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First aid oxygen administration for divers

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Key words
Resuscitation, medical kits, oxygen

Abstract

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Hypoxia in divers can result from a variety of causes, including decompression illness (DCI). The benefits of oxygen first aid in DCI are increased denitrogenation and improved oxygenation, and the sooner oxygen is provided the better the outcome. When oxygen is provided prior to recompression, symptoms may be relieved earlier, and there is a slightly lower chance of post-treatment residua. Despite this, DAN America data indicate that only 30 to 40% of injured divers receive oxygen. This provides an ongoing challenge for the diving community. There is a plethora of oxygen equipment available and careful consideration needs to be given when selecting appropriate equipment to manage a dive accident. Such equipment needs to easily provide high oxygen concentrations to responsive or unresponsive, breathing or non-breathing victims. The wide range of available devices all have advantages and disadvantages that need to be weighed against the required outcome. Important considerations include the oxygen concentrations that can be provided; the ease of use; the amount of training and practice required and the number of operators needed to use the device effectively.

Introduction

Hypoxia causes cells to change to anaerobic metabolism, which may create a shortage of energy for normal cellular function and leads to a metabolic acidosis. The acidosis further impairs cellular function, particularly in the vital organs such as the brain and heart. Body cells cannot survive for long without oxygen. Brain cells are particularly sensitive to oxygen starvation and will die within minutes because of their limited capacity for anaerobic metabolism.

There are many ways that tissue hypoxia may occur. The normal ambient oxygen tension in air is approximately 21 kPa (101 kPa equals 1 bar). Too little oxygen in the gas we breathe will affect the whole body. This will begin to occur when the partial pressure of oxygen (PO_2) falls below about 16 kPa. Many disorders of the cardiorespiratory systems or oxygen extraction by the cells will reduce oxygen availability, resulting in tissue hypoxia. Unconsciousness will occur in most people when the PO_2 falls below about 8–10 kPa, and coma and ultimate death will normally occur if the PO_2 falls below about 8 kPa.

There are several ways that tissue hypoxia can occur in divers. These include water inhalation; pulmonary barotrauma; hypoxic gas mixtures (e.g., incorrect mixing of enriched air nitrox or in rebreathers); and contamination with carbon monoxide. Decompression illness (DCI), where gas bubbles may damage or obstruct blood vessels, may reduce perfusion and local tissue oxygenation. Tissue hypoxia may also occur from disorders not specifically related to diving, such as heart attack or stroke.

In the event of hypoxia, increasing the inspired oxygen may help to increase haemoglobin saturation. Increasing the oxygen concentration will also cause more of it to dissolve in the plasma. When breathing air at 101 kPa there is 3 ml of oxygen dissolved in each 1000 ml of blood plasma. Breathing 100% oxygen at 101 kPa enables 23 ml of oxygen to be dissolved in each 1000 ml of blood. This in itself is insufficient to supply the body's needs. The higher oxygen concentration, by increasing the tension gradient for diffusion will cause the oxygen molecules to diffuse further into the tissues, possibly reaching areas that have a reduced oxygen supply due to impaired circulation. This increases the chances of survival of tissues with a poor blood supply, as well as other impaired tissues.

Rationale for oxygen use in diving accidents

For injured divers, it is important to provide an increased oxygen concentration, probably close to 100%, especially where DCI is suspected. Breathing 100% oxygen provides very important benefits for a diver suffering from DCI:

- By eliminating nitrogen from the inspired gas, 100% oxygen breathing accelerates nitrogen elimination from the body, thus reducing bubble size more quickly.
- Any reduction in blood flow due to bubble formation may cause hypoxia in affected tissues. The higher oxygen partial pressures will help to oxygenate any hypoxic tissues by increasing diffusion of oxygen to those areas. It may also assist in reducing the swelling in hypoxic tissues by drawing fluid away from injured tissue.
- Elevated oxygen concentrations can help compensate for reduced blood oxygen content resulting from

impaired gas transfer from the lungs to the blood, and reduce any breathing distress caused by hypoxia.
- Higher oxygen concentrations may help reduce circulatory shock and cerebral oedema, uncommon but serious complications of DCI.

Although pure oxygen is recommended for the first-aid management of DCI, it is possible that certain helium-oxygen mixtures could sometimes prove advantageous for nitrogen elimination.[1] However, the use of such mixtures would introduce many practical disadvantages, and 100% oxygen currently remains the gas of choice for the first-aid management of DCI.

Prompt provision of high concentrations of inspired oxygen can minimise the damage that may occur while the diver is being transported to a recompression facility, possibly in certain circumstances alleviating the need for further treatment. There have been numerous anecdotal reports of even severe symptoms of DCI disappearing while an injured diver was breathing oxygen.

In DAN America data for 2000, 57% of divers administered oxygen at some stage prior to recompression showed improvement, and 14% had complete relief of their symptoms (Figure 1).[2]

DAN Europe data on dive accidents reported for 1989–2000 indicate that 23% (302/1314) of the divers received oxygen first aid. Forty-eight per cent of the divers who received oxygen showed improvement in symptoms, compared with only 4.3 % of the divers who received no oxygen ($p < 0.001$) (Table 1). In addition, 18.8% of the divers who received oxygen first aid were asymptomatic prior to recompression, compared with 1.5% of those who received no oxygen prior to recompression ($p < 0.01$) (Table 2).[3]

FIGURE 1
RESULT OF ADMINISTRATION OF SURFACE OXYGEN FOR DECOMPRESSION ILLNESS[2]

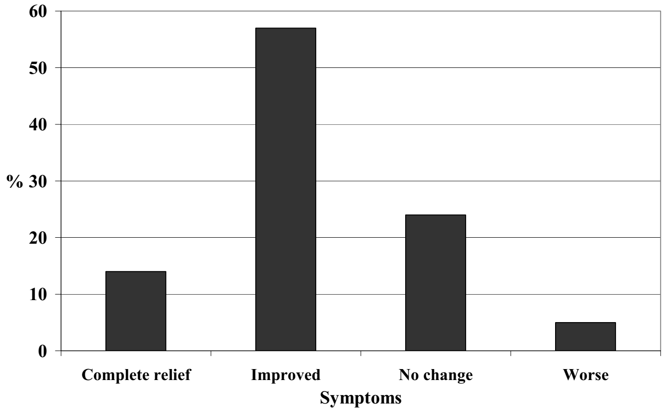


TABLE 1
RELIEF OF SYMPTOMS PRIOR TO RECOMPRESSION ACCORDING TO USE OF OXYGEN FIRST AID[3]

Evolution	O_2 first aid % divers	No O_2 % divers	Significance
Worse	15.6	22.6	n.s.
Static	20.0	69.4	$p < 0.02$
Improved	48.0	4.3	$p < 0.001$

FIGURE 2
PERCENTAGE OF DCI CASES GIVEN OXYGEN FIRST AID[2]

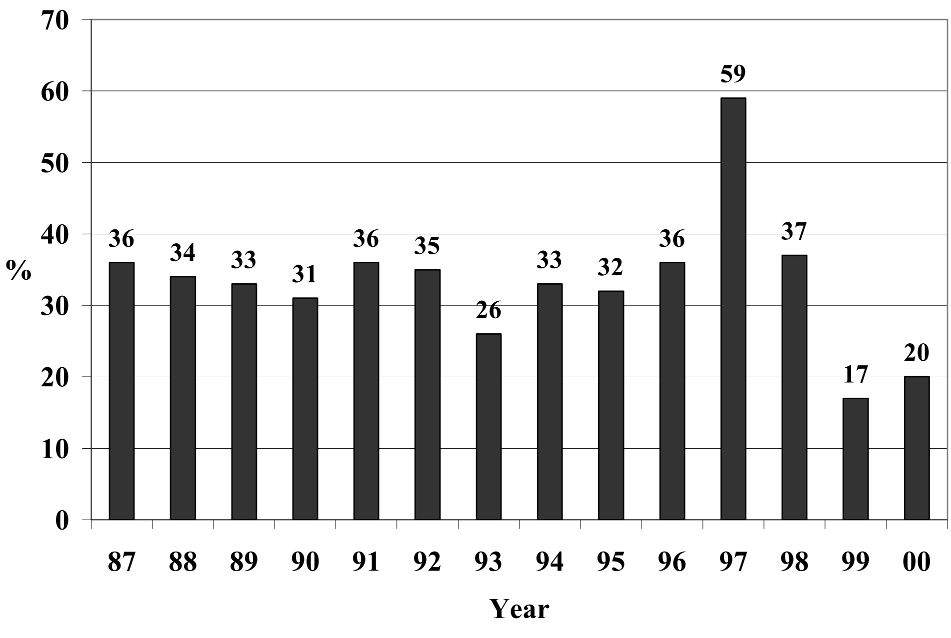


TABLE 2
OXYGEN FIRST AID AND HYPERBARIC TREATMENT RESULTS (percentage)[4]

Surface Oxygen	Complete recovery	Partial/ temporary	None	Residual symptoms
No	2	38	60	47
Yes	13	54	32	42

Oxygen breathing prior to recompression also appeared to enhance the outcome of the treatment, giving the diver the greatest possible chance of a full recovery (see Table 2).[4-6] For example, a DAN America analysis of 2192 dive accidents from 1989–93 indicates that there were significantly fewer residual symptoms in divers who had received oxygen prior to recompression, compared with those who had not received oxygen first aid ($p = 0.05$) (Table 2).[4] Although the difference in residual symptoms was only relatively small, one must remember that oxygen provision is often delayed, not continuous, and frequently is at a far lower concentration than desirable.

The requirement to have appropriate oxygen equipment and a trained oxygen provider available is now viewed as a ‘standard of care’ in the dive industry. Despite this, those of us who deal with diving emergencies are constantly reminded that many boat and diving operators still do not have appropriate oxygen equipment or adequate knowledge and training. Too often injured divers are provided with a lower than desirable level of emergency care by the ‘dive professionals’ who are responsible for them.

DAN America data of the DCI cases from 1987–2000 illustrate this. Only about one third of divers received oxygen first aid prior to recompression (Figure 2).[6] This will be due in part to the late recognition and reporting of symptoms of DCI. However, it is a depressing statistic and one that we constantly strive to improve through education and training.

Choosing oxygen equipment

There are now many different types of oxygen equipment in the marketplace and it is important to choose the most suitable gear. When looking for oxygen equipment some of the points that should be considered are:

- potential oxygen concentrations available;
- duration of oxygen supply at the desired concentrations;
- ability to provide high concentrations of oxygen to both responsive and unresponsive victims;
- ease of use by relatively inexperienced, lay oxygen providers, especially for ventilating a non-breathing victim;
- the number of inexperienced oxygen providers required to adequately ventilate a non-breathing victim (e.g., it is generally agreed that a bag-valve-mask requires two operators to safely and effectively ventilate a person in the field);[7]
- how many victims can be given oxygen simultaneously;
- the training and re-training requirements;
- durability and suitability for the marine environment;
- cost and ease of servicing.

Appropriate equipment should be capable of easily and effectively providing high inspired-oxygen concentrations to the responsive victim, the unresponsive breathing victim, and the non-breathing victim. Many people mistakenly believe that because an oxygen cylinder contains pure oxygen, and this gas flows out from the regulator and down the tubing, a person breathing from an oxygen set will be breathing 100% oxygen, no matter what mask or other delivery device is used. This is generally not true because, when the person inhales, a substantial amount of air is normally entrained, diluting the concentration of oxygen.

To supply 100% oxygen, an oxygen-delivery system must be able to provide for all of the person’s respiratory requirements. In addition, air entrainment must be prevented and expired breath must be vented effectively to prevent hypercapnia and further oxygen dilution.

Consider a person with a tidal volume of 0.5 l with a breathing cycle of four seconds, one second being for inhalation and three seconds for exhalation. With such a cycle, a person’s respiratory requirement is $0.5\ \mathrm{l.sec^{-1}}$ or $30\ \mathrm{l.min^{-1}}$. In other words, unless there is a reservoir in which oxygen can collect during the exhalation phase, an oxygen-delivery system needs to provide an oxygen flow rate of $30\ \mathrm{l.min^{-1}}$ or more in order to provide 100% oxygen. If a lower flow rate is supplied, as it is with most oxygen regulators, air will be entrained and the oxygen concentration will be reduced accordingly.

The addition of an oxygen reservoir enables a reduction in flow rate. However, such a reservoir should generally have a minimum volume of the wearer’s tidal volume.

Oxygen delivery systems

DEMAND VALVES

The easiest and usually the most effective way to provide an oxygen concentration approaching 100% to a breathing injured diver is via an oxygen demand valve (Figure 3). Most current medical oxygen demand valves are capable of providing oxygen flow rates in excess of $100\ \mathrm{l.min^{-1}}$ and so are capable of supplying all of a person’s respiratory requirements.

Demand valves are often designed to entrain some air so that the user doesn’t asphyxiate if the oxygen supply runs out. If the breathing resistance is too high, air will be entrained when the user inhales and the inspired oxygen concentration will fall. This problem may be increased if the victim is sitting with their head down or lying on their

FIGURE 3
OXYGEN DEMAND VALVE AND MASK

side, as gravity will make it harder for the valve to open.[8,9] Injured divers who are breathing only weakly or hyperventilating may be unable to trigger the demand valve and should not be administered oxygen by this method.

Apart from the above-mentioned limitations, well-designed and maintained demand valves provide a very simple and effective method of administering near 100% oxygen. They are the delivery system of choice in the first-aid management of scuba diving injuries for which near 100% oxygen is required, as well as for other conditions for which the inspired oxygen concentration needs to be maximised. They can be relatively economical with oxygen usage as long as the user's breathing rate and volume are not too high.

CONSTANT-FLOW DEVICES

The most commonly available oxygen-delivery systems are those that deliver a constant flow of oxygen at either a fixed or variable flow rate.

Many constant-flow delivery devices are not as economical on oxygen usage as demand valves. In addition, most such devices cannot provide such high oxygen concentrations. Despite these potential limitations, certain constant-flow devices are very useful in the management of a non-breathing victim, or one who cannot use a demand valve effectively.

The oxygen concentration delivered by a constant-flow

FIGURE 4
NON-REBREATHER MASK AND RESERVOIR

system depends on a variety of factors and, in almost all cases, will be well below 100%.[10] It varies from about 25–35% with a loose-fitting (Hudson) mask or nasal cannula, to up to 98% with a tight-sealing bag-valve-mask system with an additional oxygen-reservoir bag attached, and a flow rate of about 15 $l.min^{-1}$ or higher.

There are a number of different constant-flow delivery masks available and the concentration of oxygen delivered by these masks depends on how well the mask seals, the flow rate, the breathing rate and depth, and size of the wearer, and whether or not a reservoir bag is used in conjunction with the mask. A tight-sealing mask will minimise air dilution. If the flow rate is too low, hypercapnia can occur. High flow rates will minimise hypercapnia but will deplete the oxygen supply more rapidly.

There is a plethora of constant-flow delivery devices and only a few will be briefly discussed here.

Non-rebreather mask

The non-rebreather mask is now probably the most commonly used oxygen-delivery device for injured divers (Figure 4). This mask is fitted with both a reservoir bag and a set of three one-way valves. It is designed to reduce the amount of air and carbon dioxide inhaled, thereby increasing the concentration of oxygen.

For proper use, the reservoir bag must be primed and should always contain enough oxygen so that it does not deflate fully when the wearer takes the deepest inhalation. In addition, a good seal needs to be achieved and all three one-way valves should be fitted and seated properly. Under these ideal circumstances, a non-rebreather mask is capable of supplying an oxygen concentration of up to 95% with flow rates of 10 to 15 $l.min^{-1}$. However, in practice such a high concentration is difficult to achieve and the mask will

FIGURE 5
RESUSCITIATION MASK WITH OXYGEN ATTACHMENT

usually deliver a substantially lower oxygen concentration, probably closer to 70–80%. (Chan C, Williamson J, Duff M, unpublished data). A flow rate of about 25 $l.min^{-1}$ may be required to achieve an oxygen concentration near 90%.

Resuscitation mask

In general, the simplest way to provide supplemental oxygen to a non-breathing victim is via a resuscitation mask with oxygen inlet (Figure 5). Such masks are capable of providing a good seal on the victim's face and enable a rescuer to perform mouth-to-mask ventilations, supplementing their expired breaths with additional oxygen.

Using this technique and at a flow rate of 15 $l.min^{-1}$, it is possible to provide an oxygen concentration of up to 50–55% to the non-breathing victim.[11] Although this potential oxygen concentration falls considerably short of the desired 100%, because this technique is so simple to perform it is recommended by many resuscitation and oxygen-provider training bodies worldwide, including DAN.

A rescuer can use both hands to open the victim's airway and seal the mask. There is plenty of air available in their lungs to ventilate the victim adequately and compensate for any leaks. The skills required to perform mouth-to-mask ventilations are easily acquired and retained far longer than more complicated ventilation techniques.

Bag-valve-mask (BVM)

BVM devices fitted with a reservoir are capable of providing near 100% oxygen (Figure 6). However, as with most oxygen-delivery systems, the oxygen concentration delivered to the lungs depends on several factors, including the fresh-gas flow rate, the mask-to-face seal and the depth and rate of ventilation.

A major problem with bag-valve devices lies in the level of skill required to ventilate a non-breathing victim. Several studies[12,13] have shown clearly that the single-operator technique generally produces very poor ventilations, even when performed by well-trained and regular users.[10,11] Experience has shown that such devices generally require two trained operators to use effectively with the non-breathing victim. Hence, although a bag-valve-mask is capable of providing higher concentrations of oxygen to the non-breathing victim than a resuscitation mask with oxygen, it will provide little benefit if the ventilations are inadequate.

FIGURE 6. A BAG-VALVE-MASK OXYGEN SYSTEM

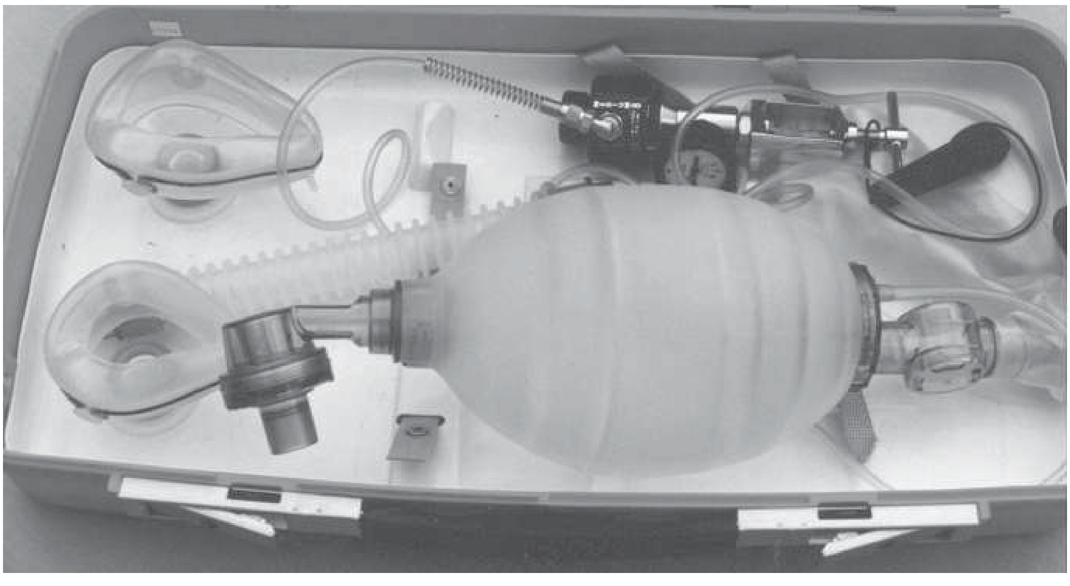
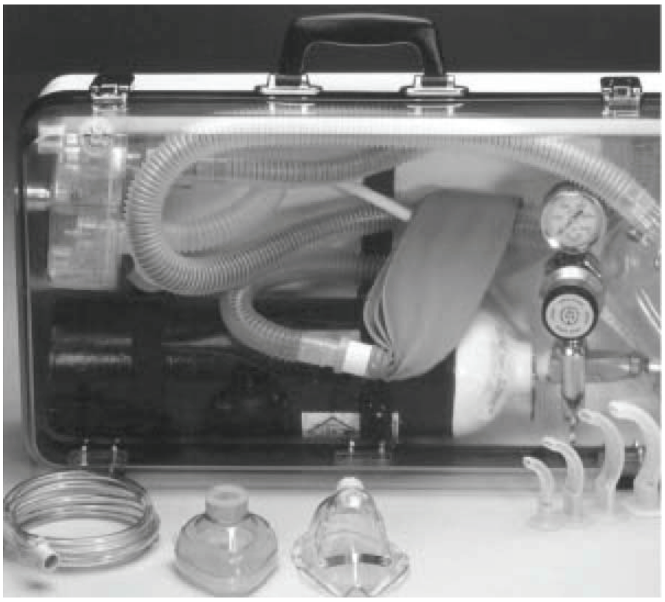


FIGURE 7
CLOSED-CIRCUIT PORTABLE OXYGEN RESUSCITATION SYSTEM



CLOSED-CIRCUIT PORTABLE OXYGEN RESUSCITATION SYSTEMS

Closed-circuit oxygen-delivery systems are based on systems commonly used in anaesthesia (Figure 7). The main benefit of such a system is the potential to increase the duration of the oxygen supply. Such units provide advantages to divers in remote areas who cannot carry a large oxygen supply. A 450 l oxygen cylinder, which would last around 30 minutes with a constant-flow device set at 15 $l.min^{-1}$, could potentially provide oxygen for up to four hours using a closed-circuit device, depending largely on the size of the carbon dioxide absorbent canister and the flow rate utilised.

Other than the considerable additional maintenance requirements, the major drawback with closed-circuit devices is again the extra training and skill required to use them effectively, especially with ventilation of the non-breathing victim in the closed-circuit mode. As with BVM devices, it usually requires two people to adequately ventilate a non-breathing victim.

Another area of some contention has been the potential for nitrogen to be trapped in the closed system, and the consequent reduction of the oxygen concentration. Due to retained nitrogen and entrained nitrogen, normobaric oxygen rebreathers typically maintain a mean oxygen concentration in the order of 80–95%.[14,15] When using such devices to provide first aid for DCI (and toxic gas inhalation) it is important to flush the circuit periodically and to use an adequate oxygen flow rate.

CHEMICAL REACTION SYSTEMS

These systems utilise a chemical reaction to produce oxygen. One such system that has been marketed to divers is known as the emOx™ (Figure 8). It consists of a plastic flask in which the chemical reaction takes place, with delivery tubing connecting the closure cap to a mask. Pre-packed quantities of the powders are placed in the flask and a measured amount of water added. The chemical reaction commences immediately and the flask is then closed to direct the oxygen produced via the delivery hose to the face mask.

Although the system has some advantages in certain, very limited situations, it is most definitely not suitable for divers with decompression illness. The most important reason for this is the inability of this system to provide anything near to 100% oxygen to the injured diver. The advertised mean flow rate of 6.4 $l.min^{-1}$ is often incapable of producing inspired oxygen concentrations higher than about 30–40% using the supplied delivery system.[16]

FIGURE 8
THE emOx™, A CHEMICAL REACTION OXYGEN SYSTEM

DAN oxygen units

The Divers Alert Network has configured and assembled a series of oxygen units, designed specifically to cater to divers' requirements. DAN oxygen units are not only effective, but also easy to use and so require minimal training.

Training

It should be obvious from the discussion above, that some types of equipment are easier to use than others. As mentioned, a demand valve is usually the simplest system to use with a breathing, injured diver. A resuscitation mask with oxygen inlet is the easiest method for ventilating a non-breathing victim. These techniques require far less initial training and continued practice than other methods, and can be performed effectively by one trained person.

All divers are strongly advised to undergo training in oxygen provision, and should be thoroughly familiar with any oxygen equipment that they might use. DAN has created relatively simple but very effective oxygen-provider programmes to train divers, and others, in the use of various oxygen-delivery devices.[17] To date, DAN has trained more than 150,000 oxygen providers worldwide, with in excess of 12,000 in the Asia-Pacific region. Some organisations other than DAN also provide oxygen training, but this is not aimed specifically at the diving environment. Skills must be regularly updated as they deteriorate relatively quickly. In Australia, the Australian Resuscitation Council recommends that oxygen-provider (and CPR) certifications are renewed annually. Re-certification should involve a demonstration of the main skill competencies as well as a knowledge review.

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Diving-related fatalities document resource

All the coronial documents relating to diving fatalities in Australian waters up to and including 1998 have now been deposited by Dr Douglas Walker for safe keeping in the National Library of Australia, Canberra.

These documents have been the basis for the series of reports previously printed in this Journal as Project Stickybeak.

These documents will be available free of charge to bona fide researchers attending the library in person, subject to the stipulation that the researcher signs an agreement that no identifying details are to be made public.

Accession number for the collection is: MS ACC 03/38.

It is hoped that other researchers will similarly securely deposit documents relating to diving incidents when they have no further immediate need of them. Such documents can contain data of great value for subsequent research.