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**ACCLERATED DECOMPRESSION FROM SATURATION AT 132 FEET OF
SEAWATER WITH ISOBARIC OXYGENATION AT 60 FEET OF SEAWATER**

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14. ABSTRACT Background: Survivors of a disabled submarine (DISSUB) would experience a rise in internal pressure, and, if awaiting rescue long enough, become saturated increasing their risk of decompression sickness (DCS) to nearly 80% Previous work has demonstrated that breathing hyperbaric oxygen before decompression reduces the risk of DCS. Hypothesis: A combination of oxygen pre-breathe, coupled with a shorter decompression schedule would enable the safe extraction of survivors from a DISSUB for subsequent re-pressurization in a chamber for a controlled decompression on the surface. Methods: Yorkshire swine (70 kg) were catheterized with an external jugular catheter via the Seldinger technique and allowed to recover. Subjects were exposed to 132 feet of seawater (fsw) in a hyperbaric chamber for 22 hr, then decompressed on one of 3 possible profiles (staged, rapid, mixed gas). Conclusions: The accelerated decompression examined here supports its consideration in emergency situations such as DISSUB. Further decompression schedules with oxygen pre-breathing merit additional study.					
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**Accelerated Decompression from Saturation at 132 feet of sea water with
Isobaric Oxygenation at 60 feet of sea water.**

Kyle Petersen, MD, Hugh M. Dainer, MD, Andreas Fahlman, PhD, Richard T. Mahon, MD

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LIST OF ABBREVIATIONS

ATA	Atmospheres absolute
DCS	Decompression Sickness
DISSUB	Disabled submarine
fpm	Feet per minute
fsw	Feet of sea water
HBO	Hyperbaric Oxygen
N₂	Nitrogen
O₂	Oxygen
OPB	Oxygen Pre-breathe
PRM	Pressurized Rescue Module, a miniature rescue submarine capable of holding 2 crew and 16 survivors.
SDC	Submarine Decompression Chamber, a hyperbaric chamber capable of holding 32 survivors and 4 tenders
SRDRS	Submarine Rescue Diving and Recompression System, a system of hard suits, rescue subs, hyperbaric chambers and supporting equipment intended for submarine rescue efforts

BACKGROUND

In the scenario of sailors becoming trapped in a disabled Submarine (DISSUB), if the hull is breached and either flooding occurs or sub's atmosphere is lost the DISSUB internal pressure may rise and approach the ambient pressure. This would result in increased nitrogen (N_2) partial pressure inside the submarine and survivors' blood and tissues. If the submarine was held at 132 feet of sea water (fsw) for a time long enough for the sailors' tissues to saturate with N_2 , it has been estimated that the probability of decompression sickness (DCS) would be close to 80% if a direct ascent to the surface was attempted (7, 11). Therefore a slow controlled decompression like a saturation diver undergoes will be required in such a situation. The US Navy linear exponential kinetics probabilistic decompression model (USN93) (10), a useful predictor of DCS in military air diving predicts >60 hour air decompression time would be required to safely surface from 132 fsw. As rescue decompression capability is limited and flooding, fire, and hypoxic or hypothermic atmospheric conditions in the DISSUB may preclude waiting this long before decompressing each wave of survivors, a shorter decompression schedule is required.

The new Submarine Rescue Diving and Recompression System (SRDRS) includes a hyperbaric chamber: the Submarine Decompression Chamber (SDC); and a rescue vehicle: the Pressurized Rescue Module System (PRM); plus PRM mission support equipment. The PRM is capable of transporting up to 16 rescued personnel under pressures up to 5 atmospheres absolute (ATA, 40 m or 132 fsw) from the DISSUB to a surface ship. The SRDRS concept of operations has been developed to support rescue of up to 155 personnel from a pressurized DISSUB. Each SDC can accommodate up to 32 rescued personnel and four Tenders. Two PRM trips, or sorties,

to and from the DISSUB will therefore be required to fill each SDC before decompression of its occupants can commence. Performance estimates conclude the PRM can ascend from 2000 feet to surface depressurize from 5 ATA to surface in 2 hours for each 16 survivors. At least 10 sorties will be required to rescue a 155-man DISSUB crew or 20 hours minimum (9).

Previous work at has demonstrated that breathing hyperbaric O₂ at 2.52 ATA (15m or 50fsw) saturation significantly reduces DCS in humans and allows for a 8-10 hour decompression schedule (4) also hyperbaric O₂ at (2.8 ATA) for 1 hour immediately before decompression reduces the probability of severe DCS from 85% to 8% and reduces the risk of death from 65% to 0% death in 70 kg swine (8). This suggests a simple method to reduce the DCS risk during DISSUB rescue efforts. It is likely that a combination of oxygen pre-breathe coupled with a shorter decompression schedule from 5 ATA might be used to safely and quickly extract survivors from a DISSUB allowing for them to be evaluated on a rescue ship on the ocean surface and then subsequently repressurized in the SDC and decompressed in a more controlled fashion (surface decompression on oxygen).

Here we report the results of 3 accelerated decompression profiles from a simulated DISSUB scenario at 132 fsw. We attempted a traditional air only decompression from 132 fsw to 60 fsw and hypothesized the final 60 feet of obligated decompression time could be shortened by using O₂ pre-breathe at 60 fsw. If that proved safe, our second hypothesis was that faster decompressions from 132 fsw to 60fsw could be done using air or oxygen pre-breathe at deeper depths and that we could compare the safety profiles of various accelerated decompression schedules. For each profile hyperbaric O₂ was breathed at 1.6-2.7 ATA as part of the decompression schedule.

MATERIALS AND METHODS

The animal experiments reported here were conducted according to the principles set forth by the National Research Council (6). Before commencing, our Institutional Animal Care and Use Committee reviewed and approved all aspects of this protocol. The institutional animal care facility is fully AAALAC accredited.

Animals

Neutered male Yorkshire swine (*Sus scrofa*, n=32, 70.8 kg $\pm$ 3.8 kg) were examined by a veterinarian upon receipt, and housed individually for environmental acclimation. Animals were housed in free running cages, with full access to water and food (2% of body weight daily) for 5 days prior to any procedures.

Pre-dive Preparation

On the day prior to hyperbaric exposure, animals were moved from the animal care facility to the surgical suite at NMRC for external jugular vein catheter placement. Anesthesia induction was performed with ketamine (20 mg/kg) and xylazine (2 mg/kg) intramuscularly. After induction, anesthesia was maintained with isoflurane (2-5%) via a face mask. After adequate anesthesia, the external jugular vein of the animal was catheterized with a 16 gauge by 20.3 cm single lumen catheter (Braun Certofix; B. Braun Medical Inc, Bethlehem, PA) via the modified Seldinger technique and advanced until 8-10 cm extended from the skin incision site. The catheter was sutured in place, taped to the skin, and then brought through a vest worn by the animal with an exit site on the dorsal thorax which secured and protected the catheter line and injection port. The vest was designed to accommodate a Tygon® tube (76 cm long, 8 cm diameter) to be attached to the catheter on the day of the dive. This allowed injection of

medication of liquid while the animal was inside the chamber under pressure (see below). Full ambulation after recovery was assessed prior to return to the holding pen, where the animal remained overnight.

On the day of the hyperbaric exposure the animals were transported from the holding pen and placed into a custom designed Plexiglas boxes (26"x54"x38") inside the Multiple Large Animal Chamber (MLAC) steel hulled hyperbaric chamber. The Plexiglas boxes allowed us to create a hyperbaric O₂ environment that the animal could breathe without physically restraining the pig. The Plexiglas boxes were fitted with a lixir for free access to water. The external jugular vein catheter was connected to a sterile line, fed through a Tygon® tube secured to the torso vest and a 360° swivel on the ceiling of the Plexiglas box. This allowed the animal to move around freely and make postural adjustments without twisting the line. The sterile line was passed through a hull penetrator port of the MLAC and connected to a high pressure positive displacement infusion pump (Mini pump; Milton Roy, Ivyland, PA) allowing intravascular infusions or withdrawals while under pressure.

Hyperbaric Exposure

The MLAC was pressurized with air to 5 ATA (40 m or 132 fsw) at a rate of 30 ft • min⁻¹. Animals were monitored via close circuit television for any signs of distress related to middle ear barotrauma. The animals remained at 132 fsw for 22 hours, a period considered sufficient for inert gas saturation in 20 kg swine (3). Water was provided *ad libitum* and the animal able to move freely within the Plexiglas box throughout the dive. The chamber and box atmospheres were monitored with separate gas analyzers (Geotech Anagas Dive Analyzer, Denver CO). The chamber O₂ concentration was maintained at 21% (± 0.02 percent) and CO₂ was maintained at < 0.05% surface equivalent. The O₂ concentration in the Plexiglas box was adjusted according to

the dive profile to allow animals to breathe either air (21% O₂) or hyperbaric O₂ (32% to 95% O₂). Changes in the Plexiglas box atmosphere was done by flushing the box with O₂, mixed gas, or air and a change in the breathing gas composition (e.g. from 95% O₂ to air) took about 5 minutes to accomplish. Temperature was maintained between 75-85°F (23.9-29.4°C) with 50% ($\pm$ 5%) humidity via an environmental control. **After 22 h at 132 fsw, the animals underwent one of the following decompression profiles:**

- Profile 1: Staged decompression

Pigs were decompressed according to a traditional air decompression schedule from 132 fsw to 60 fsw over a duration of ~ 13 hrs (Table 1). The decompression rate between stops was 30 ft • min⁻¹. At the 60 foot stop the breathing gas was switched to ~95% (2.66 ATA) O₂ which the animals breathed for 1 hour while at 60 fsw. The animals were then decompressed directly to the surface at 30 ft • min⁻¹ while still breathing hyperbaric O₂.

- Profile 2: Rapid decompression

Animals were brought directly from 132 fsw to 60 fsw on air at 30 ft • min⁻¹ (Table 1). At the decompression stop animals breathed 2.66 ATA O₂ for 1 h, followed by decompression at 30 ft • min⁻¹ while breathing O₂.

- Profile 3: Rapid decompression using mixed gases

Animals were held at 132 fsw for 22 hrs (Table 1). One hour before decompression, the Plexiglas box atmosphere was changed to 32% O₂ (1.6ATA, figure 1). After breathing HBO for 1 hr the Plexiglas box atmosphere was switched back to air and the pigs decompressed at 5 ft • min⁻¹ to 85 fsw. At 85 fsw the O₂ fraction was increased to 50% (1.79ATA) and animals breathed this mixture for 1 hr. Animals were next switched back to air and brought to 60 fsw at 1 ft • min⁻¹. The pigs were held at 60 fsw for 1 h while

breathing 95% O₂ (2.66 ATA). Following a 15 minute air break at 60 fsw, the pigs were decompressed to the surface at 30 ft • min⁻¹ on O₂.

Post-dive Observation

For the three profiles tested, the breathing mixture was switched from O₂ back to air upon reaching the surface. Observers entered the chamber to observe the animals for symptoms of DCS for 2 h. The pigs remained inside their Plexiglas containers throughout the surface observation period. Observations were recorded at ≤ 10 min intervals until death or completion of the 2 h observation period. A 2 h post-dive observation period was previously deemed sufficient to detect all symptoms of severe DCS in a swine saturation model as observed symptoms plateau at 1 hour after surfacing (2). Heart rate and arterial oxygen saturation (SaO₂) were monitored continuously via individually fitted pulse oximeters (Heska, model #4404, Des Moines, IA).

Cutis marmorata was defined as observed cyanotic patches on the animal's skin. Pain only DCS was defined as impaired limb movement without weakness or other neurological findings. Neurological DCS was defined as motor weakness (limb weakness, repeated inability to stand after being righted by the investigator), paralysis (complete limb dysfunction, areflexia, or hypotonia), sensory compromise (e.g., failure to retract from painful stimuli). Cardio-pulmonary DCS was defined as a visually observed respiratory rate of 60 breaths • min⁻¹ combined with respiratory distress, as evidenced by open-mouthed, labored breathing, central cyanosis or the production of frothy white sputum. The onset of severe DCS (neurological or cardio-pulmonary dysfunction) and all behavioral signs and symptoms were recorded to the nearest minute. Pigs with signs of severe DCS were given Diazepam (2.5 mg, i.v.) through the in-dwelling catheter as necessary to alleviate distress. If the animal exhibited signs of imminent

death or their distress was not relieved with Diazepam, the animal was euthanized with Euthasol[®] (1cc/10 lb body weight i.v., DelMarva Laboratories, Inc., Midlothian, VA). After the 2 h observation period, surviving animals were removed from the chamber and examined for signs of neurologic, cutaneous or cardiopulmonary DCS. They were then placed into holding pens for an additional 22 h. While in the holding pen each animal was observed and examined every 8 hours for signs of DCS. After 24 h, the animals were euthanized by i.v. injection of Euthasol[®] (DelMarva Laboratories, Inc., Midlothian, VA) and underwent necropsy.

Selection of dive profile

Decompression profiles were deemed to be successful based on morbidity and mortality limits determined *a priori*. The selected limits were: $\leq 10\%$ mortality, $\leq 20\%$ severe DCS, and $\leq 30\%$ oxygen toxicity during the 2 h observation period. If Profile 1 was successful based on these criteria, then Profile 2 would be studied.

RESULTS

Although we were not able to determine if animals suffered pulmonary O₂ toxicity while at depth, no animal showed symptoms of limited CNS O₂ toxicity such as seizures or tachypnea while breathing O₂ under pressure.

The pigs on Dive profile 1 were significantly heavier by 3.3 kg as compared with those in profile 2 or 3 ($P < 0.05$, t-test), but despite this they had a significantly lower DCS incidence rate compared with profile 2 (50%, $P < 0.01$, χ^2). There were no differences in DCS risk between profile 1 and 3 or between profile 2 and 3 ($P > 0.1$).

Type of symptoms and time to symptom onset are summarized in Table 2 for the three profiles. Staged decompression (Profile 1) resulted in no cases of severe DCS during the full 24 h observation period, but there were 2 cases of pain only DCS. For Profile 2, 50% of the animals

showed symptoms of severe DCS during the 24h observation period. Three animals experienced symptoms within the initial 2 h observation period and the 4th after 2 h 36 min. There were no cases of pain only DCS and 75% of the pigs experienced cutis which occurred between 31 and 112 minutes after surfacing.

Twenty one percent of the animals on Profile 3 suffered severe DCS during the 24 hour observation period, with two animals suffering severe DCS within the initial 2 hour observation period. Two animals (14%) suffered pain only DCS (1 with accompanying cutis) and 8/14 (57%) had cutis ranging from 5 to 165 minutes after surfacing.

DISCUSSION

In this study we examined the incorporation of OPB either as a traditional air decompression schedule (Profile 1), as a pure breathing gas (Profile 2) or a depth adjusted mixed gas (Profile 3) coupled with an accelerated decompression schedule. A previous study of “dropout” decompression from saturation at 60 fsw resulted in 85% severe DCS among the 13 control animals (8). Since the anticipated occurrence of DCS in a dropout from 132 fsw is anticipated to be greater than that of 60 fsw, this study was not done with control animals and we elected to use the 60 fsw historical controls. Because swine are not ambulatory in the Plexiglas boxes and often do not move about during the 2 hour observation period, some pain and neurologic symptoms were not detected until after the observation period when the animal was fully examined in its run. We noted 2 cases of neurologic DCS and 1 of cutis occurred after the 2 hour observation. However, we believe that these symptoms developed within the 2 hour observation period inside the Plexiglas box and that the delay in symptom onset was a limitation in our ability to observe, rather than delayed onset of symptoms.

Staged air decompression from 132 fsw is a lengthy process that is expected to exceed a realistic timeline for extraction of survivors from a DISSUB. A traditional air-only decompression schedule from 132 fsw requires decompression durations in excess of 60 hours. Any means to reduce this lengthy procedure without increasing the risk of decompression trauma would enhance operational capabilities of submarine rescue assets. A previous study has shown that O₂ pre-breathing (OPB) for as little as 1 hour prior to dropout from 60 fsw saturation completely prevented death in 70 kg swine (8). Thus, the decompression requirement can possibly be significantly shortened with the use of OPB either before decompressing or during a shortened decompression profile. For the traditional schedule, after saturation at 132 fsw, animals were decompressed on air to 60 fsw over a period of 13.27 hours. Traditionally, decompression in saturation exposure from 60 fsw would require an additional 20-24 hours. At 60 fsw we accelerated this profile by treating the animals with OPB (2.66 ATA) for 1 hour, followed by rapid decompression to the surface, resulting in a total decompression time of approximately 14.3 hours. This strategy resulted in a favorable outcome with no occurrences of cardiopulmonary or neurologic DCS and only 20% Type I DCS in the 24 hours observation period. While we accept this profile as safe, it is unlikely to be operationally useful due to the long turn around times for each PRM evacuation, particularly if 155 evacuees must be removed from a flooding DISSUB that is rapidly losing breathable air.

Reducing DCS risk with the use of OPB has been studied in high-altitude DCS from flying and extravehicular space activity (12). The efficacy of OPB to reduce DCS in diving situations has also been studied in medium-sized swine and goats (5, 1). In 20 kg swine, a 10 min OPB immediately before a dropout decompression from a saturation dive to 60 fsw significantly decreased DCS incidence by 33% and delayed the time of onset from 11 to 22

minutes compared with control animals (3). Having successfully reduced decompression time from 60 fsw, we postulated that the N₂ removal by traditional air decompression to 60 fsw from 132 fsw might also be rendered unnecessary by the 1 hour O₂ period at 60 fsw. Our findings however, demonstrate 1 hour of OPB does not successfully remove residual N₂, and is not safe when direct ascent from 5 ATA to 60 fsw is attempted followed by dropout. As we demonstrated, this profile (Dive profile 2) had 75% Type I DCS, 50% Type II DCS and 25% death and should be rejected as unsafe for human use.

Since O₂ speeds ascent from saturation at 60 fsw, we hypothesized it might also be employed at deeper stops to speed up the 13.3 hour time from 132 fsw to 60 fsw on air, particularly at 5 ATA prior to initiating any decompression. Breathing 5 ATA O₂ (100% O₂ at 132 fsw) is likely to cause O₂ toxicity in the majority of subjects which would cause a different set of problems. An alternative is to use a gas mixture that has an O₂ content that helps protect against DCS but is low enough not to elicit O₂ seizures. Although technically challenging, if highly effective, this might have been attractive enough to attempt the technical challenge in a DISSUB operational setting. In profile 3 we attempted to shorten decompression time from 132 fsw to 60 fsw from 14 hours, but also to improve safety over profile 2 by using O₂ in safe concentrations at deeper stops for a total of 4 hours of OPB. In this study, 32% O₂ at 132 fsw appears to be safe. However, delivering this hyperoxic gas mixture to a DISSUB or on the rescue vehicle is beyond the current recently realized capabilities of the PRM. Furthermore, our findings of the ineffectiveness of OPB initiated before ascent may represent N₂ re-accumulation during the ascent process arguing against attempting to overcome this technical hurdle. Profile 3 had 57% Type I DCS, 21% Type II DCS and 14% death and was not statistically better than profile 2. Due to the technical challenges of implementation in an operational or DISSUB

scenario, limitations of rescue equipment to mix gases and the results falling outside our established safety cutoffs therefore we reject its use as unsafe. Ultimately a profile containing between 4 and 14 hours of OPB will be the most feasible for rapid decompression from 5ATA. Using residual nitrogen time modeling to determine where to add the OPB stops deeper or shallower than 60 fsw might help optimize a profile. These results add to the body of literature supporting the benefits of OPB and should aid in planning for DISSUB rescue operations. Caution is urged given the small numbers of animals studied, and the rather rudimentary methods of eliciting neurologic deficits in unsedated swine.

CONCLUSION

We demonstrate here the feasibility of incorporating OPB into an emergency decompression strategy from saturation at 132 fsw, and that it can significantly accelerate decompression over a traditional saturation decompression schedule, without compromising safety. The accelerated decompression demonstrated here supports its consideration in emergency situations such as DISSUB. Further modification(s) to this decompression schedule with OPB merit further study.

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Table 1.

Decompression Profiles for experiments

<i>Profile 1</i>							
“Stop” Depth	132	85	80	75	70	65	60
Time (h:min)	22:00	2:28	2:33	2:39	2:45	2:51	1:00
<i>Profile 2</i>							
“Stop” Depth	132	60					
Time (h:min)	22:00	1:00					
<i>Profile 3</i>							
“Stop” Depth	132	132*	85†	60			
Time (h:min)	22:00	1:00	1:00	1:00			

Bold indicates 2.66 ATA O₂

*denotes 1.6ATA O₂

† denotes 1.79 ATA O₂).

Table 2. Outcome of decompression schedule in the two profiles evaluated (n=32)

Dive Profile	Weight (kg)	Cutis Marmorata (time of onset)	Pain Only DCS	Cardio-Pulmonary DCS	Neurologic DCS (Time/findings)
1	70.9	N	N	N	N
1	73.0	N	N	N	N
1	72.1	N	N	N	N
1	76.0	N	N	N	N
1	68.4	N	N	N	N
1	82.6	N	N	N	N
1	76.1	N	Y	N	N
1	74.0	N	N	N	N
1	70.6	N	N	N	N
1	72.9	N	Y	N	N
2	68.3	50 min	N	N	N
2	75.0	112 min	N	N	N
2	70.0	57 min	N	76 min	75min (Limb Weakness)
2	67.0	57 min	N	N	156min (Limb Weakness)
2	71.2	N	N	N	N
2	69.5	N	N	N	N
2	72.7	31 min	N	43 min	N
2	68.7	52 min	N	N	53 min (Ataxia,Seizure)
3	67.8	165 min	N	N	N
3	68.2	N	N	N	N
3	64.8	N	N	N	N
3	73.7	26 min	N	29 min	26 min (hindlimb paralysis)
3	70.7	N	N	N	N
3	71.9	5 min	N	N	N
3	64.0	40 min	N	43 min	N
3	67.8	29 min	Y	N	N
3	77.7	N	N	N	N
3	66.3	N	N	N	N
3	69.6	81 min	N	N	N
3	67.9	N	Y	N	N
3	72.6	54 min	N	N	N
3	72.6	No	N	N	148 min (lethargy, L hindlimb weakness)

Figure 1. Graphic representation of profile 3.

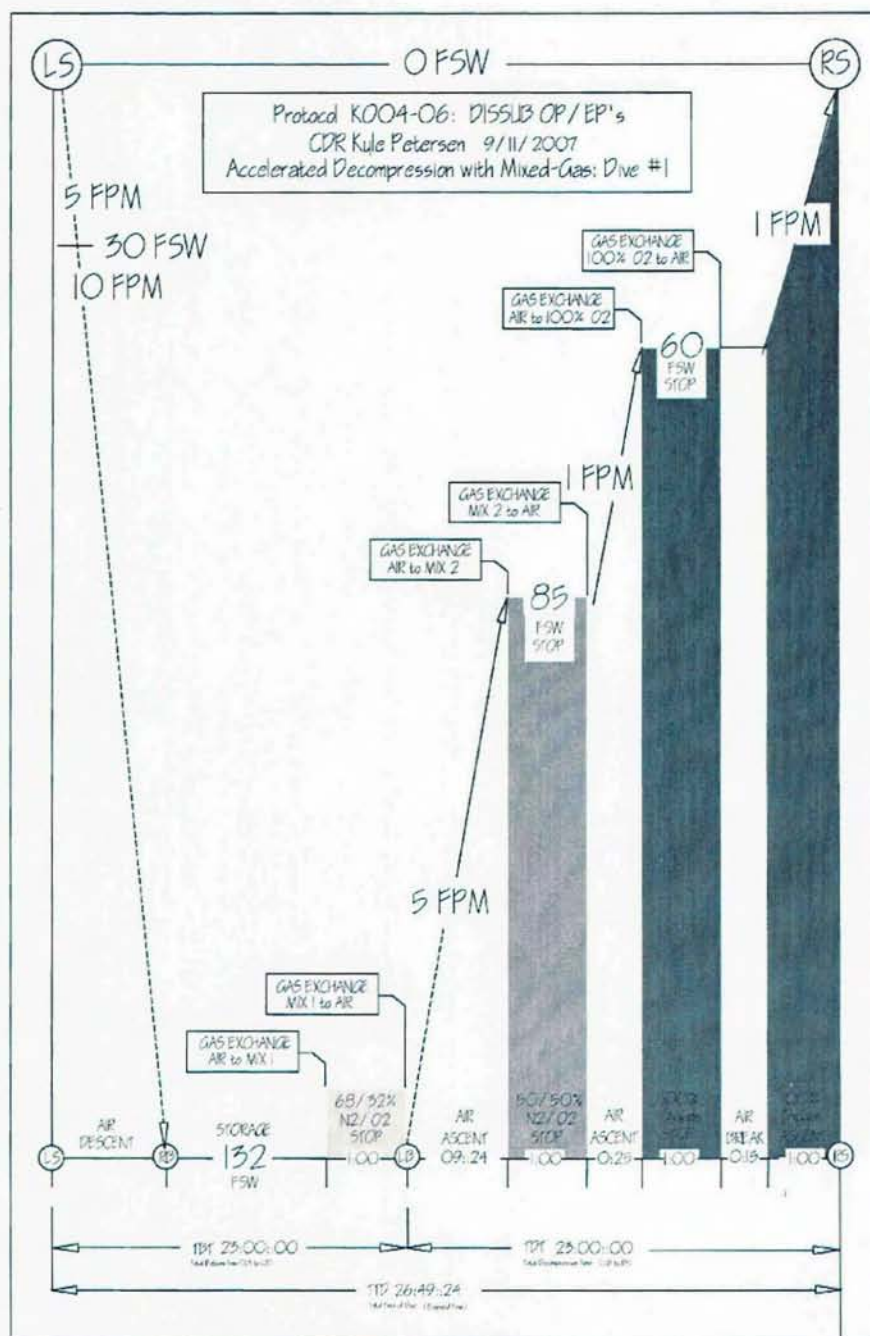


Figure 2. Kaplan-Meier plot of DCS during the 2 hour direct observation period after surfacing.

