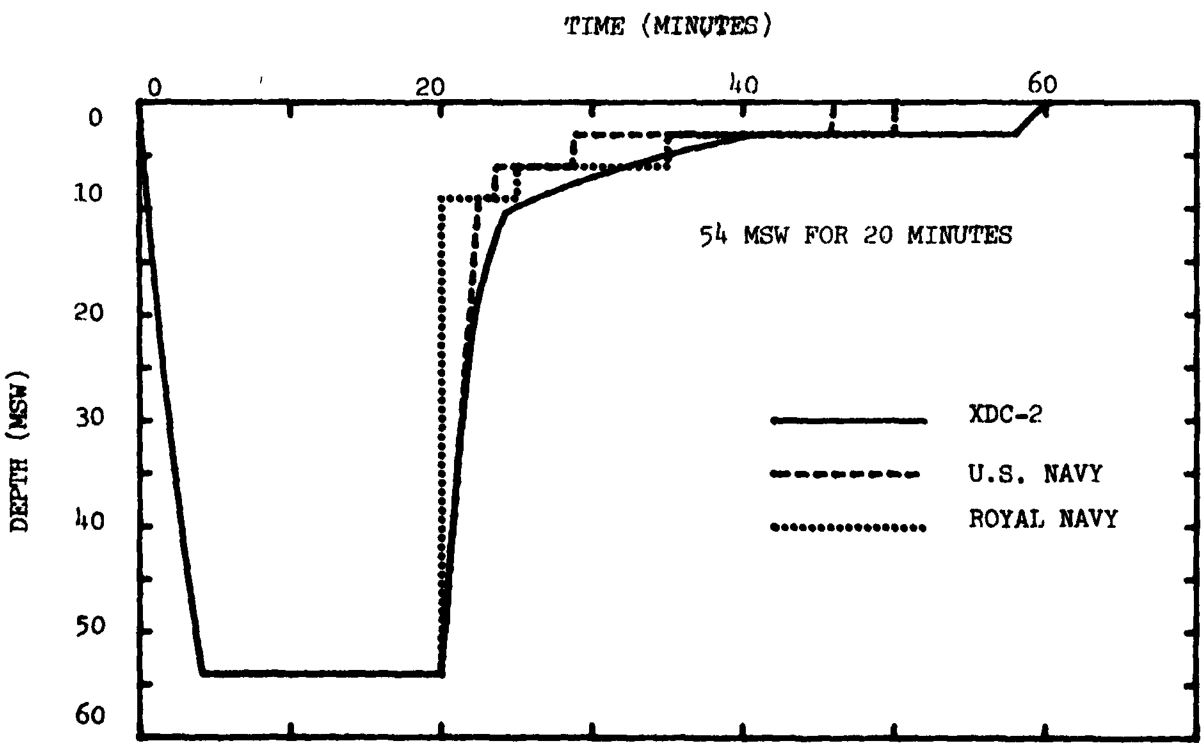

FIGURE 9: XDC-2 dive profile for 54 msw for 20 minutes with comparison to the U.S. Navy and Royal Navy tables.

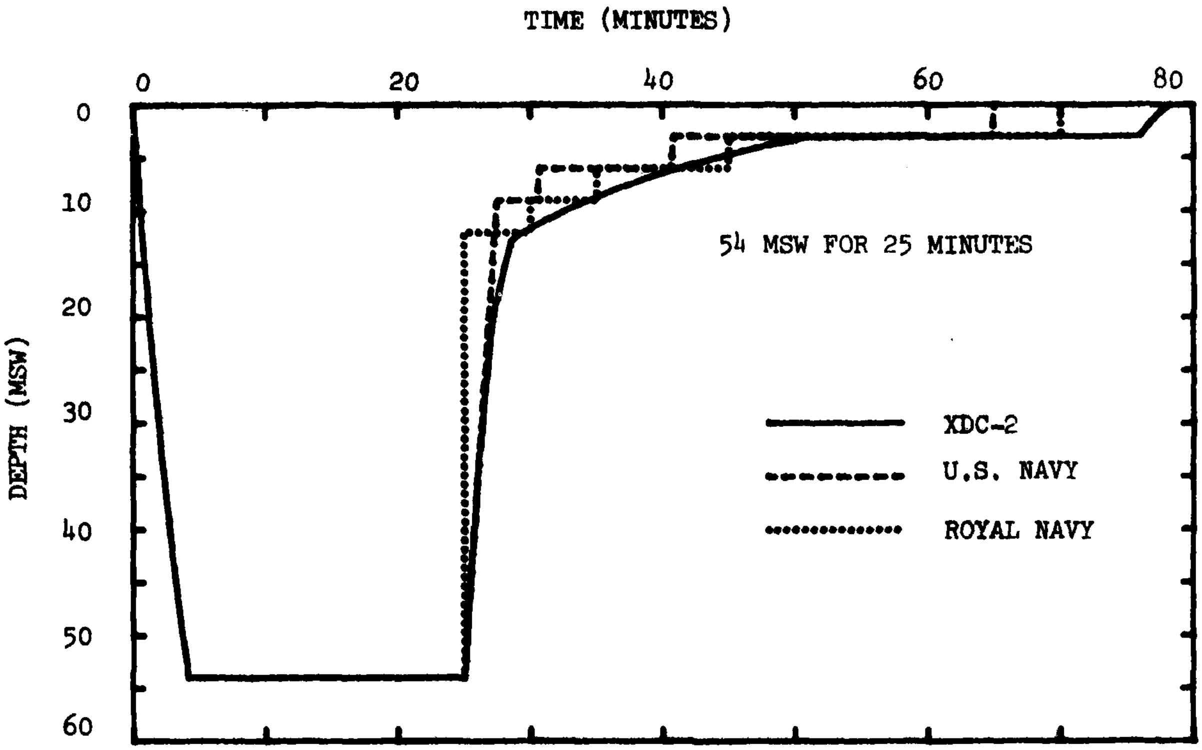

FIGURE 10: XDC-2 dive profile for 54 msw for 25 minutes with comparison to the U.S. Navy and Royal Navy tables.

Dive 36.0 msw, 50.0 min, Diver RL (a) Precordial

Movement 22 22 3+ 4 4 3+ 3+ 3 3

Rest 00 00 3 3 3 1+ 0 0 0

S
0 1 2 3 4 5 6
Time (hrs)

Dive 36.0 msw, 50.0 min, Diver GP (w) Precordial

Movement 2– 3 3 3 3 3 3 3

Rest 0 3– 2 0 1 2 0 0

S
0 1 2 3 4 5 6
Time (hrs)

Dive 36.0 msw, 50.0 min, Diver EN (a) Precordial

Movement 00 00 0 0 3 3+ 3–

Rest 00 00 0 0 3– 3– 2

S
0 1 2 3 4 5 6
Time (hrs)

Dive 36.0 msw, 50.0 min, Diver NR (w) Precordial

Movement 3+ 3 4 4– 4 4 3+ 3

Rest 3 3 3– 1+ 2+ 1 0 0

S
0 1 2 3 4 5 6
Time (hrs)

Dive 36.0 msw, 50.0 min, Diver AK (d) Precordial

Movement 0333 4 44 4 3+ 3 3 2

Rest 0111 3+ 33 3– 1 0 0 0

S
0 1 2 3 4 5 6
Time (hrs)

Dive 36.0 msw, 50.0 min, Diver RMc (d) Precordial

Movement 0010 0 3 3 3 1 1 0 0

Rest 0000 0 1 0 1 1 0 0 0

S
0 1 2 3 4 5 6
Time (hrs)

Figure 11. Example of bubble grades detected from the precordial region at rest and following movement as a function of time after the start of decompression for a severe dive (36 msw for 50 minutes - Team B). The letter "S" indicates when surface was reached. The diver roles are indicated by (a), (w), and (d).

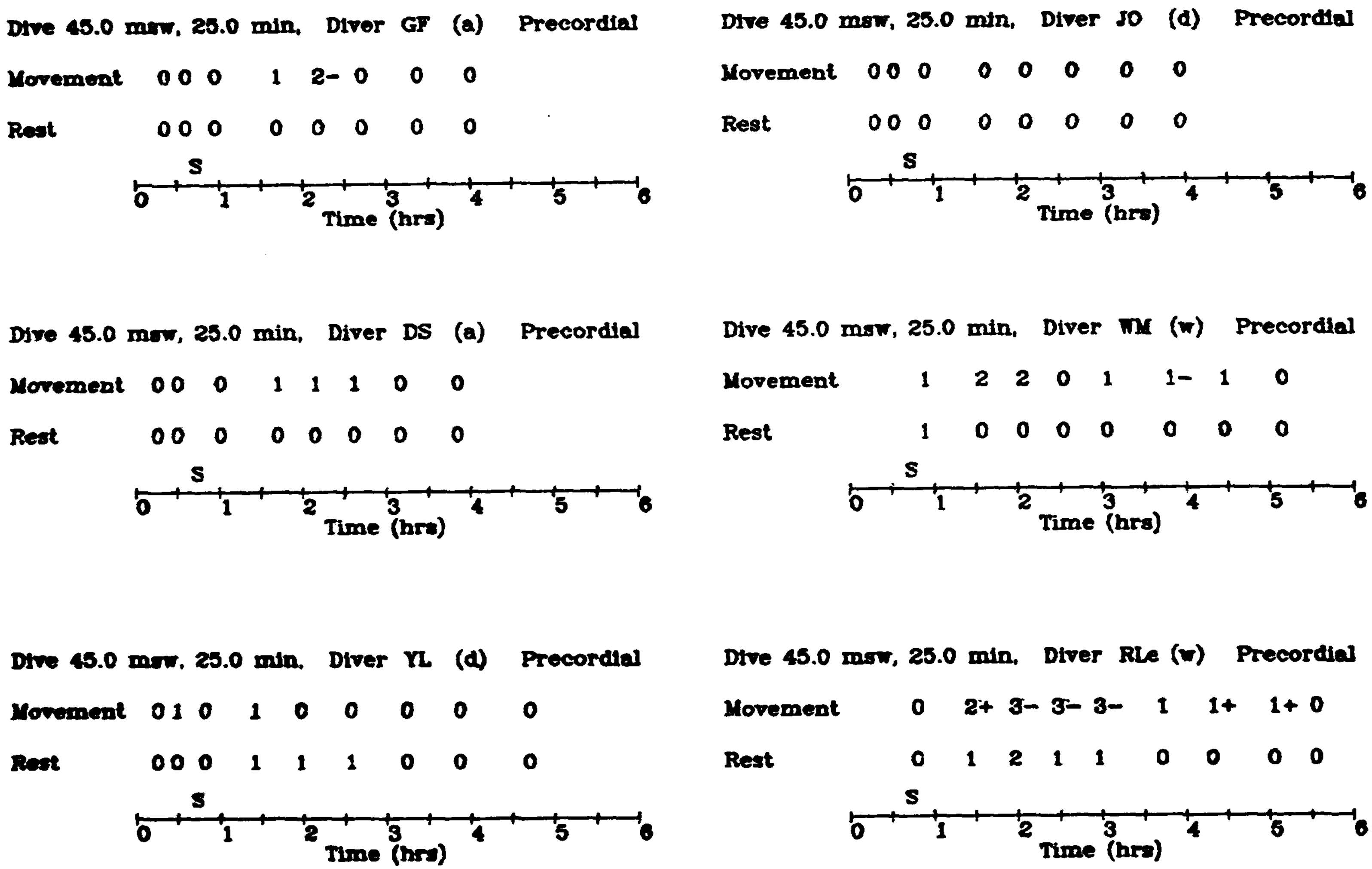

Figure 12. Example of bubble grades detected from the precordial region at rest and following movement as a function of time after the start of decompression for a mild stress dive (45 msw for 25 minutes - Team A). The letter "S" indicates when surface was reached. The diver roles are indicated by (a), (w), and (d).

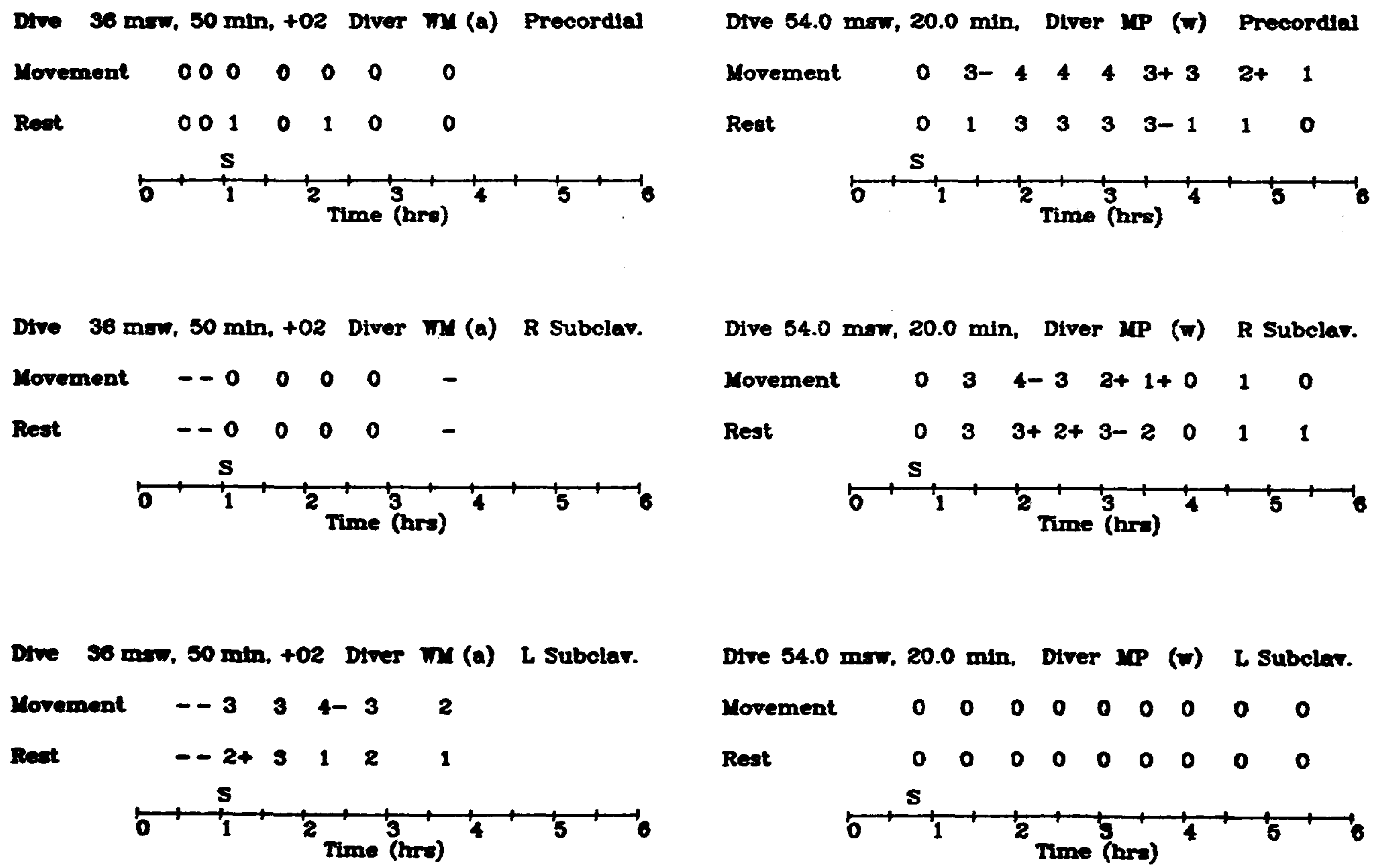

Figure 13. Example of bubble grades detected in the subclavian region compared to the precordial region for subject WM, 36 msw for 50 minutes with oxygen decompression and for subject MP, 54 msw for 20 minutes. The letter "S" indicates when surface was reached. The diver roles are indicated by (a) and (w).

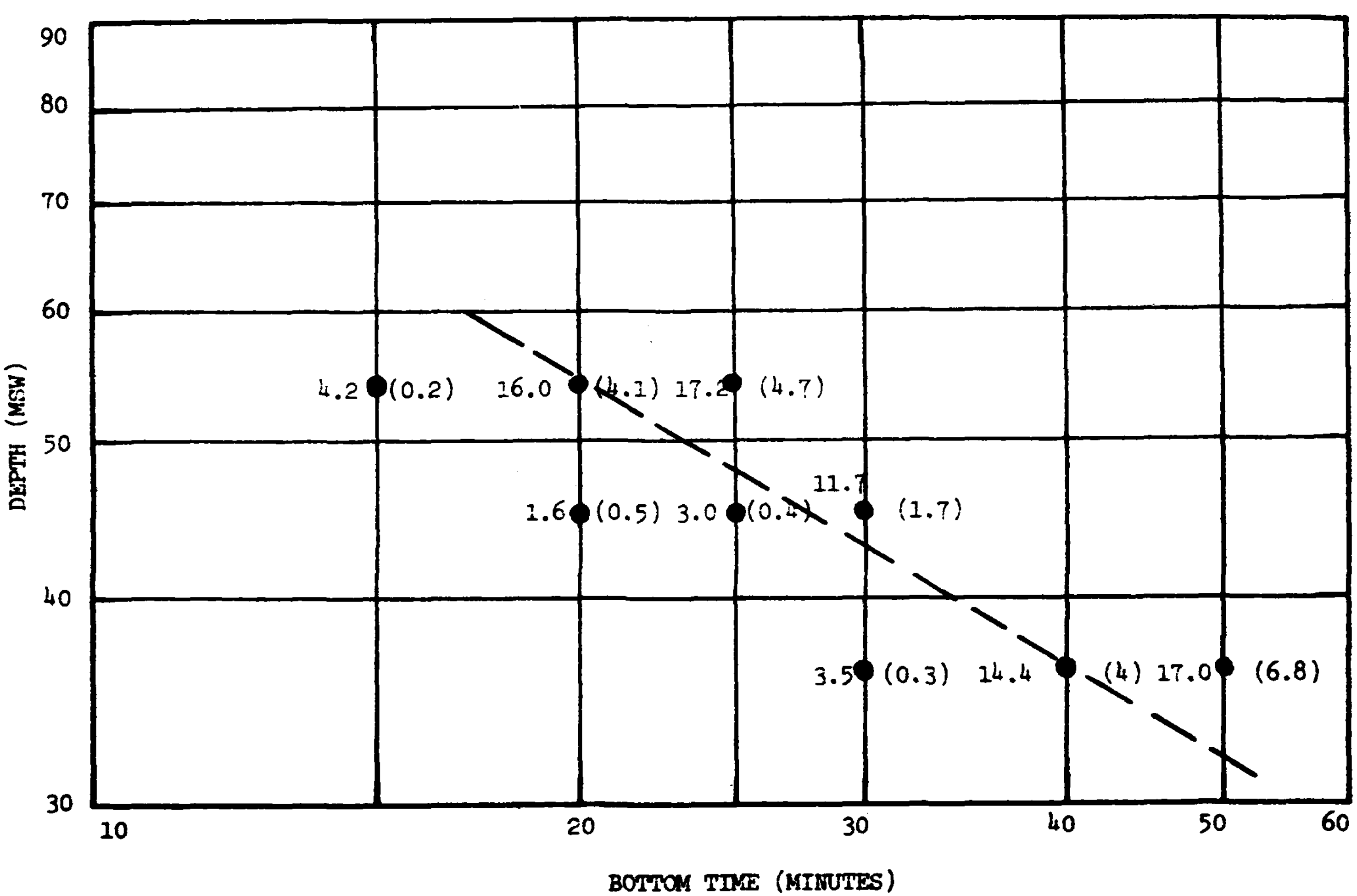

Figure 14: Limiting bottom-time line for XDC-2 decompression computer profiles. The data points show the dive profiles tested. Numbers to the left of the data points give the mean index of severity, S, for high bubblers (precordial, at rest). Numbers in parenthesis to the right of the data points give the value of S for moderate bubblers. Dives with bottom times less than the limiting values are low or mild stress dives. Dives above the limiting values are high stress dives.