Review article

Compressed breathing air – the potential for evil from within

Ian L Millar and Peter G Mouldey

Key words
Air, compressors, carbon monoxide, toxins, exogenous poison, clinical toxicology, standards

Abstract

(Millar IL, Mouldey PG. Compressed breathing air – the potential for evil from within. *Diving and Hyperbaric Medicine*. 2008; 38: 145-51.)
Human underwater activities rely on an adequate supply of breathable compressed gas, usually air, free from contaminants that could cause incapacitation underwater or post-dive or longer-term health effects. Potentially fatal but well-known hazards are hypoxia secondary to steel cylinder corrosion and carbon monoxide (CO) poisoning due to contaminated intake air. Another phenomenon may be behind some previously unexplained episodes of underwater incapacitation and perhaps death: low-level CO poisoning and/or the effects of gaseous contaminants generated within the compressor, including toluene and other volatile compounds. Many low molecular weight volatile contaminants are anaesthetic and will be potentiated by pressure and nitrogen narcosis. In sub-anaesthetic doses, impaired judgement, lowered seizure threshold and sensitisation of the heart to arrhythmias may occur. Toxic compounds can be volatilised from some compressor oils, especially mineral oils, in overheated compressors, or be created *de novo* under certain combinations of temperature, humidity and pressure, perhaps catalysed by metal traces from compressor wear and tear. Most volatiles can be removed by activated carbon filtration but many filters are undersized and may overload in hot, moist conditions and with short dwell times. A compressor that passes normal testing could contaminate one or more cylinders after heating up and then return to producing clean air as the filters dry and the systems cool. The scope of this problem is very unclear as air quality is tested infrequently and often inadequately, even after fatalities. More research is needed as well as better education regarding the safe operation and limitations of high-pressure breathing air compressors.

Introduction

Contamination of a diver's breathing air makes diving unpleasant at the very least and, in the worst cases, can prove fatal. In between these extremes, contamination may cause impairment of judgement and consciousness predisposing to accidents underwater, it can trigger cardiac arrhythmias or lower seizure threshold and may cause headache or respiratory compromise. Some long-term health effects of inhaled contaminants are also possible, but will not be addressed in this paper.

The diving environment carries special risks with respect to the use of compressed air breathing apparatus, as the increased pressure associated with depth results in a proportional increase in the partial pressure of gaseous contaminants breathed for any given volumetric level of contamination. Air that is acceptable at the surface may thus become toxic as the diver descends. To assist in preventing air-contamination deaths and critical incidents, as well as avoiding long-term health effects, various authorities publish divers' air quality standards which specify the maximum levels of various contaminants. These are generally set at a more stringent level than used for compressed air breathed at normobaric pressure.

The risk of compressor-intake air being contaminated is generally well understood, although installations are still periodically noted where intakes are capable of entraining engine exhaust or volatile contaminants such as paint and solvent vapours. What appears less well known, however, is the potential for generation of such contaminants from within the compression process and the limitations and failure modes of commonly used filtration systems. This paper aims to summarise some of these issues in the hope that readers will play a part in minimising future risks for divers.

A chance meeting between the two authors led us to conclude that there was a widespread lack of knowledge regarding the potential for compressed air to be contaminated and that it is very likely that some, and possibly many, compressed air contamination-related deaths have been unrecognised and unreported. We have, therefore, drawn upon our experience and a wide range of reference sources to prepare this overview document for readers of *Diving and Hyperbaric Medicine*. This is not a formal literature review, but a summary of issues and a set of personal recommendations that we hope will stimulate further research and discussion, and help with the ongoing refinement of standards, procedures and training aimed at minimising risk for divers and others, such as fire fighters, who rely upon compressed breathing air.

Table 1
Comparison of standards for compressed air for divers (CO_2 – carbon dioxide; CO – carbon monoxide)

Jurisdiction	Applicable Standard	CO_2 (ppm)	CO (ppm)	Oil mist (mg.m^{-3})	Volatile hydrocarbons (ppm[1])	Halogenated hydrocarbons (ppm)	Moisture content (mg.m^{-3})
Australia & NZ	AS/NSZ2299.1-2007	480	10	0.5	NS	NS	50
Canada	CSA 275.2-2004	500	5	1.0 [2]	5 [3]	5	21
USA	CGA G-7.1-2004	1000	10	5.0	25	NS	NS[4]
Europe	EN 12021-1999	500	15	0.5	NS	NS	25
UK	EN 12021 + HSE DVIS9	500	3	0.5	NS	NS	25

NS = not specified [1]methane equivalents [2]oil mist and particulates [3] volatile non-methane hydrocarbons
[4] CGA G-7.1 Grade E air

Oil mists, water vapour and particulates

The principal contaminants of concern are carbon monoxide and volatile hydrocarbons. With respect to oil mist and droplets, the lubricants used in breathing air compressors are generally chosen for their biological inertness and it has usually been assumed that small amounts of aerosolised liquid should be well tolerated. Data specifically addressing compressor oils are limited, so some caution remains appropriate. Water vapour itself is desirable with respect to the diver's airways but must be limited to avoid regulator freezing for cold-water divers and to reduce corrosion in steel cylinders. Dry air also inhibits the growth of bacteria in compressed air systems. More importantly with respect to this discussion, moisture substantially degrades adsorption filter function and is an indicator of systems at risk of supplying contaminated air. The degree of dryness required depends significantly upon pressure and compressed air standards and guidelines usually take account of this. To date it has generally been considered that particulates are well captured by filtration but this may not be so: pollens have been reported to have contaminated scuba cylinders, triggering dyspnoea in an individual with borderline airway hyper-responsiveness.[1] It can be speculated that micro-particles might have other health effects and might even act as catalysts for chemical transformation of oils and other contaminants within the compressor system but little information seems available on this subject at this time.

Air quality standards

There are some major differences between jurisdictions with respect to the testing methodology required and acceptable contaminant levels for compressed breathing air. The most dramatic difference is that both Canada and the United States set standards for volatile hydrocarbons and require air samples to be tested by a laboratory whilst the UK, most of Europe, Australia and New Zealand allow field testing with colorimetric tubes and do not specifically call for volatile contaminant testing, instead setting only general requirements for divers' air to be free from toxic contaminants (Table 1).

There are also requirements for there to be "no odour" or "no objectionable odour". The lack of a specific volatile hydrocarbon test requirement in Europe and Australasia means that, although subjective, odour detection is extremely important as at very low concentrations these substances will not be detected by testing with oil detector tubes but will generally have a detectable smell.

Carbon monoxide (CO)

CO is a colourless, odourless product of combustion which reversibly binds haemoglobin, inhibiting oxygen transport and resulting in a chemically induced hypoxia. Excess CO interacts with various intracellular energy-chain enzymes causing oxidative stress and direct cellular toxicity. CO is also a feature of normal biology, being generated from haem by the action of haem oxygenase. Endogenous CO acts as a neurotransmitter and appears to have anti-oxidant and cytoprotective qualities that are only now being elucidated. Some of the toxic effects of CO poisoning probably result from disruption of this normal CO biology but at low levels exogenous CO may not be as detrimental as previously thought, provided the person is at rest and at the surface. Clinical trials have been commenced using CO as a therapeutic gas to modulate processes such as ischaemia-reperfusion injury. Interestingly, the doses used have been as high as 500 ppm, 10 times higher than commonly set as the occupational health and safety limit for ambient air.[2,3] These trials have triggered criticism as such levels have been demonstrated to carry significant risk in patients with cardiovascular or respiratory disease.[4] Even relatively low levels of CO inhalation therefore remain undesirable for older or unfit divers as uptake will increase with depth and exertion, bringing with it an increased risk of cardiac ischaemia and/or arrhythmia. Also critical to the case for avoiding low-level CO inhalation is the significant reduction in exercise tolerance that results.[5]

Volatile hydrocarbons

Volatile hydrocarbons are those lower molecular weight hydrocarbons that exist in the gaseous form at temperatures associated with diving. These should be differentiated from the higher molecular weight hydrocarbons and fluorocarbons that are used as lubricants in compressors and to lubricate seals and breathing equipment components.

One of the most common groups of volatile hydrocarbons of concern is the so-called BTEX group: benzene, toluene, ethylbenzene and xylene. These are most commonly found in petroleum fuels and as solvents in paints, paint thinners, inks, degreasers and cleaning fluids. Unlike oil mists and droplets, which do not generally pass beyond the lungs, volatile hydrocarbons are in gaseous form at body temperature and are readily absorbed and widely distributed in the body, including the brain, in the same manner and with similar pharmacokinetics to volatile anaesthetic agents. They also act as anaesthetic agents; albeit with a less than ideal side-effect profile. They often cause initial excitation and increased cardiac irritability, predisposing to arrhythmias and sudden cardiac death, in addition to the high risk of death if divers achieve anaesthetic levels resulting in loss of consciousness underwater. At intermediate levels, cognitive impairment may increase the risk of lack of buoyancy control or other errors that may lead to injury or death. Some agents appear to lower seizure threshold.[6]

Although all volatile hydrocarbons can cause such problems, one of the most discussed reports of diving air contamination involved toluene.[7] This readily vaporised liquid is most commonly encountered as a major component of automotive petrol but is also used as a cleaning solvent, in paints and in glues including some dive suit repair glues. The lethal concentration for human toluene exposure has been estimated at 1,800–2,000 ppm for one hour but for a scuba diver underwater the threshold for impairment is probably more important.[8] The American Industrial Hygiene Association's ERPG-2 limits estimate the airborne concentration limits at which individuals are still capable of taking protective action. For toluene, this is 300 ppm and the US Occupational Health and Safety Authority sets a 'Permissible Exposure Limit' of 200 ppm.[9]

For divers' air, the British version of EN 12021 recommends that contaminant levels should be below 10% of the eight-hour time-weighted average (TWA) allowed for surface workplaces.[10] Using this principle would suggest the danger limit for toluene in divers' air may be around 20–30 ppm and the recommended limit may be as low as 2–5 ppm; from 10 per cent of the TWA up to 10 per cent of the "no observed adverse effects level" which appears to be around 50 ppm.[11] It is likely that any compressor-generated contamination would contain a mix of toxic substances and their effects are almost certainly additive, if not synergistic. In addition to this, nitrogen will further potentiate the consciousness-impairing effects. This provides a good basis for the conservative limits for volatile hydrocarbons as adopted in the United States and even more stringently in Canada.

Other volatile solvents

In addition to the BTEX group, many other agents used as industrial cleaning fluids are highly volatile and very narcotic if inhaled. Examples are acetone and chlorinated solvents such as trichloroethylene. If these are not adequately removed from compressor systems they can show up in compressed air.

Production of CO and volatile hydrocarbons inside compressors

In oil-lubricated compressors, small quantities of oil entering the compression chambers can undergo oxidative and/or thermal breakdown given the presence of oxygen (within the air being compressed) and/or sufficient heat. Some hydrocarbon breakdown pathways may also require water vapour and catalysts, which can be provided by intake air humidity and traces of metals from the wearing of compressor components respectively. This problem is most common in high-pressure (HP) compressors used for filling scuba cylinders as these are usually oil-lubricated and higher heat production is a necessary by-product of high pressure compression. HP compressors are usually three- or four-stage, air-cooled machines with inter-coolers between compression stages. Overheating is a relatively common problem, however, particularly in hot climates and when small compressors designed for filling individual cylinders are used continuously, for instance in low-budget commercial or club diving installations. HP compressors should be fitted with over-temperature alarms with automatic shut-down mechanisms but this is not always the case.

It has been hypothesised that the particular toxic oil breakdown products produced from any one oil type and compressor combination may depend upon a critical temperature range. Partial pressure of oxygen (determined by air pressure), water content and trace-metal catalyst type may also be important. An overheated or poorly maintained compressor can thus be considered analogous to an oil refinery catalytic cracking tower, which breaks down higher molecular weight hydrocarbons into smaller molecules, including acidic gases and other toxic compounds. This concept allows for a phenomenon of major concern: a compressor that produces clean air when cool may produce dangerous contamination of one or more cylinders as it heats up under load. Where cylinders are individually filled this could produce seemingly random contamination that would escape detection by routine air quality testing of the compressor with air samples taken shortly after a cold start. Where the compressor fills a large capacity air bank, any short period of contaminant production may be of less concern, as the contaminated air will be diluted in the bank with all fills from the bank receiving low levels of contamination rather than one or two cylinders being filled to a level associated with the potential for underwater toxicity.

The oil-type debate

Much is made of the advantages of one oil type over another for breathing-air compressors. Most HP compressor oils are of mineral or synthetic origin as these are generally more stable at higher temperatures. Some are classified as 'food grade'. Suitability for ingestion does not, however, imply that any particular oil is less harmful for inhalation. Oil droplet and mist contamination of breathing air is universally limited by standards and, in practice, any non-volatile oil mist inhalation that occurs seems to be relatively well tolerated. The widely used United States ACGIH limits for mineral oil contamination of ambient breathing air in a work place allow time-weighted averages of 5 $mg.m^{-3}$ for an eight-hour working day. These sorts of levels are most commonly encountered in machine shop workers operating equipment such as lathes and metal milling machines, where the cutters and the item being drilled or shaped are cooled and lubricated by a spray of 'cutting oil'.

Whilst contamination of breathing air by mists of lubricant oil is not unknown in the setting of on-line, low-pressure, surface-supply diving compressors, the major concern for HP compressors is the stability of lubricants at high pressures and temperatures and avoidance of breakdown into volatile toxic by-products. It may be that newer synthetic oils with increased anti-oxidant and thermal resistance properties are the least likely to be broken down into lower molecular weight gases. However, it remains difficult to compare manufacturers' product claims, given the non-standardized testing regimens employed. Unfortunately there is limited reporting of the actual composition of oils as this is generally considered proprietary information. Currently, the best available guidance is to review both the oil suppliers' and the compressor manufacturers' guidelines when selecting the oil for a breathing-air compressor installation.

Filtration

Compressor first-stage intakes should be protected by dust filters. Inlet-air carbon dioxide (CO_2) absorption is also sometimes employed, especially in urban or industrial settings where elevated CO_2 levels may be such as to represent a risk when breathed at up to six times atmospheric pressure. (CO_2 is not removed by standard post-compression filter systems).

Considerable quantities of oil/water mist are produced during post-compression cooling of compressed air and HP compressors typically employ oil-water separators immediately after some or all of the three or four compression stages. The oil-water condensate that is drained carries with it some of the contaminant load but the higher the intake air humidity, the more water will need to be removed and this is critical, as water logging of downstream adsorbents such as activated charcoal (AC) severely degrades their function. Some more elaborate HP installations include refrigerated dryer/separators after the final compression, providing improved protection against water overloading of the final filters.

After it is compressed, air requires filtration before it will be suitable for breathing. Filtration can be relatively minimal for low-pressure compression of clean air using 'oil-free' compressors but for high-pressure compressors, systems are needed that will eliminate not only particles but also the oil mists, residual water vapour and any hydrocarbon contamination or carbon monoxide produced by the compression process. This requires a number of different components and these may be contained in separate filter elements or combined into combination cartridges.

In addition to particle filtration, filter systems usually incorporate a desiccant bed to remove residual moisture. An AC bed then removes volatile hydrocarbons plus odour. AC beds are capable of adsorbing most low molecular weight hydrocarbons and their performance is, therefore, critical in the prevention of contamination of breathing air. AC beds have a number of critical performance factors and failure modes, however. Their performance degrades over their normal service life, but degradation increases dramatically with excessive adsorption of hydrocarbons, with elevated temperature or if desiccant failure allows moisture through to the AC bed.

AC does not absorb CO and, therefore, better filter systems incorporate a catalytic element such as a manganese/copper oxide combination (Hopcalite), which oxidises CO to CO_2 with the small amounts of additional CO_2 generated usually not presenting a problem for the diver. As with AC, most catalytic beds function best with very low moisture contents and some are extremely moisture sensitive.

The need for dry AC and catalyst means that the overall filter-system processing capacity is often limited by the type and volume of desiccant in the cartridge, and another feature of better quality filter systems is, therefore, larger capacity desiccant and AC beds to provide some redundancy. Probably the most critical factor affecting filter performance, however, is the temperature of the air entering the desiccant and AC elements. As the temperature of breathing air increases, most often due to a poorly installed compressor or high ambient temperatures, the processing life of the cartridge must be corrected downwards. As an example, one major manufacturer suggests limiting filter life to 20 per cent of normal if the filter is exposed to an air stream temperature of 50°C rather than the 'normal' 20°C.

A final critical performance element is the pressure of the air passing through the filters. Filters perform optimally if air passes through them relatively slowly, allowing adequate 'dwell time' for contaminants to be trapped, absorbed into media such as desiccant or adsorbed onto media such as activated carbon. If the pressure within the filter system is low, any given atmospheric volume will pass more rapidly, reducing dwell time. In a worst-case scenario, the high initial air velocity can also physically damage filters, releasing particles to contaminate the downstream system. Such problems can be avoided by installing a pressure-maintaining valve downstream of the filters. This will minimise the risk of contaminant breakthrough at the start of filling an empty cylinder or receiver.

Regrettably, it would appear that many compressors are purchased with a standard combination filter unit that does not include CO catalyst and which is not sized for operation at high ambient air temperature or in some cases even for the compressor's free air delivery at the start of compression when pressures are low and flows highest. Any filter that is relatively undersized will carry a high risk of allowing volatile hydrocarbon 'breakthrough', especially in the latter part of its nominal life and if used in hot and humid conditions.

The limitations of current air quality testing

Most HP compressor air testing is undertaken by periodically sending samples for analysis by a laboratory, or sampling on site by passing air through proprietary colour-change detector tubes. The maximum intervals allowable between tests generally range from three to six months. Such intermittent testing is an inherently weak system, as test samples can be taken when the compressor is first started or after installation of new filter elements, providing no certainty that the air will be clean once the compressor is hot or the filters are nearing their end of service.

To date, screening for low levels of volatile hydrocarbons has required laboratory testing, using either gas chromatography with flame ionisation detection (GC/FID) or infrared spectroscopy (IR) techniques. There is no colour-change detector tube available that is sensitive or has a sufficiently broadspectrum to detect the large number of potential volatile hydrocarbons found in compressed breathing air. In both Canada and the USA air must be tested for volatile hydrocarbons by laboratories which use GC/FID or IR techniques.

Continuous, on-line hydrocarbon monitoring would be ideal and suitable analysers have been available for some time, but these are expensive and rarely used. Recently, portable volatile hydrocarbon IR analysers have become available to the diving industry, initially to address the problem of commercial divers being affected by contamination of the diving bell with volatile hydrocarbons from pipeline or oil-well sources.[12] Some compressors are fitted with moisture detectors to alert users to desiccant exhaustion and this seems a useful feature that is available now. Continuous CO detection technology is readily available but surprisingly rarely used. Low cost CO monitors are now becoming widely available and inexpensive electronic-chip-based gas detectors of many types are expected to dramatically increase monitoring possibilities over the next few years.

What is the evidence this is a real problem?

Although deaths continue to occur as a result of compressor-intake contamination, there is relatively little concrete evidence of a widespread problem related to compressor production of either CO or volatile hydrocarbons. There is some, however, and it is of particular concern that we could be missing a wider problem. In one cave-diving incident in Florida, a near miss occurred due to toluene contamination, with the diver initially becoming disoriented and swimming in an agitated fashion before becoming lethargic, requiring rescue. Another interesting case involved a breathing-air compressor installation at a Canadian Fire Department station, which produced CO on several occasions. The contamination disappeared after a full overhaul and filter change only to recur shortly afterwards and appears most likely to have been due to a poor installation location which allowed recirculation of hot exhaust air and resulted in compressor overheating with consequent oil breakdown contaminating the breathing air.[13]

A substantial deficiency in our knowledge arises from the fact that many fatalities do not have their air tested using techniques that would detect low levels of CO or volatile hydrocarbons. Levels that do not cause loss of consciousness may still be important if they have pre-disposed the diver to cardiac arrhythmia or underwater impairment of judgement leading to fatal error. In the 1995–2000 DAN fatality data, 145 fatalities were recorded as a result of drowning or near-drowning with the initial injury or problem "unknown".[14] It seems reasonable to speculate that gas contamination may have contributed to some of these deaths. A DAN review of 451 fatalities over a five-year period suggests that only 15 per cent of the divers had a carboxyhaemoglobin (COHb) measurement taken at the time of death. Three per cent of those sampled had a fatal concentration of COHb at the time of measurement.[15]

In 2006, the UK Health and Safety Executive reported on an examination of diving equipment implicated in 54 accidents and incidents of all types. Whilst only five involved a suspected 'bad fill', 41 of the 54 air samples tested failed the moisture content standard.[16] The Swedish Consumer Agency sampled air from nine dive suppliers in 1996, finding one case of oil contamination. In 2007, five of 20 failed, two due to excess CO_2 and three due to moisture.[17] In parts of the USA where laboratory analysis of air is required rather than simple detector tube sampling, rates of failure to meet acceptable CO levels have been as high as 3 per cent in recreational dive air (10 ppm limit), and the US Navy has encountered similar problems at a frequency of 2.5 per cent using an CO specification of 20 ppm.[18,19]

Whilst this does not confirm there is a specific problem with volatile hydrocarbon contamination produced within compressors, it does suggest there is probably a systematic deficiency in the quality and performance of compressor installations.

Nitrox compression

With the rapid increase in the recreational use of nitrox, there are many instances of conventional HP air compressors being used with oxygen-enrichment systems feeding the intake in order to provide nitrox scuba cylinder fills. Although special nitrox compression systems are available commercially, make-shift arrangements are of concern with respect to the risk of fire as well as contamination of breathing air. The increased oxygen concentration passing through nitrox compressors degrades the compressor oil much more rapidly than would happen normally, which may generate toxic by-products, shorten the compressor and filter life, and increase the risk of contamination of breathing air. High-quality synthetic oils should, in theory, be less susceptible to thermal and oxidative degradation than mineral oils. Even so, evolving recommendations suggest oil changes may be needed after only 25 per cent of the time usually allowed.

Discussion

Whilst it remains unclear to what extent there may be a problem with contamination of breathing air generated by compressors, it is clear that air quality is an important issue that has been inadequately addressed. In order to better discern the extent of this potential problem and to reduce risk, we offer the following recommendations:

- All accident investigations should include laboratory testing of air by a specialist air-quality laboratory. The diver's blood should also be sampled for COHb and the time interval recorded from cessation of potential CO exposure to blood sampling with a record of whether the diver was breathing air or oxygen.
- Existing requirements for divers' breathing air to have very low levels of CO (generally < 10 ppm) remain appropriate and it may be that even lower limits would be wise to minimise risk for older and less fit individuals. Certainly all measures necessary should be taken to avoid the risk of substantially higher amounts entering breathing-gas supplies.
- Standards authorities should consider mandating maximum levels of volatile hydrocarbon contaminants and, where this does not presently exist, should also consider requirements for third-party testing or other means of quality control.
- Micro-particulates should also be considered further.

With respect to compressor installations, we suggest the following:

- Manufacturer's installation, use, oil type and maintenance recommendations should be strictly adhered to and all maintenance should be logged.
- Compressors designed for periodic filling of small numbers of cylinders should not be used for continuous service installations.
- Even basic HP compressor systems should have high temperature alarms with automatic compressor shutdown plus real-time moisture and CO monitoring.
- Installations should be in well-ventilated locations with intakes that guarantee uncontaminated air.
- If there is choice of size, filter systems should be larger rather than smaller and should be changed at intervals corrected for high ambient operating temperatures using the filter manufacturer's correction factors.
- Air purifier systems should incorporate a catalyst system to convert any entrained or internally produced CO to less dangerous CO_2.
- Air test samples should be taken with the compressor well warmed up so it is running at full temperature. Whilst testing after installing new filters will validate that the filter has been installed correctly and is not faulty, there is a case for also testing towards the end of nominal filter life so as to obtain measurements of air quality indicative of 'worst-case' scenarios.

For divers, we would suggest asking questions, looking for certificates of compliance with appropriate standards or codes of practice and investigating standards of air-quality control at destinations before travel. Particular caution should be applied for hot, humid locations, especially if compressors are installed near walls, in small rooms or if run in the heat of the day rather than at cooler times.

The most accessible and remarkably sensitive analytic method for hydrocarbons is to get into the habit of smelling cylinder air well before a dive. If the diver does not have a clear nose and intact sense of smell they should ask someone else to perform this service. Many contaminants have a significant "oily", "rubbery" or "solvent" type smell. A "musty" smell may indicate excessive moisture is present. Being odourless, CO will not be detected by smell, but CO analysers have become significantly cheaper and could well be used alongside the oxygen analysers that have become routine for nitrox divers.

If CO or unusual odour is noted, abort the dive.

Finally, it would be useful if the industry, consumer agencies and researchers were to conduct regular surveys of air quality to provide a clearer picture of how often low-level contamination is occurring.

Sources and acknowledgements

The authors have attempted to summarise information which has been gained from a variety of overlapping sources and would be difficult to individually reference. These include manufacturers' representatives, equipment suppliers, technical manuals, accident reports, various Standards and Codes of Practice, internet sources and personal experience in diving and hyperbaric medicine. We acknowledge gratefully the many who have helped inform and educate us, especially those analytical laboratory managers who have shared their insights, and, of course, the fire fighters and divers who have shared their experiences of breathing compressed air.

References

1 Astarita C, Gargno D, Di Martino P. Pollen trapped in scuba tank: a potential hazard for allergic divers (letter). *Ann Int Med*.2000; 132: 166-7.

2 Mayr FB, Spiel A, Leitner J, Marsik C, Germann P, et al. Effects of carbon monoxide inhalation during experimental endotoxemia in humans. *Am J Resp Crit Care Med*. 2005; 171: 354-360.

3 Hill-Kapturczak N, Agarwal A. Carbon monoxide: from silent killer to potential remedy. *Am J Physiol Renal Physiol*. 2006; 290: 787-8.

4 Thom SR, Weaver LK, Hampson NB. "Therapeutic" carbon monoxide may be toxic. *Am J Respir Crit Care Med*. 2005; 171: 1318.

5 Horvath SM et al. Maximal aerobic capacity at different levels of carboxyhemoglobin. *J Appl Physiol*. 1975; 38: 300-3.

6 Fang Z, Sonner J, Laster M, et al. Anesthetic and convulsant properties of aromatic compounds and cycloalkanes: implications for mechanisms of narcosis. *Anesth Analg*. 1996; 83: 1097-104.

7 Mouldey P. Toluene gas contamination incident [Internet]; 2004 Dec 5. Available from: <http://www.thedecostop.com/forums/forumdisplay.php?f=44/>

8 Hobara T, Okuda M, Gotoh M, Oki K, Segawa H, Kunitsugu I. Estimation of the lethal toluene concentration from the accidental death of painting workers. *Industrial Health*. 2000; 38: 228-31.

9 Department of Health and Human Services (US). *Toluene medical management guideline*. Agency for Toxic Substances and Disease Registry, Department of Health and Human Services (US). Available from: <http://www.atsdr.cdc.gov>

10 Health and Safety Executive (UK). *Divers breathing air standard and frequency of tests*. Health and Safety Executive, Diving Information Sheet No.9; 2006. Available from: <http://www.hse.gov.uk/pubns/dvis9.pdf>

11 Department of Health and Human Services (US). *Toxicological profile for toluene*. Section 2.2.1.4. Neurological effects. Washington DC: Agency for Toxic Substances and Disease Registry, Department of Health and Human Services; 2000. [cited 21 August 2008]. Available from: <http://www.atsdr.cdc.org/toxprofiles/tp56.html>

12 Flook V. Development of the Analox Hyper-Gas Diving Bell Monitor, *HSE Research Report 030*. 2003. Available from: <http://www.hse.gov.uk/research/rrhtm/rr030.htm>

13 Austin C, Ecobichon D, Dussault G, Tirado C. Carbon monoxide and water vapour contamination of compressed breathing air for firefighters and divers. *J Toxicol Environ Health*. 1997: 52: 403-23.

14 Pollock NW (Ed). *Annual Diving Report 2007 Edition*. Durham, NC: Divers Alert Network; 2007.

15 Caruso J, Hobgood J, Uguccioni, D, Dovenbarger J. Carbon monoxide poisoning in recreational diving: an uncommon but potentially fatal problem. *Undersea Hyperb Med*. 1998; 25(Suppl): S52.

16 Bailey N, Bolsver J, Parker C, Hughes A. *Performance of diving equipment*. Norwich: HSE Books; 2006.

17 Swedish Consumer Agency. *Market surveillance of diving air services for recreational diving: Report N*. 2007:162007. Karlstad: Swedish Consumer Agency. Available from: <www.konsumentverket.se>

18 Rossier, R. How good is your gas? [Internet] *DAN Alert Diver*. 2004 June:16-18. Available from: <http://www.co-cop.com/danarticle.htm>

19 Lillo R, Caldwell J. On-Line Air Quality Monitors for Diving Compressors. *Undersea Hyperb Med*. 1995; ????.

Submitted: 04 June 2008
Accepted: 26 July 2008

Ian L Millar, MB,BS, FAFOM, DipDHM, is the Unit Director, Hyperbaric Medicine, The Alfred, Melbourne
Peter G Mouldey, MD, DipTMH(Lond) works at Southdown Medical Centre, Mississauga, Canada.
Address for correspondence:
Ian Millar
The Alfred Hospital
PO Box 315, Melbourne
VIC 3004, Australia
Phone: *+61-(0)3-9076-2269*
Fax: *+61-(0)3-9076-3052*
E-mail: *<i.millar@alfred.org.au>*

This paper is based on a presentation by Dr Millar at the 2007 SPUMS ASM, New Zealand.

A missing diver

A 35-year-old male, with 20 years diving experience and no relevant medical history, undertook a solo crayfish dive. He told the boatman that he would be 15 minutes, but failed to surface. A search by police divers found him the following day at a depth of 9 metres' sea water. The autopsy was limited due to decomposition of the body from sea lice. The police investigation suggested that he was diving over-weighted with 17.5 kg on the weight belt which was not released. All his equipment was intact and working correctly and the cylinder pressure was 194 bar so he died very early in the dive.

Analysis of the cylinder contents revealed an extremely high carbon monoxide level, 13,600 +/- 300 ppm (NZ standard < 10 ppm), as well as increased levels of carbon dioxide and methane. A second cylinder owned by the diver returned similar analysis. Both cylinders were filled at the same time at the same dive shop.

The coroner's finding was that "*death* [was] *due to asphyxia due to his cylinder gas being contaminated with carbon monoxide, brought about by an idiosyncratic malfunction of the air compressing equipment*". There was no evidence of any other cylinders filled on that day reported as contaminated, so this was an isolated finding, the cause of which was unknown.

This case is from the New Zealand diving fatality data.