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39 Oxygen decompression in tunnelling

J. Cl. Le Péchon
JCLP Hyperbarie, Paris, France

Abstract
Although safety in compressed air tunnelling is far from being only the management of decompression sickness risks, this is often considered as a critical issue. It was understood very long ago that breathing pure oxygen during decompression results in either shorter or better quality decompressions. This is extensively used in diving as well as in space during Extra Vehicular Activity preparation. A review of the various effects of hyperbaric oxygen breathing in decompression is made: nitrogen washout is accelerated due to low nitrogen level in alveoli; the body dissolved oxygen content is increased, which prevents hypoxia that could eventually be induced by microbubbles; nitrogen content of bubbles is reduced and bubble collapse is enhanced; inflammation due to hypoxia is prevented. Safety aspects are then considered: management of oxygen breathing to prevent oxygen poisoning by proper limitations of PO_2 and duration of exposures; management of fire risk associated with the use of pure oxygen in compression chambers during tunnelling operations; oxygen systems in air-locks. An example of an air/oxygen tunnelling decompression schedule is presented and discussed in view of time saving, safety records and practicability in tunnelling operations.
Keywords: Oxygen, Decompression, Tunnelling, Compressed air work.

1 Introduction

Caisson working and compressed air have been used since the middle of the 19th century and Paul Bert (1878) explained the etiology of caisson diseases, first described by Pol and Wattelle, followed by Boycott, Damant and Haldane in the development of operational decompression procedures.

In the popular understanding, compressed air work is associated with 'the bends' and decompression sickness. However, the health and safety of hyperbaric works carried out in a confined environment include many aspects other than the short-term or long-term effects of decompression disorders (Le Péchon, 1990).

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The experience and knowledge gained from diving, in particular from the recent advances in the offshore diving industry, and from space Extra Vehicular Activities, allow man to move safely in the field of times and pressures to extreme exposures and durations. In all cases proper gases must be available for breathing, enough time should be given for gas exchanges, and environmental conditions are to be controlled within the right limits.

Application of this experience has still to be introduced into tunnelling technology even in the range of pressure where air remains an acceptable breathing medium (0-5 bars).

2 Main characteristics of decompression sickness

Decompression sickness, which may rather be called decompression illness (Francis and Smith, 1990) when resulting from compressed air work exposure is mainly a painful joint problem, occasionally a neurological syndrome and in some cases delayed symptoms of bone necrosis.

All are caused by microbubbles either located in tendons resulting in pain, or in vessels resulting in a blood disease in reaction to foreign bodies and vascular obstruction. Most of the effects are related to tissue hypoxia caused by vascular gas emboli associated with disseminated microcoagulation (Hallenbeck and Andersen, 1982). Hypoxia prevents the reduction of free radicals, and inflammation processes are triggered.

Decompression sickness is basically an hypoxia stress sickness.

3 Absorption of gases at increased pressure

It is widely accepted among physiologists that a person exposed to increased air pressure will dissolve nitrogen in his tissues according to Henry's and Dalton's laws, to reach a so-called saturation status. When breathing air this process would last about 48 hours and various compartments in the body can be identified according to their rate of nitrogen uptake. The final quantity of nitrogen (which can be expressed in pressure units like PN_2 in the atmosphere) depends only on the pressure of exposure to compressed air (Figure 1). Due to the potential harmful effects of the oxygen also contained in air, such long exposures to compressed air are only possible to pressures lower than 2.5 ATA.

When exposure lasts only a few hours as with compressed air works in tunnelling, the nitrogen uptake into the various compartments of the body is gradual and must be evaluated with a gas-uptake model. Generally, Haldanian models are used with a variable number of compartments from 4 to more than 16 (only 2 are displayed on Figure 1).

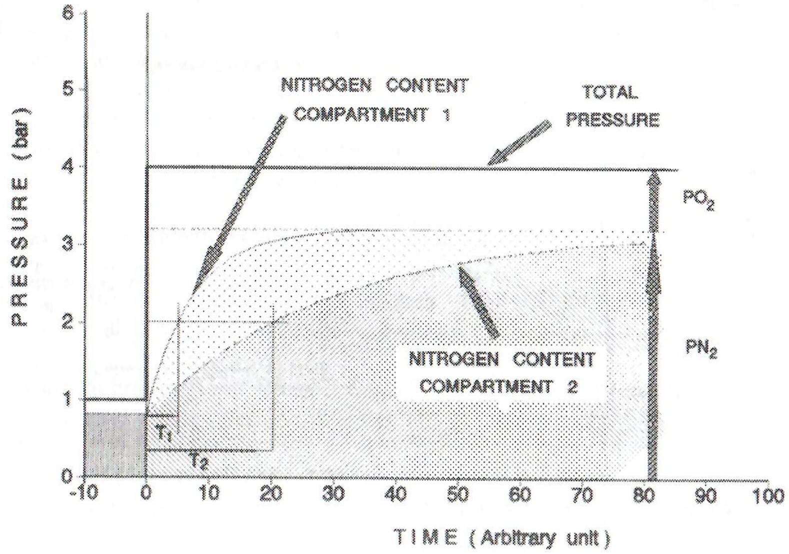

Fig.1. Nitrogen absorption kinetics

4 Gas elimination process

Gas elimination is not symmetrical to the absorption process. When, after a pressured top, the dissolved nitrogen content (expressed in pressure units) in a compartment becomes higher than the ambient pressure, microbubbles may form. Most of these are tolerated in the body until their size and number become unacceptable, then decompression sickness (DCS) is triggered which may develop into symptoms some time later.

Decompression persons from Nitrox saturation exposure is easy and uneventful although many unsuccessful procedures have been tried. This can be done with a slow pressure bleed at decreasing rate, and not on a linear decompression profile or with decompression stops (Le Péchon, 1981).

Decompression from a single short-duration exposure to compressed air is well documented and produces statistically an acceptable or at least accepted number of DCS cases (Shields and Lee, 1986; Imbert and Bontoux, 1989). Most protocols are calculated to control oversaturation (Figure 2) and eventually the bubble growth as a function of the various compartment gas kinetics (Hills, 1977; Van, 1989; Schreiner and Hamilton, 1989).

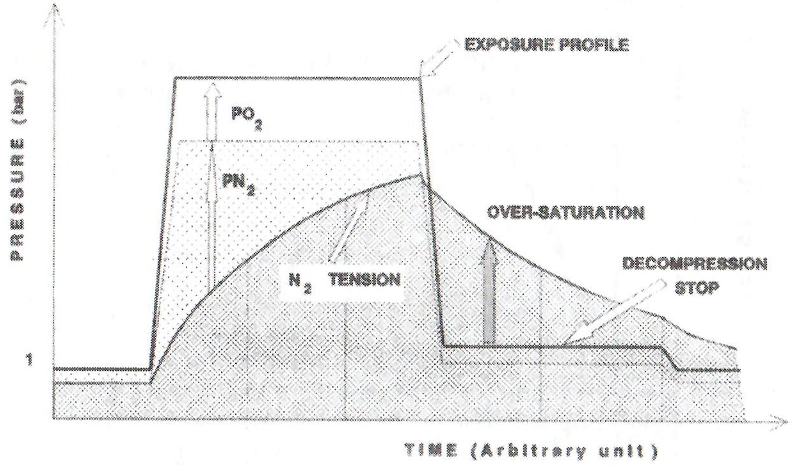

Fig.2. Oversaturation during a stop

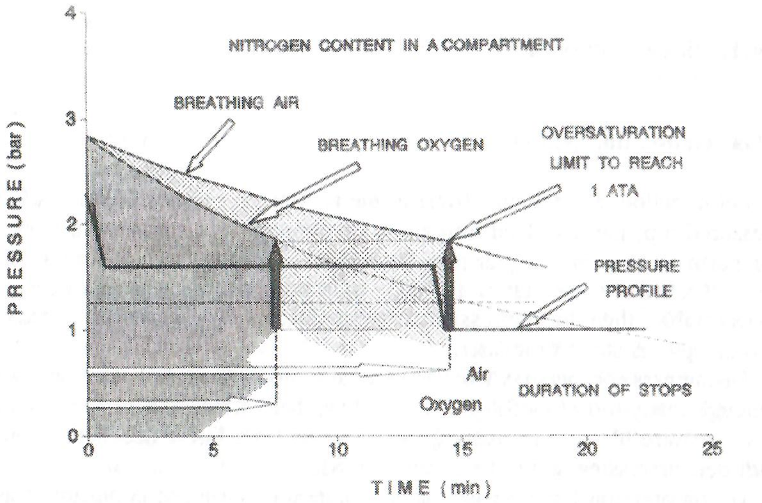

Fig.3. Effects of breathing air or oxygen

Compressed air work and repetitive diving exposures are still a potential health hazard. The durations involved stand in between saturation decompressions and short-exposure decompressions, both familiar and considered safe in the world of commercial diving.

To keep an efficient nitrogen driving force, the nitrogen partial pressure in the lung should be kept minimal; and to prevent bubble growth the external pressure should be kept as high as possible. This can be performed by breathing

'nitrogen-free' gases during decompression and by selecting high pressure stops.

Following both previous conclusions: that decompression sickness is by nature an hypoxic stress and that during decompression one should breathe nitrogen-free gases; the issue becomes very obvious as had already been suggested by Paul Bert in 1878 which is to breathe pure oxygen during decompression.

Unfortunately, breathing pure oxygen under pressure acts as a drug which triggers various physiological reactions in the body among which are:

- Vaso-constriction in many oxygen-sensitive tissues, the central nervous system for example
- Modification of surfactant-producing cells in the pulmonary membrane
- Biochemical induction of seizure.

Oxygen may become toxic when breathed under increased pressure and symptoms may appear after a latency period related to the oxygen partial pressure during exposure (see Figure 4).

The variation and limits of pure oxygen hyperbaric exposure have been evaluated in detail for diving applications (Lambertsen, 1988; Sterk and Hamilton, 1991), medical use in hyperbaric oxygen (HBO) as well as for treatment of decompression sickness (Goodman and Workman, 1965) (see Table 1).

A calculation method of pulmonary oxygen toxicity is available (Unit Pulmonary Toxicity Dose, UPTD) and acute exposures are well documented. In particular, it has been demonstrated that short interruptions of oxygen breathing postpone the occurrence of oxygen intolerance (Clark, 1982).

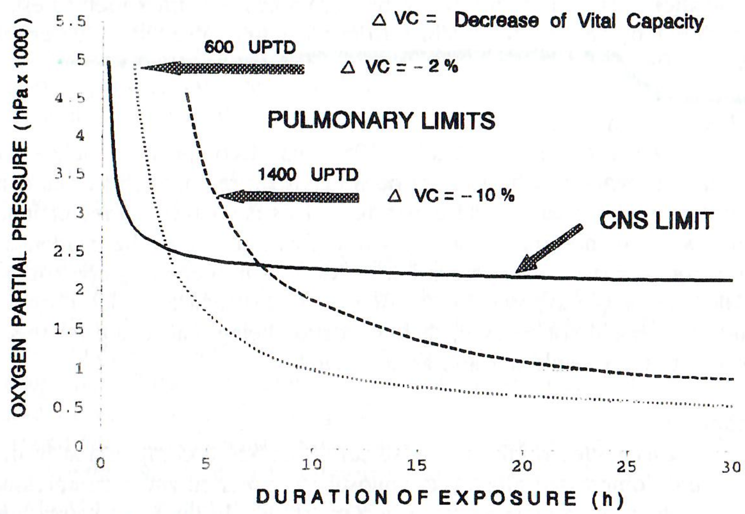

Fig.4. Oxygen toxicity limits

$$UPTD = t\left\{\frac{500}{PO_2 - 500}\right\}^{-0.833} \quad (1)$$

with: t = Duration of high PO_2 exposure in minutes
PO_2 = Oxygen partial pressure in hectoPascals (hPa)

Table 1. Oxygen exposure limits

Situations	UPTD Limits
Single exposure	615
Daily exposures	400
Emergencies and medical	1415

Specific air diving tables with oxygen decompression have been published by several countries or organisations, but very few oxygen tables have been used in tunnelling (Faesecke, 1990; Kindwall, 1989; Nashimoto and Mano, 1974; French regulations, 1990).

It must also be remembered that diving tables are grossly inadequate for caisson work, first because the bottom times are not in the same range, and secondly because the exposed population and the type of work performed under pressure are very different. Validation of diving tables has not been made on a compressed air work population. The correction factor on decompression times used to establish the new French compressed air work tables from air diving tables has been estimated to be about + 25%.

4.1 Acclimatisation

It has been observed (Paton and Walder, 1954) that decompression sickness was more frequent in workers who had not been exposed previously, and that some acclimitisation occurs after several exposures. This is contrary to recreational diving experience which demonstrates that every day diving promotes the incidence of decompression sickness. Decompression tables used in tunnelling operations should be validated for people exposed for the first time. Procedures which show acclimatisation should not be used, their validation being inadequate for this purpose. Then acclimatisation would not appear any more.

4.2 Decanting

Decanting is a technique similar to the so-called surface decompression in diving. Workers are decompressed directly to atmospheric pressure and recompressed in a compression chamber to undergo the necessary stops. In diving, air breathing during the chamber recompression phase is scarcely used, and most of surface decompression procedures include oxygen breathing by masks (Shields and Lee,

1986). Even with oxygen breathing, limitation of exposures had to be introduced due to the high incidence of decompression sickness involving neurological symptoms in air diving in the North Sea (87% carried out with surface decompression and oxygen). In our opinion, decanting should not be carried out on air breathing and should be strictly used only for emergency evacuations from the working chamber.

5 How to use pure oxygen decompression in tunnelling

5.1 Equipment requirements

Oxygen safety. Oxygen constitutes a serious fire hazard and its use must be associated with a number of safety precautions:

- Use oxygen-safe clean plumbing.
- Distribute oxygen at low pressure in solid copper tubing.
- Maintain a maximum of 25% of oxygen by volume in the air lock by ventilation and using an overboard dump system. Monitor oxygen fraction.
- Have an hyperbaric fire extinguisher in air-lock.
- Train caisson workers (this is now compulsory by law in France for any type of hyperbaric work).

Breathing equipment:

- Use ergonomic masks with low-resistance overboard dump systems.
- The masks should be easy to remove from the airlock and easy to clean (most of the diving-type Built-In-Breathing-Systems are not convenient because removing and cleaning are too difficult).
- Use a clean individual mask for each decompression.

Oxygen quality standard. Medical or diving oxygen are acceptable. Any oxygen with analytic control better than 99.9% is acceptable.

5.2 Selection of decompression tables and procedures

When decompression tables with oxygen are not available, the use of oxygen breathing instead of air during standard stops will much improve the quality, people will be less tired, and bone necrosis will not appear.

A reduction of 20% in the stop times carried out on oxygen instead of air is a very conservative short cut if the original tables were safe ones (which remains to be demonstrated for most of them). Start breathing oxygen at the 0.9 bar stop and stay at 0.6 bar for the total time specified at 0.6 and 0.3 bar. The resulting extra oxygen toxicity will remain within acceptable limits.

Long-duration stops on pure oxygen breathing must be interrupted by air breathing for 5 minutes every 25 minutes, this time on air is not to count as stop time in the decompression profile.

Final decompression from 0.6 bar to atmospheric pressure is done during the last 2 minutes of stop time.

5.3 French compressed air decompression tables

The French Ministry of Labour published in 1992 (see Règlementation Française in the list of references), a comprehensive set of decompression tables covering most of the occupational hyperbaric situations and which includes air and oxygen decompressions for compressed air work at pressures up to 4.8 bar.

An example of Compressed Air Work Tables with oxygen breathing is shown in Table 2. All tables have been calculated by Imbert and Bontoux (1989) on the basis resulting from the validation of the French Air Diving Table 1974. They are now the tables to be used in France from June 1992. The mean ratio of decompression times on oxygen tables to the decompression time on air tables for the corresponding exposures is 55%.

Table 2. Times (minutes) for working pressure 3.3 bar – oxygen decompression

Duration of work	Transit time to 1st stop	1.5 bar air	1.2 bar air	0.9 bar oxy	0.6 bar oxy	0.3 bar oxy	Total decomp. time *	Period under pressure
20	10	-	-	-	-	5	15	35
25	9	-	-	-	5	5	19	44
30	8	-	-	5	5	5	23	53
45	8	-	-	10	10	10	43	88
60	7	-	3	15	15	20	65	125
90	6	3	15	25	30	30	124	214

* Total decompression time includes the air breaks between oxygen sessions

The last line is the emergency decompression to be used only if work duration accidentally exceeds the time above.

A formal structure for data collection and analysis is under consideration and effective validation will take place in the next years (Sterk and Hamilton, 1991).

7 Conclusions

Oxygen decompression in tunnelling is an efficient manner to improve the quality of decompressions; according to the French tables it reduces decompression times to about 55%. It requires the enforcement of hygiene precautions in the use of the masks and of stringent safety rules to control the fire risks. It is probably the only safe and practical means for decompressing from working at pressures above 2.5 bar.

No compressed air work is now permitted in France without formal training of personnel.

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40 Procedures for safe working at high pressures in a TBM chamber using special breathing gas mixtures

G. Luther, R.W. Hamilton*, M. Heineke, G.A. Nietsch** and J. Vollbrandt
GKSS Forschungszentrum, Geesthacht, Germany
**Hamilton Research Ltd., Tarrytown, USA*
***Dyckerhoff & Widmann AG, Hamburg, Germany*

Abstract
Strait crossing by means of a tunnel boring machine is becoming more frequent and will continue in the future. The normally automatic tunnelling progress needs occasional human intervention in the pressure-exposed part of the shield even at pressures beyond those considered acceptable for breathing air. It is important to establish that with due attention to the physiological and human exposure requirements, this work can be done safely, and it may be less expensive than doing it by other methods. The need is likely to be for short (<2 h) interventions by specialists, but could involve multiple shifts of an entire team. In addition to the usual considerations of working with a tunnel boring machine, the high-pressure work situation involves many other factors like selection and management of breathing gases and breathing equipment, later re-use of pressure chambers, effects of gases on human performance, selection of decompression patterns, fire and oxygen safety, mobilisation time and integration with normal work shifts and training at several levels. Many of the risk factors and redundancies necessary for diving are not applicable here. Decompression procedures are better if designed for the operational situation, not the reverse. Partial saturation profiles not commonly used in diving for economic reasons may work well in the tunnel situation.
Keywords: Tunnel work, Partial saturation, Decompression computation, Heliox, Nitrox, Storebælt-tunnel.

1 Introduction

The Storebælt tunnel will be part of the fixed link between the islands of Funen and Zealand in Denmark. It consists of two tubes with a length of about 8 km each and its deepest point is approx. 80 m below sea level. Only little experience is available about tunnelling beneath straits with comparable depths and water pressures. Although there have been reasons for the management of the tunnelling works to expect largely impervious underground conditions one has to be prepared to encounter water-bearing layers at full pressure corresponding to the depths below sea

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