A review of accelerated decompression from heliox saturation in commercial diving emergencies

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Abstract
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Introduction: Saturation diving is a specialised method of intervention in offshore commercial diving. Emergencies may require the crew to be evacuated from the diving support vessel. Because saturation divers generally need several days to reach surface, the emergency evacuation of divers is based on dedicated hyperbaric rescue systems. There are still potential situations for which these systems cannot be used or deployed, and where an emergency decompression provides an alternative solution.
Methods: Our objective was to describe historical cases and assess the benefit of emergency decompressions, with the collection of data from the authors' direct experience and networks, providing witness or first-hand information.
Results: We documented three cases of emergency decompression following bell evacuations, and six cases of accelerated decompression performed in the chamber or hyperbaric rescue chamber. Review of these cases showed: 1) the complicated nature of such emergencies that make decisions difficult; 2) the variety of solutions implemented; and 3) the surprisingly safe and successful outcomes of several operations. Analysis of the accelerated decompression occurrences allowed derivation of the options used; upward initial excursion, increased chamber partial pressure of oxygen associated to increased ascent rates, and inert gas switching. We identified four published procedures for accelerated decompression.
Conclusions: Despite modern hyperbaric rescue systems, accelerated decompression remains an essential tool in case of emergency. The diving industry needs clear guidance on what can be achieved, depending on the saturation depth and the level of emergency.

Introduction

Saturation diving is a specialised but common method in commercial diving. While working at sea, undesired events may occur requiring crew evacuation. In such situations, it is impossible for saturation divers to be evacuated at atmospheric pressure. They must perform a decompression that will take several hours to days before reaching surface pressure.

Equipment for hyperbaric evacuation has evolved; initially, the diving bell was the only option. In the late 1970s, diving companies in the North Sea developed hyperbaric rescue chambers (HRCs) i.e., floating chambers to be deployed overboard. Later, the concept evolved into a self-propelled lifeboat containing a chamber capable of accommodating the full dive team with support crew and gas reserve, until recovery and connection to a specific life support package (LSP) could be achieved.

Although some saturation diving projects still proceed without meeting state-of-the-art criteria, a modern hyperbaric evacuation system is based on the following:

1. Transfer of the divers from the endangered saturation chamber system to the connected self-propelled hyperbaric lifeboat (SPHL).
2. Disconnection and launch of the SPHL.
3. Recovery and transport of the SPHL on a nominated rescue vessel carrying a LSP to be connected to the SPHL for additional breathing gas, control equipment, thermal balance capabilities, power supply, etc.
4. Final connection of the SPHL to the hyperbaric reception facility (HRF); located either onshore or offshore, on board a suitable vessel or facility.

5. Decompression in controlled conditions inside the HRF where medical care can be provided.

The framework for the design of the equipment was provided by guidance notes from international organisations and industry trade associations. The first guidelines were published in 1998 by the International Maritime Organisation (IMO).[1] In 2013, the International Marine Contractors Association (IMCA) published the D052 guidance note that became the reference for the offshore oil and gas industry (now available as rev 2018-08).[2] Subsequently, in 2014, the International Oil and Gas Producers (IOGP) issued requirements for hyperbaric evacuation.[3]

However, events still occur where an accelerated decompression offers the only option for bringing the divers back to surface pressure. For example (see later case studies), the wave height did not allow the launching of the Resolute's HRC, while fire rendered the Samudra Suraksha's SPHL unusable, so accelerated decompression became the only realistic alternative.

In 2011, the Diving Medical Advisory Committee (DMAC) organised a workshop on accelerated emergency decompression from saturation in commercial diving.[4] The consensus reached provided the basis of DMAC 31, a guidance note that covers risk assessment, oxygen levels, hydration and thermal balance, though not the rates of ascent.[5] Recently, the Petroleum Safety Authority (PSA) in Norway has commissioned and published a report on emergency decompression from heliox saturation.[6]

The availability of an accelerated decompression procedure should not become an excuse for poor planning and ignoring duty of care. It should never be a substitute for a specific and comprehensive hyperbaric evacuation plan. Accelerated decompression exposes divers to a high oxygen dose and a greater risk of decompression sickness (DCS).

To preserve the knowledge learned from past incidents, we have reviewed the known cases of emergency accelerated decompression. In addition, we detail published accelerated decompression procedures. The objective of this review is to recall the contextual operational justifications made during these events, to document those decompression profiles, and to assess their respective risks and benefits.

Methods

INCLUSION CRITERIA

This review includes historical cases where decompression was required in an emergency, for example, cases where the situation required a combination of intermediate pressurisations/depressurisations, and cases where decompressions ended with a normal decompression once the situation was stabilised. The cases are categorised into two groups:

- Bell evacuation followed by an emergency decompression, not necessarily accelerated, but differing from standard conditions.
- Emergency decompression with accelerated ascent in the chamber system, HRC or SPHL.

EXCLUSION CRITERIA

The review excludes:

- Cases where the divers were transferred into a bell, HRC or SPHL but not actually decompressed, as the event improved quickly after a transfer back to the main chamber system.
- Cases of emergency decompression for medical evacuation. Such cases involve different decision pathways and responsibilities.

SOURCES

Data were drawn from the literature, books and reports, or use of our network to contact direct or indirect witnesses.[7] These data are not exhaustive, as there may be cases that we are unaware of. All the contributors have reviewed the manuscript and approved the inclusion of their data and the use of their names.

UNITS

By convention, the pressure unit most used in saturation diving is metres of seawater (msw). The original data for these case studies have been reported in msw and to facilitate comparison we have retained this throughout the description and converted feet of seawater (fsw) to msw using the USN Navy conversion factor of 1 fsw = 0.30643 msw.

Case studies

REVIEW OF BELL EVACUATIONS WITH EMERGENCY DECOMPRESSION

1975, Discovery one, Comex, Nigeria

Source: Internal Comex account archived by the '*Club des Anciens de Comex*'. Reviewed by author (JPI).

The drill ship 'Discovery One' was working offshore Nigeria. Two divers had returned from a bell bounce dive to 90 msw and were finishing their decompression in the deck chamber. A drilling blowout occurred. All power sources were shut down to avoid fire. Because the seawater/gas emulsion threatened to sink the ship, everyone on board evacuated except for the dive team. They managed to attach a cable from a supply boat to the diving bell. The divers then transferred into the bell, the cables and umbilical were cut, and the supply boat pulled until the bell was finally torn off the deck.

The bell remained hanging below the supply boat for one day. Finally, a crane was found that put the bell onto the supply boat deck allowing a decompression to be planned and then completed in Port Harcourt. The divers controlled the oxygen level in the bell using the manual metabolic oxygen make-up system. Two days were spent decompressing in the full heat on the deck, with fire pumps spraying sea water over the bell to reduce its temperature. As there was no bell emergency lock at the time, divers were fed with soup served through a hose and a set of skin valves. They finally reached surface without DCS. The Comex team used the 1974 standard decompression protocol after an initial ‘pull up’ of 10 msw.

1982, Taipan one, Comex, Gabon

Source: JPI interview with Michel Plutarque, '*Club des Anciens de Comex*'.

In September 1982, the Comex barge ‘Taipan One’ was working in Cameroon alongside a single point mooring buoy. Diving operations were in progress at around 30 msw. Welders were working on the deck and a fire started from an oil leak. The crew managed to cut the anchor lines and a supply boat pulled the barge away from the buoy. In the process, the bell was dropped to the bottom and lost.

A rescue diver from a nearby diving support vessel (DSV) found the bell half submerged in the mud and after cleaning the porthole, saw the divers were alive. The bell was recovered on to the deck of a supply boat that sailed to Douala. In the meantime, a saturation chamber was mobilised in the harbour. After 24 h, the bell was clamped to the chamber and the two divers finished their decompression using normal saturation procedures and without any symptoms of DCS.

This accident is the first that we are aware of to illustrate the chain of hyperbaric evacuation, onshore reception facility and decompression.

1985, Garupa PGP-1 Platform, Comex - Marsat, Brazil

Source: JPI interview with Jean Francois Irrmann, Brazil Comex diving manager at the time, '*Club des Anciens de Comex*'.

The PGP 1 platform on the Garoupa field, offshore Campos in Brazil, had a saturation system with four Comex divers at 126 msw when a gas leak occurred. The platform was abandoned, and only key personnel remained on site. The divers’ evacuation was organised by wet transfer from bell to bell with the nearby DSV Stena Workhorse, which had a Marsat team in saturation at around the same depth. The vessel came alongside the platform, but the captain was reluctant to get too close. Fortunately, at that time, diving bells in Brazil used 120 m long umbilicals. The two bells were lowered to 120 msw and a Stena diver installed a swim line in between them. The four Comex divers were transferred in a single dive and the six divers found themselves squeezed into the very small Stena bell.

Once back on deck and clamped to the Stena system, the opening of the bell door took over 25 minutes because all divers were standing on it. Some divers had to climb into the upper part of the bell before the door could be opened. The team was finally decompressed according to Marsat saturation procedures, which at the time used an adaptation of the US Navy diving manual procedure.

REVIEW OF EMERGENCY EVACUATIONS WITH ACCELERATED DECOMPRESSIONS

1981, Norjarl Semi Sub, Oceaneering, North Sea

Source: JPI interview with Dr Philip James, who was directly involved in the emergency management.

In February 1981, the semi-submersible ‘Norjarl’ barge, operated by Oceaneering, had four divers in saturation at 87 msw. The barge collided with a supply boat. One of its hulls was damaged below the water line. The barge began to list. She was then ballasted, and it was decided to attempt to tow her to Norway for repair. Due to the risk of capsizing, Dr James started an upward excursion according to the US Navy tables (87 msw to 63 msw). He then initiated an accelerated decompression using an elevated chamber PO_2 of 75 kPa and an ascent rate three times faster than the standard Oceaneering ascent at that time. He specified that the divers should drink one litre of water per hour.

During the transfer to Norway, a storm threatened the safety of the barge. Dr James’s plan was to reach 18 msw and finish the saturation decompression with a US Navy Table 6. Fortunately, 24 h later the weather improved, the situation stabilised, and the end of the saturation was conducted without having to switch to Table 6 (see Table 1). There were no symptoms of DCS in any of the divers.

Table 1
Summary of the Norjarl emergency decompression; FO_2 – inspired fraction of oxygen; msw – metres of seawater; PO_2 – inspired pressure of oxygen

Depth (msw)	Breathing gas	Ascent rate ($msw \cdot h^{-1}$)
63.0–49.5	Heliox PO_2 = 80 kPa	4.5
49.5–18	PO_2 = 80 kPa	3.6
18–0	FO_2 = 23%	1.8

Table 2
Summary of the DLB 269 emergency decompression; BIBS – built in breathing system; BIBS 20/5 – BIBS 20 min, chamber gas 5 min; DCS – decompression sickness; FO_2 – inspired fraction of oxygen; msw – metres of seawater; PO_2 – inspired pressure of oxygen

Depth (msw)	Breathing gas	Ascent rate (msw·h^{-1})	Comments
30–20	Chamber gas (heliox) PO_2 = 60 kPa	1.2	Normal decompression 16 h ascent per day
20–10	BIBS 20/5 BIBS heliox, FO_2 = 50%	1.5	Start of accelerated decompression
10–3	BIBS 20/5 BIBS FO_2 = 100%	1.5	
3	Chamber gas	Hold	110 min stop
3–0	BIBS BIBS FO_2 = 100%	Unknown	Described as a slow ascent
Surface	BIBS 10 min, air 20 min for 6 h BIBS FO_2 = 100%	Hold	No DCS symptoms reported

1981, Sedco Phillips Semi Sub, Oceaneering, Ekofisk Field, North Sea

Source: JPI interview with Dr Philip James, who was directly involved in the emergency management.

This incident was related to one of the worst storms recorded in the North Sea. In November 1981, the semi-sub barge ‘Sedco Phillips’ was operating with Oceaneering in the Ekofisk field when she was hit by the storm. The situation became critical. The barge had eight divers in saturation at a depth of 70 msw. The decision was made to transfer the divers into the HRC and to disconnect from the system. However, the HRC was not launched as the waves were breaking over the crane. Dr James directed an accelerated saturation decompression on the same principle as for the Norjarl event described previously. The divers reached surface with no DCS symptoms.

1981, Transworld 58 Semi Sub, Argyll Field, North Sea

Source: JPI interview with Dr Philip James, who was directly involved in the emergency management.

During the same November 1981 storm, the Transworld Rig 58 broke all anchor lines and drifted for several hours in hurricane winds. Four divers were in saturation on-board at 30 msw. Dr James initiated an upward excursion to 18 msw at 6 msw·min^{-1}. Decompression then proceeded at 1.2 msw·h^{-1} to surface with a progressive gas switch from heliox to air. Divers were instructed to drink 1 L of liquid per hour. The divers reached surface with no DCS symptoms.

1995, DLB 269, McDermott, Mexico

Source: the book by Michael Krieger “*All the men in the sea*”[8] and author (PB) personal communication with Tim Cheshire and Tony Greenwood.

The McDermott derrick lay barge ‘DLB 269’ was finishing a tie-in offshore the Bay of Campeche at 48 msw, when a tropical storm turned into hurricane ‘Roxanne’. The barge master decided to face the storm with two tugs pulling the barge to maintain position. The divers’ decompression was initiated with normal procedures, as they thought they had three or four days before the storm would arrive. However, onshore support was contacted to obtain an accelerated decompression profile and a procedure was faxed back with input from Dr Russ Petersen and Dr Bill Hamilton. The hurricane moved faster, and six hours before Roxanne was due to reach the DLB 269, the divers agreed to be decompressed via this emergency procedure. The most likely profile for the DLB 269 decompression is presented in Table 2. The divers surfaced in the middle of the storm without any symptoms. The following day, Roxanne moved away to the North.

Two days later, Hurricane Roxanne turned back and hit DLB 269 again. The hull developed several leaks and water filled compartments; tow lines parted one after the other. Anchors were dropped but did not hold. The bow slowly went into the water, swept by giant waves. The crew had to abandon the barge before it sank. Six people lost their lives.

2005, S. Suraksha, Bombay High Field, India

Source: Dr Ajit Kulkarni who was directly involved in the emergency management.[9] This is an updated report following the discovery of further information.

A cook cut his finger onboard the ‘S. Suraksha’ diving support vessel working on the Bombay high field in India. It was decided to evacuate the patient with a crane basket to the nearby Bombay high north platform. During manoeuvring, the vessel struck a gas riser. Both the platform and the vessel caught fire.

The S. Suraksha had six divers in saturation at two levels; the deepest storage depth being 42 msw. The deepest operating depth in the area is 85 msw and the SPHL was kept pressurised at that depth. As the vessel was on fire, the diving superintendent asked the divers to be pressurised to 85 msw to enter the SPHL. However, the first diver to enter could see the flames through the port hole and the bulkhead was hot; the SPHL was on fire. The divers returned to the living chamber. The trunking had heated considerably and two of the divers sustained burn injuries. Inside the chamber, the internal depth gauge indicated 70 msw. The vessel was abandoned. The emergency power supply in the saturation control failed. Left alone, the divers managed to decompress themselves to 54 msw using the bilge valve.

During the night, the diving superintendent of another vessel, the 'S. Prabha', which had been fighting the fire, boarded the S. Suraksha. All divers reported that they were OK. Communication was established using a sound-powered telephone. The diving superintendent and the life support technicians (LSTs) who had been rescued by a supply boat, came back on board the S. Suraksha. After flushing through the system and passing fruits and fluids in, they started decompression.

When Dr Kulkarni arrived on-board in the morning, the LSTs had decompressed the divers from 54 to 34 msw using gas mixtures available on board. The fire had not been extinguished completely, however the vessel did not appear to be in imminent danger. An 8 h hold was decided because the divers had undergone severe pressure variations in the previous 24 h. After the hold, the decompression resumed according to standard procedures without stops.

During the night, the fire erupted again at which time the system was at 23 msw pressure. The LSTs raised the chamber PO_2 to 60 kPa and abandoned the vessel. The divers were instructed to decompress at 3 $msw \cdot h^{-1}$. The next morning, when Dr Kulkarni and the LSTs could board the vessel, the chambers were pressurised at 11 msw. The situation was deteriorating rapidly; the list of the vessel had increased, probably from ingress of firefighting water. It was then decided to carry out an abort decompression and transfer the divers to the nearby S. Prabha that was engaged in firefighting but also had divers in saturation. These divers had been decompressing for the past two days and were at shallow depth. The abort decompression was delayed for 45 min to allow the S. Prabha to recompress its divers to 30 msw. The S. Suraksha divers were rapidly decompressed to surface, jumped in a lightweight inflatable boat and arrived on-board the S. Prabha where they were immediately pressurised to 30 msw in the saturation system where they met with the other S. Prabha divers. One diver complained of pain in knee which relieved on reaching 30 msw. Later, all the divers surfaced safely.

The information collected from Dr Kulakarni's report permits reconstruction of the emergency decompression which is presented in Table 3.

2013, Barge Resolute, East Java, Indonesia

Source: Dr Phil Bryson and Dr Jean Yves Massimelli who were directly involved in the management of the emergency.[10]

In January 2013, the 'Resolute', a pipelay barge equipped with a mobile saturation diving system, lost anchors in bad weather offshore Jakarta. Six divers were in saturation being held in the main chamber at 45 msw, while three other divers were passing 28 msw during their decompression from saturation. These three divers were in the HRC that was being used as a living chamber. Containers and heavy gas cylinders had been wiped out by the waves and were crushing other deck equipment. The dive control station was flooded. While the rest of the barge's crew were already at the muster station preparing themselves to abandon ship, all members of the diving team were present on deck, to protect the saturation diving system. The diving superintendent noted the seriousness of the weather with the winds and massive waves slamming into the barge. He felt that there was a significant risk of the HRC losing its seal with the rest of the saturation system as well as the risk of capsizing.

He decided to recompress the three divers in the HRC and then transfer the six divers from the main chamber into the HRC. The HRC was then compressed with all the divers to 80 msw (seabed depth + 20 msw) to secure the seal. The HRC was disconnected from the system. However, launching the HRC in such a sea state would have led to the HRC being crushed against the hull. A decision was made to delay the decompression and to wait for the anchor-handling tug to hook up a tow line which, eventually, was successfully completed. Thereafter, the barge came back to level and could keep a more stable position. With the immediate danger of capsizing removed, the diving superintendent instructed the HRC to be re-connected to the surface supply and the divers to remain in the HRC.

The circumstances remained perilous and unpredictable with the safety of the barge still at risk. An accelerated decompression was initiated under the shore guidance provided by the company medical advisors and by Dr Bryson. The situation was continuously monitored by the offshore and onshore teams who had acknowledged that, following surfacing, it would have been practically impossible to re-compress the divers as the diving system was damaged. Communication was difficult due to the weather and on-site conditions. Near the end of the decompression, these concerns and the improved barge stability were conducive to reducing the decompression rate and enforcing a hold

Table 3
Summary of the S. Suraksha emergency decompression; BIBS – built in breathing system; FO_2 – inspired fraction of oxygen; LST – life support technician; msw – metres of seawater; PO_2 – inspired pressure of oxygen; USN – United States Navy

Depth	Breathing gas	Ascent rate	Comments
Initially 28 and 42, compressed to 85 msw			Two separate teams of divers compressed to deepest operating depth in the area
85–54 msw	Chamber gas (heliox) FO_2 = 6% (uncertain)	~4–5 msw·h^{-1}	Empirical decompression carried out by the divers
54–34 msw	Chamber gas FO_2 = 8–12%	2.50 msw·h^{-1}	Decompression during the night, under the control of the LSTs on site No power, no scrubber, divers on emergency rebreather
34 msw	Chamber gas FO_2 = 12%	Hold	Eight hour hold decided by Dr Kulkarni
34–23 msw	Chamber gas FO_2 = 16%	1.20 msw·h^{-1}	Standard decompression under the control of LSTs
23–11 msw	Chamber gas PO_2 = 60 kPa	3.00 msw·h^{-1}	Decompression performed by the divers
11 msw	Chamber gas FO_2 = 20%	Hold	Decision to transfer Stop for 45 min waiting on the S. Prabha to prepare for divers' reception
11–2.4 msw	BIBS FO_2 = 100%	1.00 msw·min^{-1}	8.6 min from 11 to 2.4 msw
2.4–1 msw	BIBS FO_2 = 100%	0.16 msw·min^{-1}	10 min from 2.4 to 1 msw
1 msw to surface	BIBS FO_2 = 100%	0.08 msw·min^{-1}	12 min from 1 msw to surface
Surface			Divers transferred to the S. Prabha
Recompression to 30 msw in less than 30 min			One case of knee pain in one diver relieved on arrival at 30 msw
30 msw to surface		USN heliox saturation diving decompression schedule	No DCS symptoms reported

at 10 msw to help reduce the risk of DCS. This event illustrates the need for a reliable communication capability, continuous monitoring and assessment, and flexibility in these situations.

In summary: After 4–5 hours hold (maintaining chamber pressure unchanged), the decompression was initiated from 76 msw (the depth after cooling of the chamber following a fast compression to 80 msw).

The divers took aspirin and fluids (initially 1 L·h^{-1}) and managed to 'exercise' during the decompression as far as possible in a full nine-man HRC. The doses of aspirin and the quantity of water were not accurately recorded. The decompression is presented in Table 4.

Medical examinations were conducted by the barge's medical officer following surfacing, and then by the diving medicine specialist in Singapore, one week later. No signs or symptoms of DCS or pulmonary oxygen toxicity were seen. All divers resumed their commercial diving careers.

Immediately after the initial incident notification, the medical assistance provider had mobilised an airplane able of maintaining a 1 atmosphere cabin pressure in flight. If a medical evacuation to a recompression facility had been required, it would have been carried out in optimum conditions.

Table 4 and Figure 1 display the PO_2 breathed by the divers along the ascent. The overall UPTD (units of pulmonary toxicity dose) exposure was 1265 UPTD during the decompression.

Table 4
Summary of the Resolute emergency decompression; 20/5 – BIBS 20 min, chamber gas 5 min; 25/5 – BIBS 25 min, chamber gas 5 min; BIBS – built in breathing system; FO_2 – inspired fraction of oxygen; msw – metres of seawater; PO_2 – inspired pressure of oxygen

Depth (msw)	Breathing gas	Ascent rate ($msw \cdot h^{-1}$)	Comments
76–55	Chamber gas (heliox) PO_2 = 60 kPa	7.8 (average)	Ascent of 21 msw performed in 2 h 42 min
55–43	Chamber gas PO_2 = 60 kPa BIBS 20/5, 5 sessions heliox, FO_2 = 20%	5	Decompression
43–20	Chamber gas PO_2 = 60 kPa BIBS 20/5, 2 sessions BIBS 25/5, 7 sessions heliox FO_2 = 35%	5	Decompression
20	Chamber gas PO_2 = 60 kPa BIBS 25/5, 2 sessions heliox, FO_2 = 50%	Hold	3 h 35 min hold
20–16	Chamber gas PO_2 = 60 kPa	1	Decompression
16–10	Chamber gas FO_2 = 23%	1	Decompression
10	Chamber gas FO_2 = 23% BIBS 25/5, 3 sessions FO_2 = 100%	Hold	5 h hold
10–0	Chamber gas FO_2 = 23% After 4 h chamber gas BIBS 20 mins every 2 h to surface. FO_2 = 100%	0.5	Decompression No DCS symptoms reported

Figure 1
Depth (left axis) and inspired PO_2 (right axis) time profile of the Resolute emergency decompression

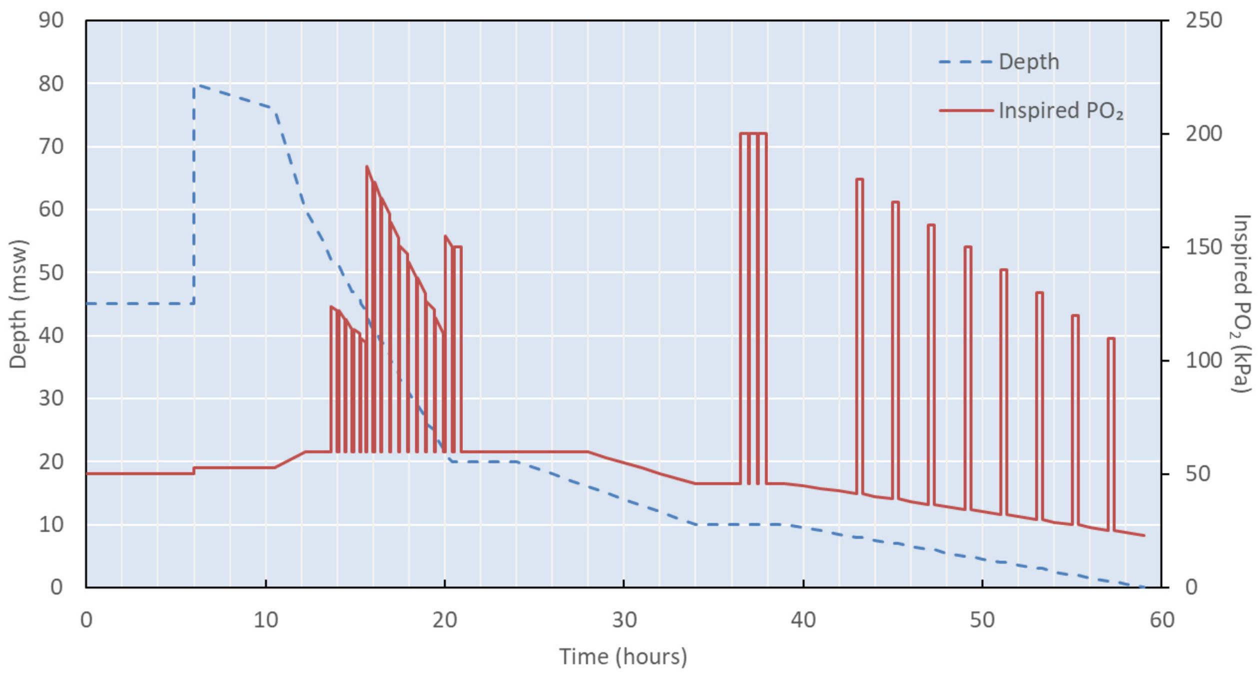


Table 5

Comex 1974 heliox saturation decompression; FO_2 – inspired fraction of oxygen; msw – metres of seawater; PO_2 – inspired pressure of oxygen

Depth (msw)	**Chamber gas**	**Ascent rate (min·msw^{-1})**	**Ascent rate (msw·h^{-1})**
280–240	PO_2 60 kPa	20	3.0
240–160		25	2.4
160–80		30	2.0
80–20		35	1.7
20–15		40	1.5
15–10	FO_2 24%	40	1.5
10–5		45	1.3
5–0		50	1.2

Table 6

US Navy diving manual Rev 7, 2016, emergency abort decompression; FO_2 – inspired fraction of oxygen; msw – metres of seawater; PO_2 – inspired pressure of oxygen

Depth (msw)	**Chamber gas**	**Ascent rate or duration**
Decompression from 306.4–83.7 msw with 60 kPa chamber PO_2		
306.4–61.3	PO_2 = 60 kPa	1.53 msw·h^{-1}
61.3–16.1		0.88 msw·h^{-1}
16.1–1.2	FO_2 = 23%	0.88 msw·h^{-1}
1.2–0		4 min
Decompression from 83.4–62.5 msw with 70 kPa chamber PO_2		
83.4–61.3	PO_2 = 70 kPa	1.67 msw·h^{-1}
61.3–20.4		0.97 msw·h^{-1}
20.4–1.2	FO_2 = 23%	0.97 msw·h^{-1}
1.2–0		4 min
Decompression from ≤ 62.2 msw with 80 kPa chamber PO_2		
62.2–61.3	PO_2 = 80 kPa	1.67 msw·h^{-1}
61.3–24.8		1.02 msw·h^{-1}
24.8–1.2	FO_2 = 23%	1.02 msw·h^{-1}
1.2–0		4 min

Table 7

Italian accelerated decompression procedure; FO_2 – inspired fraction of oxygen; msw – metres of seawater; PO_2 – inspired pressure of oxygen

Depth (msw)	**Chamber gas**	**Ascent rate (msw·h^{-1})**
180–90	PO_2 = 65 kPa	3.0
90–30		2.4
30–18		1.2
18–0	Air flushing to never exceed an FO_2 of 23.5%	0.6

Table 8
Comex accelerated saturation decompression procedures; FO_2 – inspired fraction of oxygen; msw – metres of seawater; PO_2 – inspired pressure of oxygen

Depth (msw)	Chamber gas	Ascent rate (msw·h^{-1})
Decompression from not deeper than 130 msw		
130–16	PO_2 = 60 kPa	1.4
16–0	FO_2 = 23%	0.6
Decompression from not deeper than 90 msw		
90–20	PO_2 = 70 kPa	1.6
20–15	FO_2 = 23%	1.2
15–0	FO_2 = 23%	0.6
Decompression from not deeper than 70 msw		
70–25	PO_2 = 80 kPa	1.7
25–15	FO_2 = 23%	1.2

REVIEW OF AVAILABLE ACCELERATED DECOMPRESSION PROCEDURES

Early Comex saturation decompression procedures

In the early 1970s, decompressions that were considered as standard procedures appear today as excessively fast ascents. Unfortunately, the procedures at the time were a mixture of bounce and saturation diving and cannot be directly translated into modern practice. However, some profiles provide useful references to what can be done in terms of rapid decompression.

In 1974, Comex published their first set of original heliox saturation procedures that were used until 1979. The ascent could be initiated by a 10 msw upward excursion depending on the last dive interval. Decompression was continuous over 24 hours. Chamber oxygen was controlled to a PO_2 of 60 kPa when deeper than 15 msw, and then adjusted to a FO_2 of 24% when shallower. It took five days and 16 hours to decompress from 280 msw storage depth to surface (Table 5). The overall safety performance based on data from the Comex database indicated a DCS risk of 5 to 10%; all symptoms were related to joint pain occurring in the last 10 msw of ascent.[11]

US Navy 2016 emergency abort procedures

Revision 7 of the US Navy diving manual,[12] paragraph 13.23.7.2, provides a specific procedure for emergency abort decompression, defined for serious life-threatening emergency, however, no information is provided on its validation. The emergency ascent includes several phases: an initial upward excursion, a hold, and an accelerated decompression (Table 6).

The ascent rates are defined (Table 6) according to the starting depth, which decides the chamber PO_2. These ascent rates appear very slow compared to the emergency situations studied and seem of little practical use. We could not find any instance when these procedures were used.

Italian accelerated decompression procedures

An accelerated decompression procedure can be found in the Italian UNI 11366 diving regulations.[13] The procedure has continuous decompression varying with depth and constant chamber PO_2 until 18 msw when the chamber is flushed with air to change from helium to nitrogen (Table 7). We could not find any instance when these procedures were used.

Comex emergency decompression procedure

In the 1994 revision of its diving manual, Comex introduced an accelerated decompression procedure that provided three options depending on the starting depth. These procedures were based on a higher level of chamber PO_2 and thus allowed faster ascent rates. Considering pulmonary oxygen toxicity as the limiting factor, the PO_2 selected controlled the maximum decompression time, and therefore the depth of use. Three depth ranges were proposed: 70 msw, 90 msw and 130 msw, with their respective chamber PO_2. For an emergency deeper than 130 msw, the only possibility was to decompress the divers to 130 msw using standard saturation decompression and then consider the possibility of using an accelerated decompression to the surface (Table 8).

An option was available where decompression could be further accelerated by putting the divers on a higher FO_2 via the built-in breathing system (BIBS) during the last 10 msw of the ascent to the surface. The ascent rate could be increased to 60 min per msw. To our knowledge, these procedures have never been used by Comex.

Discussion

THE EVENTS

Weather was clearly a critical factor in four out of the six incidents discussed. It prevented the evacuation via an HRC in the Sedco Phillips SS, the Transworld 58, the DLB 269 and the Resolute cases. Accurate planning and preparedness are critical in risk management.

It is notable today that HRC's are not accepted in the UK or Norwegian sectors of the North Sea and other regions due to their limitations of life support and seaworthiness.

THE OPTIONS

Faced with an event requiring an emergency decompression, a commercial diving company will mobilise its safety response network and involve the diving medical advisor in the decision-making process. The decisions will be made on information received via telecommunication systems, generally with limited real time knowledge of the actual situation and its evolution. The circumstances are often dramatic and changeable, with emotional pressure to manage. History has shown that decisions often must be revised promptly according to the development of the situation.

Upon deciding whether to use an emergency decompression, the first consideration will be the depth of the divers. An accelerated decompression is only useful if the divers are close enough to the surface and the time scale allows them to be brought to safety. If these criteria are fulfilled, then methodological options for the rescue would be:

- To decide on a starting depth. The situation may require the recompression of a team in decompression or at a different storage depth to a deeper depth.
- To perform a rapid large excursion to get the divers closer to the surface. However, too great an excursion might cause DCS and impair further decompression.
- Decompress with increased ascent rates. However, too rapid an ascent rate might cause DCS.
- Decompress with an increased PO_2 to allow faster ascent rates. However, too high an oxygen exposure might induce oxygen toxicity.
- Possibly store the divers at a depth close to the surface waiting for the best time to evacuate.
- A combination of the above.

The decision is therefore a balance between the time left to decompress to surface and the accepted risk of DCS and/or oxygen toxicity. This may lead to a graded response where two levels of emergency could be considered:

- A 'level one emergency' where time is available and a fast, but still reasonable ascent rate could be employed to minimise the DCS risk.
- A 'level two emergency' where the immediate integrity of the system is at risk and a life-threatening situation involves the whole saturation team. This could justify an aggressive ascent protocol and the acceptance of a higher risk of DCS and oxygen toxicity.

Finally, operational constraints must be evaluated:

- Feasibility:
  - ○ Are communications reliable enough to direct the decompression?
  - ○ Is the diving support vessel a safe place to decompress, and for how long?
  - ○ Are LSTs present?
- Acceptability:
  - ○ Can the divers be informed of the options and involved in the decision?
- Control of decompression:
  - ○ Is the chamber atmosphere breathable?
  - ○ Can a breathing mix be supplied on BIBS?
  - ○ Is the chamber temperature within limits?
- Treatment options:
  - ○ In case of DCS, would it be possible to treat a diver during the emergency decompression or would the diver have to wait until he is evacuated to a hyperbaric facility?
  - ○ How long would it take to take the divers to a nearby vessel of opportunity or a shore-based facility equipped with a saturation diving system?

INITIAL EXCURSION

In several recorded instances, the immediate strategy was to perform a rapid upward ascent or excursion to bring the divers closer to surface. This protocol is described in the US Navy diving manual (paragraph 13–23, revision 7) that allows the start of a final decompression to begin with an upward excursion. The excursion amplitude can be quite significant, for example, a 30 msw ascent from 120 msw to 90 msw.

Diving companies have become more cautious about upward excursions. This is because the data from the Comex diving database, the Hades database from Seaways, and the US Navy have all shown that too great an excursion may induce vestibular DCS symptoms, which could have a dramatic impact on the rest of the emergency management.[11,14,15]

One way of controlling the risk of DCS is to perform this initial ascent at a slower rate, as during the Resolute case (approximately 7.8 $msw \cdot h^{-1}$). Alternatively, the divers may be kept at constant depth for a while after the excursion, as per the US Navy abort decompression procedure, which requires a two hour hold before any further ascent.

FINAL EXCURSION

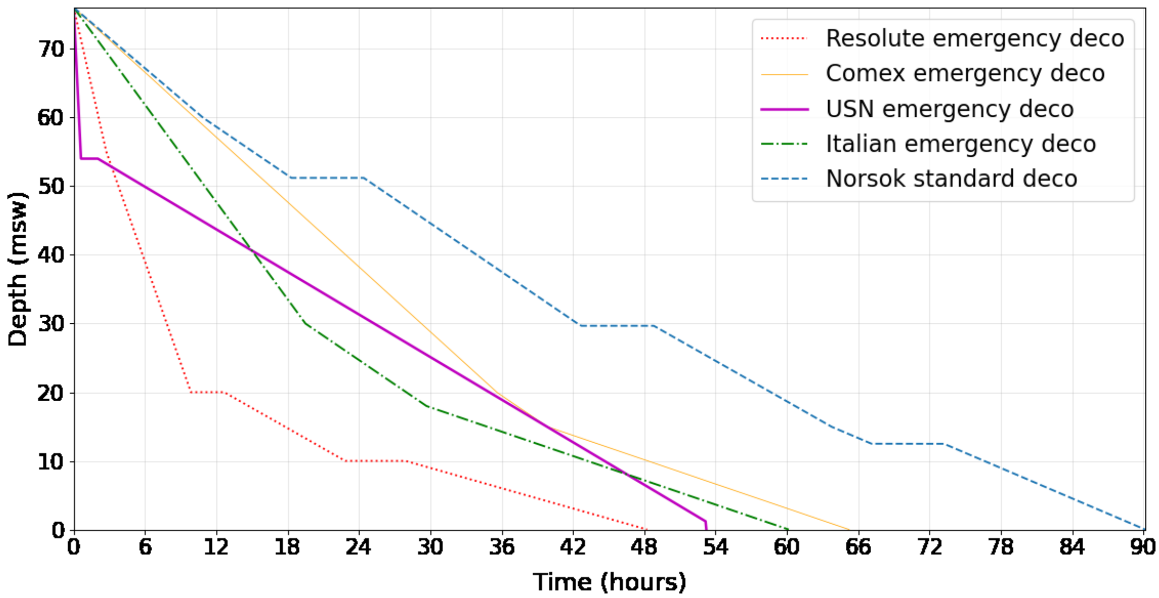
Another documented emergency decompression strategy consists of decompressing the divers to a depth close to surface and keeping the divers at this depth until the situation is controlled. The 'holding' depth was 10 msw during the Resolute case, 3 msw during the DLB 269 case, and 11 msw during the S. Suraksha case. This hold has the advantage of stabilising the divers in terms of decompression, providing a higher PO_2 on BIBS (if required for a DCS treatment) and still permitting a rapid escape to surface if needed. The S. Suraksha case showed that divers could ascend from 11 msw to surface in 30 minutes and then be recompressed to 30 msw in a nearby vessel system, with only one case of DCS (pain only) among six saturated divers.

FASTER ASCENT RATES

During decompression, the ascent rate and the inhaled PO_2 are closely related. This relationship is linear, according to Vann's model.[16] With the use of data from commercial saturation decompressions, a regression line has been

Figure 2

The depth/time profile of the Resolute emergency decompression compared to the Comex, US Navy and Italian emergency decompression procedures for the same starting depth. The Norsok standard saturation profile is added to allow a comparison to a standard saturation decompression. One profile includes an initial upward excursion to initiate the ascent (24 msw for the US Navy Procedures)



established between the safe rate of ascent and chamber PO_2 in the deeper part (> 60 msw).[17] This is the design principle of the US Navy and Comex emergency procedures that propose three values of chamber PO_2 associated with three different ascent protocols. To control oxygen toxicity, each decompression PO_2 is associated with a time limit, translated into a limitation in starting depth.

To compare emergency protocols, we first considered the Resolute case and displayed its actual depth/time profile (Figure 2). We then added the profiles of the US Navy, Italian and Comex emergency decompressions, for the same starting depth. The Norsok profile was also added to provide a reference associated with a standard and conservative saturation decompression.[18]

Two strategies emerge from this figure. The US Navy and Comex procedures have relatively slow decompression rates (1.5 to 1.8 $msw \cdot h^{-1}$) and are adapted to the evacuation of a diver with an injury or an illness, where the risk of DCS must be controlled. These situations we class as Level 1 emergencies. The figure shows that ascent rates can be significantly increased in a life-threatening situation. On board the Resolute, the decompression was initiated with an upward excursion at approximately 7.8 $msw \cdot h^{-1}$ from 76 msw to 55 msw and then continued at 5 $msw \cdot h^{-1}$ from 55 msw to 20 msw. This situation represents a Level 2 emergency, and these are imbued with a higher risk of DCS and oxygen toxicity, which are accepted given the circumstances.

Estimation of DCS risk is a key decision factor. For standard saturation decompressions not exceeding 200 msw, a study using data from the Comex database, based on 60 kPa chamber PO_2, showed that DCS cases were associated with pain symptoms alone, which occurred in the last part of the ascent.[19] Therefore, with Level 1 emergency decompression, the risk seems to be limited to mild DCS. For deeper dives, three cases of vestibular symptoms have been reported during historical deep experimental dives with an initial rapid decompression. These included: a Comex PLC I dive made in 1968, from 335 msw, with an initial ascent rate at 3.5 $msw \cdot h^{-1}$; in 1971, a Royal Navy RNPL 457 msw (1500 feet of seawater) dive, varying ascent rates starting at 12 $msw \cdot h^{-1}$;[20] and in 1974, a Comex Physalie VI dive, 610 msw, initial ascent rate at 2.4 $msw \cdot h^{-1}$.

With Level 2 emergency decompressions, a tangible risk is vestibular symptoms associated with DCS. Current experience and algorithms do not allow the control of this risk.

CENTRAL NERVOUS SYSTEM (CNS) OXYGEN TOXICITY

Increasing the PO_2 allows the ascent rate to be accelerated. However, oxygen toxicity may lead to convulsions, which are dangerous due to their sudden onset and limited warning signs that are either difficult to recognise or absent. The simplest way of managing CNS toxicity is to consider it as a matter of threshold and set limit values to the PO_2. During immersion, the limit for pure oxygen breathing is set to 175 kPa.[21] In the dry environment of a deck decompression chamber, the PO_2 is set to 220 kPa during normal bounce diving and can reach up to 280 kPa during treatment (US Navy table 6 for instance).

Data from animal studies have documented that oxygen breathing interruptions delay CNS oxygen toxicity.[22,23] In practice, BIBS sessions are associated with interruptions, generally five minutes 'off BIBS', then 25 minutes 'on BIBS'. These breaks in oxygen breathing provide divers with the possibility to rest, talk and drink. It is believed that they also allow a recovery from CNS toxicity. Arieli's oxygen toxicity model suggests that a five-minute break after a 25-minute exposure can reduce the CNS toxicity dose by 67%, for this range of PO_2 breathed.[24] If Arieli's model is applied to the Resolute case scenario, a detailed PO_2 profile can be derived, whereby the index computed for CNS toxicity reaches a score of 80 during the BIBS sessions, but is almost zero by the end of the decompression due to recovery. The computed index remained below the threshold score of 196, which is associated with a 4% risk of CNS oxygen toxicity.

Our review has shown that in several instances, the people managing the emergency did not hesitate to provide the divers with high PO_2 in the BIBS breathing mix, but with interruptions to allow a safe, rapid decompression. Based on the Resolute case, it seems that sessions of 200 kPa PO_2 on BIBS can be managed over a two–three day decompression. It all depends on the interruptions and the expected recovery process, which is difficult to estimate. Interruptions also assume that the chamber atmosphere remains breathable, and this might not always be the case (as in the S. Suraksha event). Finally, we note that during the DLB 269 case, the BIBS sessions were continued out at surface pressure for six hours after the end of the decompression. This may be operationally difficult in some circumstances but certainly helps to protect the divers from developing DCS symptoms, especially if the divers omitted significant decompression.

In relation to CNS oxygen toxicity, benzodiazepines could, in theory, be used as secondary prevention agents. However, their prophylactic effect remains unknown. In fact, the respiratory depressant effects of these drugs could potentially lead to CO_2 retention,[25] which would increase the risk of CNS oxygen toxicity.[26] They would also introduce sedation into an unfolding emergency, which could have disastrous consequences. For these reasons, pre-emptive use of such drugs during emergency decompression to mitigate the risk of CNS oxygen toxicity is not justified.

PULMONARY OXYGEN TOXICITY

Another recognised type of oxygen toxicity affects the lung (pulmonary oxygen toxicity). The symptoms include coughing, chest pain and dyspnoea. Extreme exposures may lead to pulmonary oedema.

The difficulty is setting the upper PO_2 limit to avoid severe pulmonary toxicity. One study exposed 12 subjects for 48 h at PO_2 = 105 kPa during a simulated air saturation dive.[27] Pulmonary oxygen toxicity symptoms occurred, and pulmonary function changes consisted of significant decrements in vital capacity, flow rates and diffusing capacity for carbon monoxide. Subjects showed a complete recovery in both symptoms and pulmonary function in about eight days.[27] In 1979, Comex conducted a deep saturation dive with eight divers to 450 msw. Decompression lasted 10 days and 5 h (corresponding to an average 44.1 msw per day), using 70 kPa chamber PO_2 from 314 msw to surface pressure. No DCS or pulmonary oxygen toxicity of note was reported (Imbert JP, personal communication 2022). These data suggest that PO_2 may be raised significantly in the event of an emergency, but a mathematical tool is required to evaluate this limit.

Several mathematical models can be used to estimate the pulmonary toxicity dose: the unit pulmonary toxic dose (UPTD) calculation from Clark and Lambertsen;[28] the oxygen tolerance model from Harabin;[29] and the more recent oxygen toxicity index from Arieli.[24] However, these models do not translate well to data drawn from conditions different from their validation.[30] Their weakness is multiple injury pathways and the obvious individual variability that may confound models.

The simplest model is the UPTD, which provides an immediate dose evaluation in an emergency. However, it has well-known limitations. First, it was validated with a PO_2 higher than 152 kPa and its prediction curves were extrapolated to the lower range of PO_2; it tends to overestimate toxicity in saturation diving. Second and more importantly, it does not account for any recovery. The computation of UPTD on emergency dive profiles generally leads to doses higher than 1,000 UPTD that far exceed the daily limit of 625 UPTD set for a 5% decrement in vital capacity. Arieli's toxicity index offers a new alternative, accounting for recovery.[31] It provides a more relevant dose/limit indication, but its calculation might not be practical during an emergency. We applied both models over the Resolute PO_2 profile and obtained a dose of 1,265 UPTD and a cumulative value of 36 with the Arieli's pulmonary index.

This overall 1,265 UPTD dose is not regarded as excessive; in the early Comex experimental dives it was documented that a dose of 1,300 UPTD was acceptable during saturation based on vital capacity measurements.[32] The index computed with Arieli's model for pulmonary toxicity reached a maximum value of 566 during the BIBS sessions but was very low by the end of the decompression. This would indicate that divers' vital capacity decrement reached 7.5% but a recovery took place.

Pulmonary oxygen toxicity remains the limitation of accelerated decompression. A high chamber PO_2 accelerates the decompression but can only be tolerated for a few days.

Therefore, efficient accelerated decompressions can only be carried out from depths shallower than 100 msw.

DIVERS' HYDRATION

There is a considerable literature suggesting the importance of hydration during or after immersion. Immersion exposes the diver to heat and cold, exercise, dry gas breathing and modifies cardiac function. In particular, it has been shown that hydration before immersion reduces the level of circulating venous gas emboli post-dive.[33] However, these situations are not pertinent to saturation decompression, where the divers are in a dry environment with controlled humidity and temperature. We could not find studies on divers' hydration during saturation decompression. However, one study showed a diminution of the plasma volume and haemoconcentration between pre- and post-saturation measurements.[34]

There is a general assumption that if vascular volume is maintained, it will optimise perfusion and help to eliminate dissolved gases during decompression, thus reducing bubble formation. The DMAC report on emergency decompression from saturation recommends encouraging divers to drink as much as they can.[5] Plain water or oral rehydration mixtures are preferred.

DMAC guidance note 31 mentions possible additional treatments, such as analgesics and non-steroidal anti-inflammatory agents but acknowledges that there is no human evidence that such drugs would offer benefits.[5]

INERT GAS SWITCHING

Inert gas sequencing (helium, nitrogen and argon) was developed in the sixties by Dr Bühlmann to accelerate gas exchange during deep bounce decompressions.[35] He reported decompression time of 22 h after a 6 h bottom time at 100 msw and 40 h decompression time after 6 h at 150 msw.[36] Another study reported 62–64 h decompression time from 220 msw with 66–68 h bottom time using an inert gas switch from 30 msw.[37]

Based on the same principle, chambers were flushed with air at around 10 msw by the end of the heliox decompression during the Predictive Study experimental dives at the University of Pennsylvania.[38] A gas switch was introduced by slowly venting the chamber with air during the 1981 Transworld 58 incident. An air switch is also prescribed in the Italian accelerated decompression procedures.

The difficulty with an inert gas switch is the control of the dynamics of the gas exchange, which depends on the physical properties of the gas and the depth of switch. When the technique is performed under controlled conditions and the decompression is previously validated, inert gas sequencing allows the design of efficient bounce tables (as for instance, historical Comex Cx 70 or Oceaneering bell bounce tables with transfer to an air-filled deck chamber). In case of an emergency, if the divers have already been subjected to an accelerated decompression, it is difficult to assess the gas kinetics without a complex mathematical model. In fact, the University of Pennsylvania stopped using inert gas switches because of the occurrence of specific DCS symptoms that were difficult to treat. In practice, inert gas switching should not be recommended in an emergency as it would add complexity to an already difficult situation, for example, at which depth should the change occur, what decompression rate after the change, and how to treat associated DCS?

EMERGENCY RESPONSE AND RESPONSIBILITY FOR DECISIONS

Diving companies have based their emergency response on a supportive network, that includes all their departments in addition to their medical advisor. In an ideal case, all parties involved cooperate and share the decision. In real cases, the operational personnel are often in the front line before reliable communication can be established with shore-based resources. In most of the cases reviewed, the medical advisor, once contacted, had to take the decision on the emergency decompression. The authors believe that the duty of the medical advisor is too often perceived as exclusively focussed on the responsibility of making therapeutic decisions as an event is unfolding. Ideally, medical advisors should be involved from the earliest stage of project design and elaboration of diving procedures, until project completion. We noted, however, that in several cases, the divers were instructed on the available options and shared the decision on the accelerated decompression (DBL 269) or took the decision themselves (S. Suraksha). The diving industry needs optimised guidance on what can be achieved, depending on the saturation depth and the level of emergency. This guidance must be developed with the involvement of the diving teams themselves.

Conclusions

The use of emergency decompressions procedures to substitute for appropriate resourcing, planning and the provision of reliable hyperbaric evacuation systems is not justifiable.

The present review of the literature and case studies shows that emergency decompressions have saved lives over the years and suggests that further investigations of methods to accelerate saturation decompression are of definite worth. The review includes 37 divers involved in six emergency decompression profiles with one case of articular pain. No meaningful DCS risk value can be attributed to emergency decompressions from this review considering the variety of scenarios.

Emergency decompression protocols known in the industry are derived from a limited number of original procedures. These procedures propose the following options for accelerating the decompression:

- An initial excursion
- Increased ascent rates
- Increased respired PO_2
- A combination of the above

The existing procedures for accelerated decompression remain conservative and could be considered for controlled situations, like the evacuation of a diver with an injury or an illness, where the risk of DCS must remain controlled. We defined these situations as Level 1 emergencies where time is of the essence but the life support system (the integrity of the diving support vessel, of the saturation diving system and of the surface-support team) has not been impaired.

We defined Level 2 emergencies as disaster situations where the life support system is compromised and there is an imminent threat to saturation divers' lives. There is a lack of available procedures for these Level 2 emergencies. In the dramatic cases reviewed, accelerated decompressions were generated and carried out during the management of the emergency.

We believe that advances in decompression algorithms and oxygen toxicity models could allow the design of accelerated procedures, and that databases containing historical rapid decompression data should allow the validation of these procedures.

Emergency or accelerated decompression procedures should be:

- Simple in their description to ease communications.
- Flexible during their execution, to account for the situation evolutions.
- Published in the public domain and endorsed by industrial and professional associations.
- Supported by: medical resources, i.e., specialised medical teams, and adequate medical equipment; the life support team and the divers themselves; and highly reliable communication systems.

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