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Recompression Treatment of Diving Accidents

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Overview

1. Ensure continued first aid measures
2. Check and confirm diagnosis
3. Hyperbaric treatment
4. Other treatments
5. In-Water Recompression

Ensure continued first aid

- Direct transport to hyperbaric centre ? Or stop at first medical centre for stabilising patient ?
  - Depends on condition of patient (CPR, ALS)
  - Prepare for transport (O2, fluids)

Ensure continued first aid

- Prior notification via e.g. Divers Alert Network telephone hotline
  - Triage
  - Advice
  - Alert HBOT Centre to prepare

Ensure continued first aid

- At arrival in (hospital with) hyperbaric centre: adequate first aid
  - Oxygen 100%
  - Fluids
  - Advanced life support, shock management

Normobaric oxygen treatment

- Usually no respiratory compromise
  - → Increased PaO_2
- 100% O_2 increases inert gas wash-out
  - Maximising oxygen window
  - De-nitrogenation of tissues → re-uptake of N_2 diffusing out of "trapped" bubble
- Improves endothelial function
  - Reduction of fluid extravasation
- Increases oxygen delivery to tissues

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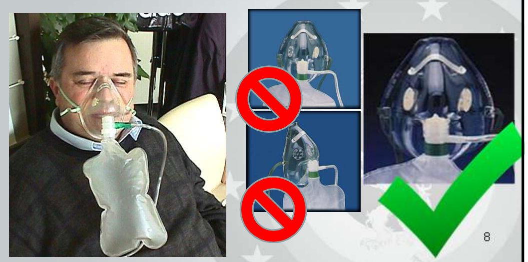
Normobaric oxygen treatment

- Delivery efficiency: $FiO_2 = 1$?
- Non-rebreather mask, 15l/min → 85%



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Normobaric oxygen treatment

- Delivery efficiency: $FiO_2 = 1$?
- Demand valve mask → 85-95%
  - Regulator = familiar to divers
  - Oxygen sparing

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Check and confirm diagnosis

- Remote locations: "diver = recompress"
  - Risks of recompression treatment:
    - Technical hazards
    - Medical hazards
    - Delay in adequate treatment
  - Costs of recompression treatment:
    - Highly variable: between 2000-45000 USD
- Diagnosis sometimes unsure: "trial recompression" justified

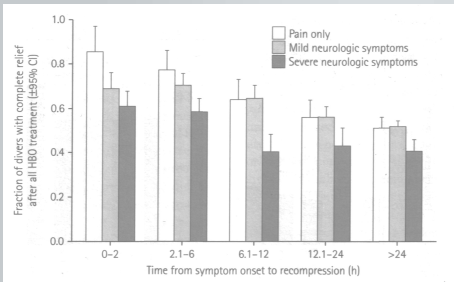
Check and confirm diagnosis

- DOES NOT NEED recompression treatment:
  - Barotrauma (except: pulmonary barotrauma with CAGE)
  - Immersion Pulmonary Oedema
  - No DCI
  - Cutaneous DCS if no other symptoms, adequate normobaric oxygen treatment and delay of >2 hours
  - Missed decompression stops (except: important stop time missed, early HBO possible DAN Europe recommendation: if no symptoms – 30minutes of oxygen, then observe 24 hours

Check and confirm diagnosis

- NEEDS recompression treatment:
  - Neurologic DCS symptoms Even when symptoms regressed/disappeared with normobaric oxygen and fluids
  - Musculoskeletal DCS
  - Pulmonary DCS May lead to cardiovascular shock
  - Optimal delay: < 6 hours May be much longer in case of serious, persisting symptoms

Hyperbaric treatment



Moon RE, Gorman DF. Treatment of the Decompression Disorders. In Bennett and Elliott's Physiology and Medicine of Diving. Ed. AO Brubakk, TS Neuman. Sounders 2003.

Hyperbaric treatment

- Factors
  - Pressure
  - Time
  - Oxygen
  - Other inert gases (nitrogen, helium)
  - General care
    - multiplace vs monoplace

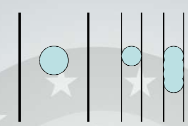
Hyperbaric treatment: pressure

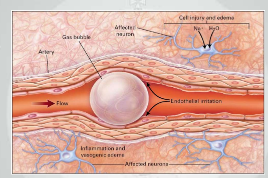
- „Re-compression" *per se* is a therapeutical procedure because it decreases gas volume
  - ↑P → ↓V

  but
  - $V = 4/3 \cdot \pi \cdot r^3$
  - which means that:
    - doubling the pressure (2·P) decreases volume by half (1/2·V), but radius is decreased only by 1/5 (to $80\% \cdot r_o$)
    - to get radius halved (to $50\% \cdot r_o$) you must increase pressure 6 times (6·P)

Hyperbaric treatment: pressure

- Gas bubbles are spherical only in large vessels or extravascular space
- In small vessels they are sausage-like
  - Which means that making them smaller does not mean opening the vessel





Hyperbaric treatment: pressure

- Fixed approach vs Flexible approach
  - Recompression schedules/tables vs Relief pressure
- Local application
  - Tourniquet test to confirm DCS diagnosis
- Pressure by itself is enough for decreasing gas volume, but is not enough for their elimination
- You need <u>time</u> for gas diffusion to dissolve gas bubbles, especially in „slow" compartments

Hyperbaric treatment: time

- Time is needed for:
  - diffusion of gases from inside of gas bubbles into surrounding tissues and into the lungs
  - resolution of symptoms
- Difference between:
  - persistence of symptoms
  - recurrence of symptoms
- Remember:
  - The very first recompression session is of greatest importance!

Hyperbaric treatment: time

- Theoretically:
  - If recompression is applied early enough to relief pressure and applied long enough, the problem of DCS is solved, so **Time × Pressure = Solution**
    - Example 1: Surface Oxygen Decompression
    - Example 2: DCS during saturation decompressions
    - Example 3: On-site recompression after emergency surfacing training

Hyperbaric treatment: time

- Example 1: Surface (O_2) Decompression

DCD DECOMPRESSION TABLES 2015: *Revised NDC tables* Copyright: DADCODAT 2015

air diving, surface decompression tables with oxygen Code: **sox15**

maximum diving depth 33 metres

ascent speed is max. 10 metres/minute

stop time starts after arrival at stop

repetitive interval is 12 hours

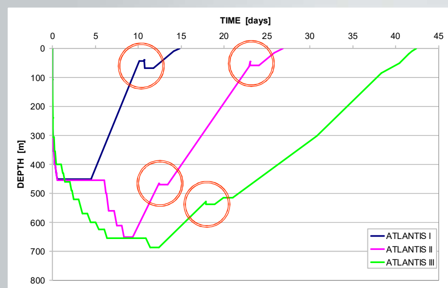
dive time (min.)	till 1st stop	in water stops (metres)					stops in deco-chamber							tot. deco time (min.)	tot. OTU
		21 air	18 air	15 air	12 air	9 air	12 ox	9 air	9 ox	6 air	6 ox	3 air	3 ox		
10	3.3						10	-	-	-	-	-	-	14.5	36
20	3.3						10	-	5	-	-	-	-	19.5	57
30	2.4					1	10	-	10	5	5	-	-	35.5	87
40	2.1				1	2	10	-	10	5	15	-	-	47.5	115
50	2.1				2	3	10	-	10	5	20	-	-	54.5	133
60	2.1				4	3	20	5	20	5	15	-	-	76.5	183
70	2.1				6	5	20	5	20	5	20	5	5	95.5	208

Hyperbaric treatment: time

- Example 1: Surface (O_2) Decompression

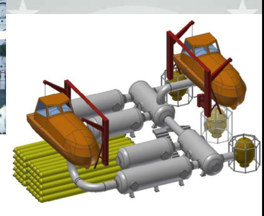
Hyperbaric treatment: time

- Example 2: DCS symptoms during Sat decompression



Hyperbaric treatment: time

- Example 2: DCS symptoms during Sat decompression



Hyperbaric treatment: time

- Example 3: immediate surface oxygen recompression – submarine escape training

Hyperbaric treatment: time

- Example 3: immediate surface oxygen recompression – submarine escape training

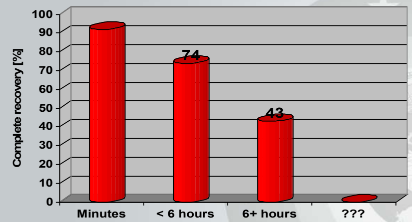
1970/80/90-ties
•AGE (?)
•DCS (?)
•AGE+DCS (?)

Immediate recompression

High effectiveness
= complete recovery
60/65 (92%)

Hyperbaric treatment: time

- Example 3: immediate surface oxygen recompression – submarine escape training



1970/80/90-ties
•AGE (?)
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•AGE+DCS (?)

Immediate recompression

High effectiveness
= complete recovery
60/65 (92%)

* Elliott D. Workshop on Arterial Air Embolism and Acute Stroke. Toronto, Canada, 1977

Hyperbaric treatment: time

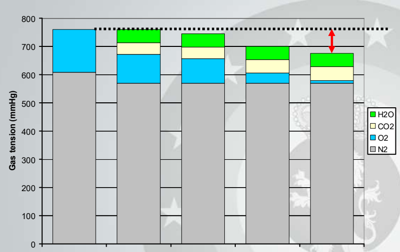
- Theoretically:
  - If recompression is applied early enough to relief pressure and applied long enough, the problem of DCS is solved, so **Time × Pressure = Solution**
- Practically:
  - we need something more because of:
    - delay in recompression
    - limitations for time and pressure of treatment
    - gas bubble consequences (endothelium irritation, complement activation, coagulopathy, inflammation processes)

Hyperbaric treatment: oxygen

- Oxygen window for:
  - elimination of gas bubbles
  - enhancing elimination of inert gas(es)
- Hyperbaric oxygenation:
  - Anti-inflammatory effect

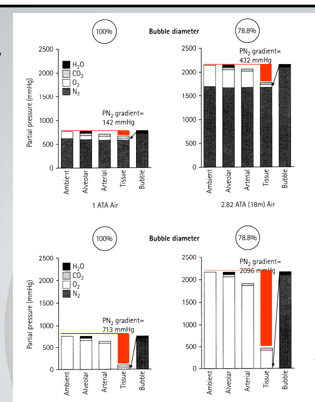
Oxygen window = inherent unsaturation

- Sum of all gases in the cell (N_2+O_2+CO_2+H_2O) is not equal to ambient pressure



Oxygen window

- Sum of all gases in the cell (N_2+O_2+CO_2+H_2O) is not equal to ambient pressure
- The magnitude of the **oxygen window increases linearly with the inspired oxygen partial pressure.**



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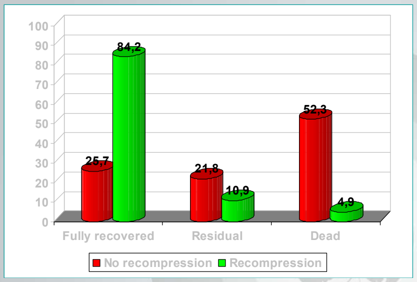
Hyperbaric treatment: oxygen



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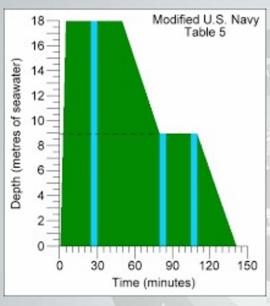
Hyperbaric treatment: other gases

Name	MaxP	Gas	Time	Notes
US Navy T9	2.5 ata	O_2 / Air	1h42m	
US Navy T5	2.8 ata	O_2 / Air	2h15m	
US Navy T6	2.8 ata	O_2 / Air	4h45m	
Catalina Table	2.8 ata	O_2 / Air	11h52m	Modified USN T6
US Navy T7	2.8 ata	O_2 / Air	unlimited	Deco 36h
Comex Cx30 Stolt Offshore Table 30	4.0 ata	O_2 / Air	7h30m	Also He-O_2, N_2-O_2
US Navy T6A	6.0 ata	O_2 / Air	5h50m	Also He-O_2, N_2-O_2
US Navy T4	6.0 ata	O_2 / Air	40h36m	Can be only air
US Navy T8	7.8 ata	He-O_2 / N_2-O_2 / O_2 / Air	Unlimited	Deco 56h29m
RN T71	8.1 ata	He-O_2 / O_2 / Air	47h44m	
Lambertsen/Solus Ocean Systems Table 7A	unlimited	He-O_2 / O_2 / Air	36+h	From 50 msw USN T7

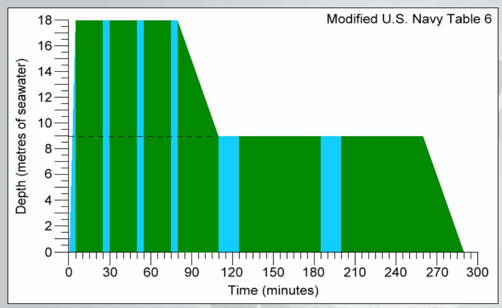
Hyperbaric treatment: other gases

USNavy TT5 = RN TT61 = Cx18C



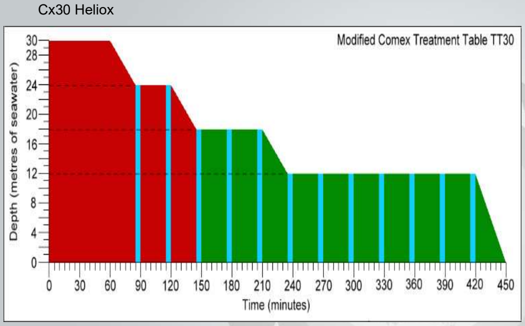
Hyperbaric treatment: other gases

USNavy TT6 = RN TT62 = Cx18L



Hyperbaric treatment: other gases

Cx30 Heliox



ECHM Consensus Conference 2004

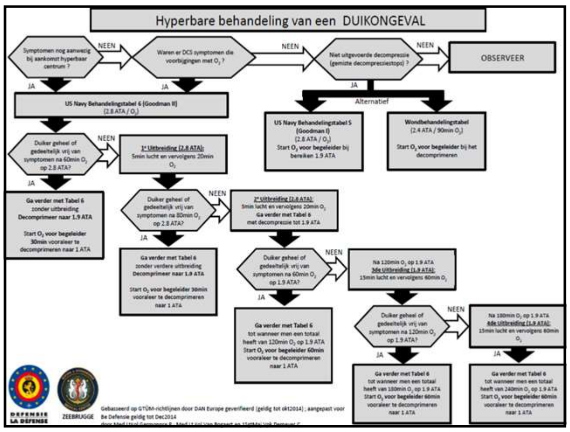
- Decompression accidents are true medical emergencies that should receive the benefit of specialised treatment in dedicated centres as soon as possible.
- A specialized centre is considered a hospital-based recompression facility with permanent and adequately trained medical and paramedical staff.
- On-site 100% oxygen first aid treatment (Type 1 recommendation, level C)
- On-site fluid administration (Type 1 recommendation, level C)
- After immediate stabilization and medical evaluation, the victims of a decompression accident should be immediately directed to the closest specialized centre (Type 1 recommendation, level C)
- In water recompression should never be performed as the initial recompression (Type 1 recommendation, level C)
- Major accidents should be treated with hyperoxygenated tables either at moderate pressure (USN T6) or at high pressure (Cx30 HeOx). Minor decompression accidents (pain only) can be treated with only oxygen recompression tables at 2.8 ATA maximum (note: this is based on the experience and the good results observed in commercial diving) (Type 1 recommendation, level C)

Choice of treatment table

- In recreational diving:
  - Independent of “accident dive” depth & gas
  - USN TT6 or Cx30 preferred
  - Staged approach: for minor, doubtful or very late presenting DCS → start with USN TT5, convert if needed to TT6
- In professional diving:
  - Saturation diving: recompress to relief depth
  - Oxygen toxicity may be a concern

Choice of table: USN TT6 or Cx30 ?

- Theoretical and animal data: Heliox reduces bubble faster than O_2; O_2 recompression: sometimes initial growth of bubbles *(Undersea Biomed Res 1989, 1991, 1994)*
- Case and series reports of succesful Heliox treatment for air dive DCS:
  - 3 cases, including 2 cases after 3d Sat with partial/full recovery and 1 case of 36-hour Sat at 40msw with significant improvement *(Undersea Biomed Res. 1988)*
  - 7 cases, full recovery in 5 cases & improvement in 2 *(Undersea Hyperb Med. 1993)*
  - 50 cases in offshore diving *(Proc of 45th UHMS Workshop, Florida, USA, 1995)*
- The only prospective, randomised, double-blind study comparing 50/50 heliox or 100% O_2 at 2.8 ATA
  - Testing for ’multiple recompressions required’ (more than 2): 9/25 (**36%**) for Heliox vs 20/31 (**64%**) for Control (**RR=0.52**) *(SPUMS 1992; UHMS Conference (abs.) 1993; UHMS Conference (abs.) 1994)*
- Prospective study planned during COST B14 Action (1998-2004) but never started



New developments ?

- French Navy approach:
  - Short oxygen tables rather than Cx18L, even for serious DCS (B18)
  - Heliox table: like Cx18L but with 66% Heliox ?
  - Other adjunctive therapies: fluoxetine, lidocaine, xenon ?
- Scoring systems to predict outcome
  - Boussuges score 1996
  - Mitchell score 2000
  - Revised Boussuges score 2011

Hyperbaric treatment: time

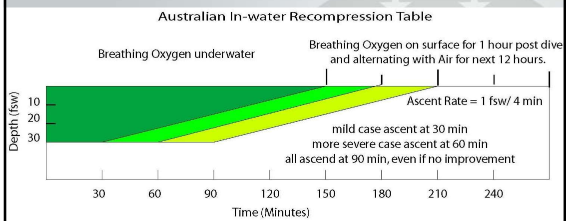
- Theoretically:
  - If recompression is applied <u>early enough</u> to relief pressure and applied <u>long enough</u>, the problem of DCS is solved, so **Time × Pressure = Solution**
    - Example 1: Surface Oxygen Decompression
    - Example 2: DCS during saturation decompressions
    - Example 3: On-site recompression after emergency surfacing training
    - Example 4: In-Water Recompression (IWR) ?

The case for in-water recompression

- Debated for a long time
  Edmonds C. Underwater Oxygen Treatment of decompression sickness. SPUMS 1979; 9(1).
- No unanimous decision ever reached
  - SPUMS – in remote areas : with proper training and preparation, can be undertaken
    Edmonds et al 1997
  - Europe: not an option
    (ECHM Consensus Conference 2004)
- Why this reluctance ?

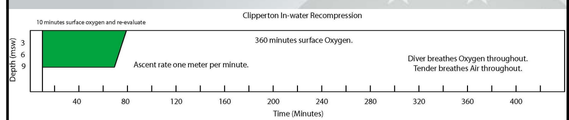
IWR Protocols

- Edmonds protocol – Australian Navy 1960



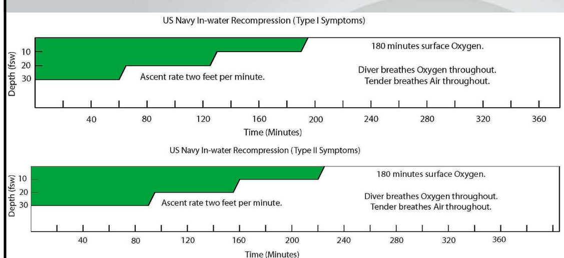
IWR Protocols

- Clipperton protocol – French Navy 2008



IWR Protocols

- US Navy protocol – USN Diving Manual Rev 6



In Water Recompression

- Risks are obvious : sick diver in the water for up to 3 hours
  - Hypothermia
  - Dehydration
  - Oxygen convulsions
  - Neurologic/vital impairment at depth
  - Controlled situation ?
    - Current
    - Visibility
    - Oxygen stores
    - Support divers

In Water Recompression

- Benefits of immediate recompression are obvious too !
  - Animal experiments
  - Experimental dive protocols: immediate recompression in case of symptoms
  - Saturation diving recompression: in case of symptoms during ascent
  - IWR case reports and informal "knowledge" from divers: only the successes reported ?
  - French report 2013: Vietnamese fishermen, Clipperton protocol - seems to indicate effectiveness (23 cases, retrospective evaluation)
- Time to recompression = critical
  - Time window: probably not longer than 5-10 (?) minutes
  - Coagulation, inflammation, induction of apoptosis…

In-Water Recompression

UHM 2018, VOL. 45, NO. 3 – CONSENSUS GUIDELINE: PRE-HOSPITAL DCI MANAGEMENT

Consensus guideline: Pre-hospital management of decompression illness: expert review of key principles and controversies

Simon J. Mitchell [1], Michael H. Bennett [2], Phillip Bryson [3], Frank K. Butler [4], David J. Doolette [5], James R. Holm [6], Jacek Kot [7], Pierre Lafère [8]

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[8] ORPHY Laboratory EA4324, Université de Bretagne Occidentale, Brest, France

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In-Water Recompression

- Recompression and hyperbaric oxygen administered in a recompression chamber is acknowledged as the gold standard of care for DCI.
- However, in locations without ready access to a suitable hyperbaric chamber facility, and if symptoms are significant or progressing, in-water recompression using oxygen is an option.
- This is only appropriate where groups of divers (including the 'patient') have prior relevant training (see below) that imparts an understanding of related risks and facilitates a collective acceptance of responsibility for the decision to proceed.

In-Water Recompression

- IWR should not be conducted if there is hearing loss, vertigo, vomiting, altered level of consciousness, shock, respiratory distress or a degree of physical incapacitation that makes return underwater unsafe.
- The team, which at a minimum includes the patient, a dive buddy who will accompany the patient throughout the in-water recompression, and a surface supervisor, must all be trained, certified and practiced in decompression procedures using 100% oxygen underwater.

In-Water Recompression

- The team must be suitably equipped for IWR using oxygen including: adequate thermal protection; an adequate oxygen supply and a means of supplying 100% oxygen (or close to it) for the duration of the anticipated protocol (both in-water and surface phases); a means of maintaining stable depth; a method of communication (e.g., a slate). A full-face mask or mouthpiece retaining device is strongly recommended.

In-Water Recompression

- IWR should be accomplished with the patient breathing 100% oxygen, and at a maximum depth of 9 msw (30 fsw), according to a recognized protocol. The use of breathing gases other than oxygen for IWR is not recommended.
- IWR may not result in complete resolution of DCI, and signs or symptoms may recur. Any injured diver completing an IWR procedure should be discussed with or reviewed by a diving medicine physician at the earliest possible opportunity.

Recognised protocols include the "Clipperton protocol", "Australian method", and the oxygen IWR method of the US Navy.

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