

A technical diving-related burns case: treatment in a remote location

Fiona C Sharp¹, Martin DJ Sayer²

¹ *Fiona Stanley Hospital, Murdoch, Western Australia*

² *West Scotland Centre for Diving and Hyperbaric Medicine, Scottish Association for Marine Science, Dunbeg, Oban, Argyll, Scotland*

Corresponding author: Fiona C Sharp, Fiona Stanley Hospital, 11 Robin Warren Dr, Murdoch, WA 6150, Australia
sharpief@doctors.org.uk

Abstract

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Injuries suffered as a result of a rebreather oxygen explosion and fire occurred to a diver on vacation in the island state of Chuuk, Micronesia. The medical and logistical management of the diver in a remote location are described. The mechanism of both the fire and the subsequent blast and burn injuries are discussed. Prevention of and preparation for such incidents are discussed in the context of the increasing frequency of dive and adventure travel to remote areas.

Key words

Burns; Fire or explosion; First aid; Medical kits; Rebreathers/closed circuit; Remote locations; Case reports

Introduction

Chuuk (or Truk) Lagoon, is part of the Chuuk State of Micronesia in the Western Pacific. It is a popular destination for wreck diving with many Japanese World War II shipwrecks lying in tropical waters.¹ The depth of some of the wrecks in the lagoon attracts technical and rebreather divers to Chuuk. Recreational technical diving methods and related decompression issues have been reviewed recently.^{2,3} Chuuk is considered a remote diving location as medical facilities in the islands are limited and the commercial airline link *via* the island of Guam, which occurs once every one to two days, is frequently subject to cancellations and delays.

In 2013, a group of rebreather, technical and open-water scuba divers visited Chuuk to dive the wrecks. With organizational support from a diving travel company, the local dive operation provides helium, nitrox and oxygen to support rebreather, trimix and enriched air decompression diving. Compressed gases with oxygen percentages (PO₂) ranging up to 95% require special handling and precautions to prevent oxygen fires through frictional or adiabatic heating.⁴ This case report describes the management of a critical incident caused by the explosion of a cylinder of oxygen-rich gas and the attached rebreather fire. Management is discussed within the context of a remote location.

Case report

An experienced, 37-year-old male diver suffered a serious injury on the fifth dive day of the trip. The incident occurred on the dive boat prior to leaving the dock. Three rebreather divers had placed their equipment on a small, motorized

diving boat (see cover) after setting up and checking them on land, where the divers had also performed their pre-breathe routines.⁵ On completion of their preparations, the divers had turned off the cylinders to wait for departure.

With the rebreather on the floor of the boat, the diver leant over and turned on the diluent and oxygen cylinders; the oxygen cylinder had a water capacity of 3 litres (L) and was assumed to have been pressurized to approximately 200 bar. The oxygen first stage regulator exploded, causing a blast injury to the diver's hand (Figure 1) and the top of the rebreather caught fire (Figure 2). The subsequent fire burnt the diver significantly on the left upper arm (Figure 3), shoulder and neck; his lower arm and face were also partially affected. The diver promptly and voluntarily fell over the side of the small boat into the 1.5 m deep water to cool the burn. The rebreather burnt itself out, with no-one else injured, and minimal damage to the boat. The diver was removed from the water after approximately five minutes, and cooling of the burns continued under an outdoor shower. He was visibly shaken with a rapid, weak pulse of approximately 120 beats per minutes (bpm); blood pressure was not monitored at that time.

The travel company responsible for this diving group has a policy of employing a physician trained in diving medicine to accompany technical and deep diving expeditions. In the present case, the group doctor was a specialist anaesthetist (FCS) who was on-site when the explosion occurred and so was in immediate attendance. The diver was placed on a chair under the shower as he was getting syncope. He had severe pain from the burn on his arm. After removal of a short sleeve rash-guard, a full thickness burn was evident distal to the sleeve (Figure 3), with a partial thickness burn

Figure 1

Blast injuries to the diver's hand



surrounding this area. There was no evidence for or any symptoms of an airway burn or other signs of blast injury. His eardrums were not examined.

Cooling with freshwater continued in the diver's hotel room. IV cannulation was achieved with some difficulty, and analgesia and sedation were administered (morphine 15 mg IV, midazolam 10 mg IV total) with good effect. Antibiotics (cephazolin 2 g) and IV fluids (Plasmalyte 2 L total) were commenced after checking for allergies. Wound care was provided with antiseptic cream (Sulphasalazine) and cling-film dressings. The patient's blood pressure was taken for the first time and was 150/110 with a heart rate of 120 bpm. Pain relief was supplemented with oral paracetamol and his pain score remained 6 out of 10 on an analogue scale. With the supply of morphine now exhausted, a supply of oral analgesics was obtained from local sources (paracetamol/codeine 500 mg/30 mg, ibuprofen 200 mg and tramadol 100 mg). With these medications the diver was more comfortable that evening and was able to ambulate and eat.

The patient and buddy arranged for transfer back to Australia for definite care on the next flight available from Chuuk, three days following the injury. The plastic surgical unit at an Australian hospital advised by phone on on-going management of the patient's injuries. The wound was cleaned in the shower prior to dressing with an application of silver sulfadiazine and continued wrap with the cling film.

On day two, the patient awoke with malaise, lethargy and was apathetic. He was dehydrated with marked oedema of

Figure 2

The rebreather after the fire with explosive and thermal damage to the oxygen cylinder (A), the damaged head of the rebreather (B), burnt counter lung (C) and scrubber casing (D)

**Figure 3**

The diver's arm after being cleaned on day 1



the left arm and the wound dressing had an offensive smell. The wound was redressed after cleaning in the shower, and the antibiotic dose was increased. He increased oral fluids whilst keeping his arm elevated; the analgesics were continued with good effect. He had improved sufficiently the next day to be repatriated to Australia under medical escort. On the morning following his arrival to his home city he underwent debridement and skin grafting to the arm wound. He has healed well with minimal scarring.

Discussion

Diving with closed-circuit rebreathers on wrecks in relatively deep water offers numerous advantages. These include the lack of bubbles, their gas efficiency and the optimized decompression that constant PO₂ diving permits.⁶ There are many confounding factors associated with wreck diving but, in general, studies of decompression illness (DCI) indicate incident rates of between 0.25 and 1.12 cases per 1,000 person-dives for wreck diving^{7,8} compared with rates of between 0.05 and 0.10 for other recreational scuba diving.⁹⁻¹² The added risks of using mixed gases are largely unknown, but studies of diving deaths show that using a closed-circuit rebreather possibly carries a four- to ten-fold increase in the risk of dying while diving.¹³ The combined additional risks of diving wrecks using rebreathers, while also in remote locations with limited medical support, are the reasons that many tour groups will employ physicians with practical experience in emergency medicine.

Previous reports of treating diving accidents in remote locations have focussed mainly on DCI from the perspective of managing that illness alone and the potential effects delays in treatment may have on subsequent outcomes.¹⁴⁻¹⁷ Chuuk does have a stand-alone recompression facility but this is only sporadically operational, depending on whether the technical operator is on the island. The lack of many fundamental medical services complicates the treatment of non-DCI diving-related incidents.

Diving rebreather fires are very rare. Of 153 incidents reported during a series of 14,000 rebreather dives undertaken by the French military, none involved explosions or fires.¹⁸ A fire has been reported in a Canadian underwater mine-countermeasure rebreather unit.¹⁹ In that case, the fire occurred as the oxygen cylinder was being opened by the diver while on the surface; the subsequent investigation indicated that the origin of the fire was in the first stage regulator. There has been one case reported of a technical diver, diving at a depth of 90 m, sustaining severe burns when wearing a drysuit along with four air-activated heat packs.²⁰ The burns were caused by the exothermic chemical reaction of the heat packs accelerating out of control because the diver was using his decompression gas, which contained 83% oxygen, for suit inflation.

The risk of an oxygen cylinder fire is low; for example, it has been estimated that there are several million medical

oxygen cylinders in service in the UK annually, that are filled many times each year with very few reported incidents.^{21,22} One UK incident of an oxygen cylinder that exploded in an intensive care unit causing a fatal burn injury was reported in 2013,²¹ with a further three oxygen cylinder fires occurring in the UK during a recent four-year period.²²

It is suggested that the oxygen fire in the intensive care unit was caused when the cylinder valve was turned on;²¹ this was the same in the present case. The internal design of a cylinder valve includes O-rings, valve seats and lubricants, all of which will have an auto-ignition temperature (AIT). Components designed for high-pressure cylinders have AIT values of over 300°C in a 100% oxygen environment.²² Impeding the flow of pure oxygen from high-pressure cylinders causes instantaneous compression and adiabatic heating. If that heating exceeds the AIT of one or more of the valve components then spontaneous ignition can occur; that ignition releases more energy which raises the temperature further igniting other adjacent materials with higher AIT. This is known as a “*kindling chain*” whereby the fire escalates rapidly in the valve causing an explosion.²² Reducing the likelihood of adiabatic heating of oxygen decreases the probability of fires and explosions and is why valves on high content oxygen cylinders should be a ‘needle’ design. However, there is still a need to open needle valves slowly when dealing with high-pressure oxygen.

The present case reports on a cause of morbidity (burns and blast injury) other than DCI when diving on rebreathers and in a remote location. Non-governmental deep-diving groups travelling to remote locations where medical support may be lacking should have available to them sufficient medical supplies, medical expertise and communication options as deemed appropriate by the group’s organisers. There are many published examples of medical kits that should be available to support diving operations or remote expeditions, such as that of the Diving Medical Advisory Committee in the United Kingdom.²³ The contents of the medical kit will be determined by a variety of factors, including the training and skills of personnel involved, medical registration and local drug regulations, the geographical location and its available health service resources, meteorological conditions, whether ship- or shore-based and weight limitations (e.g., for commercial flights).^{17,24} The contents of kits used by the authors in different settings can be obtained by contacting them. What did turn out to be essential in the present case, so that narcotics could be included, was that a letter of recognition that the kit was for use by a qualified medical practitioner was carried along with copies of the doctor’s current Medical Board certificate; one copy accompanied the medical kit while the doctor carried another copy.

In the present case, even though a comprehensive medical kit was carried, there was still a need to seek additional supplies as soon as it became apparent that the treatment would become prolonged. An assessment of what medical support is likely to be available in the location to be visited

should be used to prioritise what is in the medical kit, whilst accepting local legal restrictions. However, treatment should always be started immediately based on what the treating physician or other has to hand. Wider area searches should only be initiated after the patient has been stabilised.

Conclusions

Deep-diving and rebreather divers, along with remote dive expedition organisers should always be cautious of the use of cylinders containing pressurised high concentration oxygen gases. Divers should continue to remember or to be reminded to turn on oxygen cylinders slowly and to avoid contamination of first-stage valves in particular. Some diving-related travel companies employ physicians with specialist knowledge in diving medicine (and preferably with emergency medicine experience) to accompany deep technical-diving orientated expeditions. In planning a medical kit to support such expeditions, it is possible that involved organisers, paramedics and physicians may become overly focused on the potential management of DCI. This is understandable; however, because oxygen fires are known to occur with rebreather systems and other non-DCI problems are by far commoner, the medical kit should reflect this. Remember the adage, “*expect the unexpected*”!

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