Vol 26 No.1 March 1996 Supplement

SPUMS JOURNAL

ISSN 0813 - 1988

South Pacific Underwater Medicine Society Incorporated

PEARL DIVING SUPPLEMENT

A modern pearling vessel out of Broome showing outriggers, lines and hoses

Supplement contents detailed on the back cover

Print Post Approved
PP 331758/0015

PRINTED BY *Snap Printing*
344 Burwood Road
Hawthorn, Victoria 3122

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To provide information on underwater and hyperbaric medicine.
To publish a journal.
To convene members of the Society annually at a scientific conference.

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References

The Journal reference style is the "Vancouver" style, printed in the Medical Journal of Australia, February 15, 1988; 148: 189-194. In this references appear in the text as superscript numbers.[1-2] The references are numbered in order of quoting. Index Medicus abbreviations for journal names are to be used. Examples of the format for quoting journals and books are given below.

1 Anderson T. RAN medical officers' training in underwater medicine. *SPUMS J* 1985; 15 (2): 19-22
2 Lippmann J and Bugg S. *The diving emergency handbook.* Melbourne: J.L.Publications, 1985

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PEARL DIVING SUPPLEMENT

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THE AUSTRALIAN PEARLING INDUSTRY 1892

DIVER'S PARALYSIS

P W Bassett-Smith, Surgeon Royal Navy

While on board HMS PENGUIN, employed in surveying a part of the north-west coast of Australia, which was then an important centre of the pearl oyster fishery, several cases of this disease came under my notice now and then. The luggers contain about six men, mostly Japanese, occasionally Europeans, and are accompanied by a schooner which acts as a store ship and hospital ship. They are away many months at a time, sometimes a year; the food supplied was good. All the work was done in diving dress in depths from ten to twenty five fathoms, the period of submersion being often four or five hours. Cases of slight paralysis were common, coming on suddenly on removal of the dress but generally recovering completely. The following is the worst case I saw:-

Sept 5th. Japanese aged about thirty. Had been working in thirty two fathoms (by all considered to be a dangerous depth) about three weeks ago; immediately on removal of the dress he became suddenly paralysed, and has been so ever since. His condition was one of great emaciation, free from pain, but very apathetic. Temperature 103°F; pulse 120; tongue furred; complete paraplegia with loss of control of bladder and rectum, and loss of sensation to the level of the umbilicus. There was a large deep bedsore over the sacrum extending from the tuber ischii on either side to the crest of the ilium above, with a thick, black, extremely offensive slough partially detached; it had eaten through the skin, fascia, and gluteus maximus, and in places exposing the bone; there were also small sores over the ankles and knees. He had had a catheter passed twice a day, caster oil once a week, poultices and strong carbolic lotion to the sore, good diet, and port wine.

7th. No marked change. Temperature 103°F.

8th. Refusing food; diaphragmatic spasm; moribund; died at 4 p.m.

This was no doubt a case of severe haemorrhage into the lumbar centre of the cord, with subsequent myelitis, death being due to septic poisoning. The mate attending on him stated that he had been as bad himself with bedsores and paralysis for eight months; he now walks with a limp, but muscular power is fair and tissues firm, knee jerks increased. He said that a very bad sign is a localised swelling of the abdomen, from which, if allowed to get under the ribs, death is certain, and that they apply any pressure to keep it down, even "sit on it", probably a paralysis of intestinal muscles and collection of flatus. Those in charge told me that they try to prevent men from going down over twenty fathoms, but as they are paid by results it is very little use.

Reprinted, by kind permission of The Editor, from The Lancet 1892; i (Feb 6): 309-310.

Modern measurements

10-25 fathoms	18-45 m or 60-150 ft
32 fathoms	58 m or 192 ft
20 fathoms	36 m or 120 ft
103°F	39.4°C

Key Words
Deaths, decompression illness, occupational diving.

THE AUSTRALIAN PEARLING INDUSTRY 1900-1908

NOTES ON DIVER'S PARALYSIS

Graham Blick, M.D. Durh, M.R.C.S., L.R.C.P. Lond.
(Late District Medical Officer, Broome, Western Australia)

From 1900 to 1908 I have had medical charge of probably the largest pearling centre in the world, including in its population upwards of 400 professional divers who are daily engaged gathering pearl shell at depths varying from 7 to 20 fathoms. I have myself seen a diver bring up shell from a depth of 25 fathoms (150 ft), but this was an exceptional feat. This means that these men are working under pressure, roughly, from 20 to 50 lb. per square inch above normal, the shifts varying in length inversely as the depth of working. In the lesser depth a diver will remain down one, two, or more hours, in the greater generally under half an hour. The ordinary rubber diving dress with metal helmet is the apparatus used, air being supplied by three barrelled pumps worked by hand wheels. The divers are of various nationality, whites, Japanese, Filipinos, Malays, etc., the majority being Japanese, the whites being the least numerous. They work from small schooners of 10 to 14 tons, and range over many hundred of miles off one of the most forlorn and desolate coasts in the world. Consequently, when an accident happens they may be several days' sail from port, and so have not the advantages of their colleagues the "caisson" workers, with their decompressing and recompressing chambers and immediate medical attention. Hence, many severe and often fatal cases of diver's paralysis occur.

For eight years I have impressed on these men and their employers the fact that they can with very little extra time and trouble obtain all the safety conferred by the decompressing chamber by a slow and gradual return to the surface, and when this course has been followed few, if any, cases of paralysis have occurred.

Since 1900, not counting the slighter cases characterised by the men themselves as "rheumatics", I have had upwards of 200 cases of diver's palsy; 60 of the patients were dead before a doctor could be reached and I made *post- mortem examinations.* Among the 140 odd who reached me alive I have had to deal with all degrees of paralysis, from slight paralysis of legs and inability to pass urine (always present) up to total paraplegia and loss of sensation. Clinically, the salient features of the paralysis are its bilateral distribution and the constant loss of the power of micturition. The legs are attacked before the arms and recover later. Sensory nerves seem to suffer much less than motor, but I am bound to add that many cases had to be examined through an interpreter, and it is difficult in any case to get correct replies on such a matter from coolies. Out of these 140 cases 11 died, 8 from septicaemia consequent on sloughing and cystitis, and from supervening meningitis. The rest, after a longer or shorter time, recovered, most of them completely, about 10 per cent, being permanently affected with slight paresis, generally of the anterior muscles of the legs.

I have had patients who have been twice, thrice, or even oftener paralysed, and who have more or less completely recovered. I have never seen extensive secondary degeneration of the cord follow, though one would expect this from the lesions found in the cord *post mortem.*

The treatment after the establishment of paralysis is that of all organic nervous disease - one can only wait on Nature's efforts, though in this disease Nature is kinder than usual. General hygiene, massage, and electricity, all are useful to some extent, and, of course, any complications which arise must be treated. I have been often astonished at the way apparently hopeless paraplegics have recovered in the course of many months.

The most troublesome cases were those complicated by cystitis and deep sloughing. The former complication is very frequently set up by imperfectly cleaned catheters used by the diver's friends, often for several days, while making for port. The paralysis of micturition is so well known among the men themselves that no diver would consider his outfit complete without a soft catheter. The sloughing is also the result in many cases of the treatment applied as first aid by the patient's friends, and is especially common among the Japanese, whose unbounded faith in very hot baths too often leads to parboiling and damage to the enervated tissues, forming the starting point of frightful sloughing, which often defies all efforts of nursing to restrain. I have seen the sacrum, portions of the ilium, and the capsule of hip-joint absolutely denuded, and several of the deaths in my cases resulted from this condition. A few very bad cases, however, made wonderful recoveries. One case, a Filipino diver, was admitted to hospital with total paraplegia and sloughing over the buttocks, which extended till the right hip-joint, most the sacrum, and the posterior portion of the crest of the ilium could plainly be seen; yet after more than twelve months in hospital and several plastic operations he made a fair recovery, and was able to return to the Philippines.

Owing to the distance from port at which these boats work, I have never been able to see a case in the earliest period of attack. The general history is that the diver has worked longer and deeper than usual, and then has hurried to the surface. He has felt quite well below, and gets aboard as usual. Often he has had the dress removed and even sat down to his meal before symptoms appear. Then he suddenly drops, sometimes "as if shot", or he may remark he is not feeling well, and the symptoms come on more gradually. He may or may not lose consciousness. Some rapidly fatal cases have occurred without initial loss of consciousness, and it is practically never lost in slight attacks. Death may occur within an hour or not until after a day or two.

Clinical experience directs attention to the spinal cord in this disease, and my sixty autopsies have amply corroborated the inference that here is to be found the greatest mischief. I have never found the classical "bubble of nitrogen" in the hearts of my cases; indeed, I honestly confess I doubt my ability to recognise a bubble of nitrogen. I have, however, often fancied that during the rapid putrefaction of these bodies there has been a larger evolvement of gases and greater distension of the tissues than is the case with other bodies after equally sudden death. I have only once found an infarct in the lungs, and only twice clots in the heart, and then to no great extent; and in these cases beri-beri, with its often insidious onset and clotting in the heart, has always to be remembered. Beri-beri used to be the greatest scourge known to the pearling fleets, but segregation and sanitation have greatly diminished its ravages. Almost invariably the heart, lungs, and large veins are engorged with dark liquid blood. So marked is this that on one occasion a medical man present at one autopsy frankly told me he would, from the thoracic examination alone, have been quite content to certify asphyxia; yet, on exposing the spinal cord, the characteristic "teased" appearance and minute haemorrhages were present, together with free blood, in the dural canal.

In my experience the following appearances are typical of diver's paralysis on *post-mortem* examination of a rapidly fatal case. The thoracic viscera and large veins of the neck are engorged with dark liquid blood. There is nothing noteworthy in the abdomen. There is more or less venous engorgement in the meninges of the brain, markedly increasing towards the base, especially round the medulla. Section of the brain is generally negative; sometimes the blood points seem rather larger than usual. I have only once found a haemorrhage in the brain; it was about the size of a horse-bean, and situated in the left internal capsule, and was accompanied by another haemorrhage practically severing the spinal cord opposite the body of the fifth cervical vertebra. The most characteristic signs are found on exposing the spinal cord. The dural cavity contains blood or blood-stained fluid, the meninges of the cord are congested with blood, and the congestion appears to be most intense in the cervical region, say the portion corresponding to bodies of the fourth to the sixth cervical vertebrae. This portion of the cord appears to me to be the diver's calx Achillis. It is here that the characteristic "teasing" is most apparent. I call it teasing for want of a better word to explain the appearance in the section of cord; it looks as if one had stippled the face of the section with a fine knife or needle, a semi-disintegrated appearance. With this condition is nearly always associated haemorrhage of greater or less extent, also most marked in the above portion of the cord; indeed I have never found an effusion of any size except in this part; here they may range in size from mere points of blood to, as I have seen in nine cases, large haemorrhages practically cutting the cord in two, and forming clots filling the meningeal tube for over 1 1/2 in. I had neither time nor appliances for microscopic pathology, which in such a hot climate would need exceptional apparatus, and, I may add, exceptional skill, to obtain good results. In this respect, however, I hope my omission will soon be rectified by more competent pathologists, for I have reason to believe steps are being taken to get a specimen cord for examination.

When I first met with this disease I was greatly handicapped by the want of literature on the subject - in fact, all I had was comprised in one page of Osler's Medicine. Consequently I was presented with a pathological problem which I had to unravel as best I could, and was often sorely puzzled. For instance, I noticed that though the divers started work about March there were practically no cases of paralysis before September, and from thence to the end of the working season, about the end of November, cases came in almost daily. All sorts of theories are current among the men themselves accounting for this well-known fact - for example, working further out in deeper water, that the water itself "gets heavier" at this end of the season, etc.

The mystery was elucidated by the discovery in one autopsy of signs of scurvy. There was the simple explanation of the prevalence of the disease among men who live for months on small boats, eating salted and tinned foods, and also of its infrequent occurrence till the blood vessels have been somewhat weakened, as we know happens in scurvy. Acting on this knowledge I preached an anti-scurvy crusade, and noted that in fleets where my advice was taken and extra vegetables and other antiscorbutic precautions used there was a very considerable reduction in the number of cases of paralysis.

The points which have particularly impressed me in dealing with diver's paralysis are:

(a) Signs of asphyxia are nearly always present; it would appear from this that in the rapidly fatal cases death is usually due to affection of the breathing centres.

(b) In roughly 2 per cent of the cases in which death was not immediate meningitis set in about a week after paralysis. In this respect, however, considering the damage done to the central nervous mechanism, the only wonder is that it is not a more frequent occurrence.

(c) The question arises as to the cause of the congestion found in the meninges on *post-mortem* examination of fatal cases. Is it due to over-expansion of vessels by gases suddenly released from pressure, or is it simply part and parcel of the condition of asphyxia? From concomitant appearances in the thorax, it would appear that the latter is the true explanation, yet when one considers the blood or blood-stained cerebro spinal fluid, one is forced to think of the former as being equally applicable. Probably both factors are often present.

(d) The paralysis of the bladder and loss of the power of micturition are constant, and occur in cases so slight that it is practically the only symptom calling for attention. I have had patients walk up to hospital for catheterisation. Why this centre should be attacked so early and constantly is a problem I have failed to solve, more especially as the lumbar enlargement of the cord does not show nearly so much damage as higher up.

(e) The apparent point of selection for the most striking lesions of this disease is in the cervical portion of the spinal cord. The part of the cord where all the large haemorrhages were found without exception could be covered by three cervical vertebrae. Even in the cases in which apparently the disintegration of the nervous substance was the chief lesion, and no large blood effusions occurred, this portion of the cord showed the curious teased appearance more plainly than any other. Why such is the case is a problem for anatomists and physiologists. I can only make two modest suggestions: First, the comparatively large size and great mobility of the spinal canal at this point. Secondly, and this is a mere bow drawn at a venture, this portion of the cord is movable in the metal helmet of the diver, the rest being covered by the rubber dress closely pressed to the body by the water pressure. Theoretically, there should be nothing to choose from the pressure point of view. Is there anything in the movement? It must be remembered that a diver's dress at a great depth precludes bending the back beyond a very slight degree.

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Key Words

Death, decompression illness, occupational diving.

PEARL DIVING
THE AUSTRALIA STORY

Carl Edmonds

Full fathom five thy father lies;
Of his bones are coral made:
Those are pearls that were his eyes:
Nothing of him that doth fade,
But doth suffer a sea change
Into something rich and strange.

The Tempest, Shakespeare.

Overview [1-5]

Ancient Greek jewelers used fine quality pearls in their delicate workmanship. They were collected from the Persian Gulf, the waters north of Ceylon and in the tropical waters of South-East Asia. The pearl shell was collected for the nacre or mother-of-pearl.

Australian Aboriginals used mother of pearl for decoration long before the coming of the white man. In the Kimberly region of Western Australia, carved pearl shell rigars, hung from human hair belts, were worn like fig leaves by tribal warriors.

Traders from Makassa bartered with the Australian Aboriginals three centuries ago, and the Aboriginals exchanged their women, pearls, trepang and coveted turtle for various commodities such as tobacco, rice and axes.[1] Around the Kimberly coast these Makassa traders built fortifications on the continent for protection against Aboriginal assaults.

Pearl shell was also used as a trading item between the Aboriginal tribes. It had natural and magical qualities promoting cloud production and rain making. No medicine man could be initiated without maban, the enchanting shell, if he was to cure the sick or conduct sorcery.

Dampier, who died in 1715, discovered much of the Australian coastline. On his visit to north-west Australia he recorded the presence of pearl shell.

By the late 1850s the Ceylonese pearl grounds were depleted, permitting the development of the Australian pearl industry. At about the same time the mother of pearl became fashionable, being used in the international button industry. The female fashion for thinness required strong fasteners.

In 1850 the colonial schooner *Champion*, under the command of Lieutenant Helpman, was sent to Shark Bay, in Western Australia, to stop poaching of guano fertiliser by foreign vessels. The sailors found extensive beds of the small pearl-producing oyster *Pinctada albina*..

In 1861 the surveyor Francis Gregory led an expedition to Nickol Bay aboard the vessel *Dolphin* to explore the Pilbara. While he explored the interior, the *Dolphin*'s crew were attracted to the pearl shell rigas worn by the aboriginal warriors and collected these shells as curiosities. Several tons of pearl shell, worth 300 English pounds (100 times a weekly wage), and a number of pearls were obtained.

The traditional Aboriginal method of gathering shell was by beach combing (or dry shelling) during the 3 or 4 hours of each day when the shores were bare at low tide. When flour was offered as an inducement, there was no shortage of shell gatherers, more so when the Aboriginals became dependent on tobacco (binghi twist or niggerhead).

In 1861 a naturalist, Pemberton Walcott, discovered beds of highly prized *Pinctada maxima* or silverlip shell, at Nikol Bay. Several tons were collected. A grazier, W F Tays, approached some Aboriginals dressed only in large pearl shells and they agreed to show him the source of their adornment. The industry was firmly established in October 1866, near Roebourne, Western Australia.

The subsequent pearling at Shark Bay was a dredging, not a diving operation. In Denham, a small settlement at Shark Bay, the town was the only one in the world that had its streets paved with pearl shell. Unfortunately, in the 1960s a government roads department brought in a bitumen tanker and destroyed the towns only claim to fame.

The first lot of pearl shell from the Torres Strait, in North Queensland, was collected around 1870. This was used for mother of pearl but pearls were an added bonus. They seldom achieved the shape and lustre of those found on the west coast.

By 1885, prices were beginning to fall and there were reports of good shell grounds to be found in King Sound in the west. A decision was made by the leading pearlers of the Northern Territory and the Torres Strait to move their headquarters to the west coast, centered in Broome.

Japanese divers moved into Australia at the end of the 19th century. The description given of them was as follows: "They are the Scotchmen of the East. They are industrious, frugal, clean, tractable and law abiding.....their frugality impels them to forward their savings to Japan instead of squandering them".

The Japanese government, conscious of its international image, rejected any contracts for its subjects to work as coolies or in lowly occupations. Pearling however was regarded as a skilled task. Six Japanese crews were contracted on the 10th October 1883 to dive in the area. The payments were liberal, with divers, tenders, interpreter and crew receiving $50, $20, $15 and $10 a month respectively. Divers also received a bonus of $50 for each ton of shell raised.

World War I was declared in August 1914. The presence of Japanese caused no embarrassment as Japan had aligned herself with the allies against her long standing enemy, Russia.

In the early years mother of pearl was the main product and Broome provided raw material for 80% of the shirt and trouser buttons of the world.

World War 2 depleted the pearling industry due to both the Japanese divers withdrawing and the Australian pearlers enlisting for armed service.

The industry experienced a rebirth after the war. The shell had been undisturbed for 5 or 6 years and for a few years at least, there were easy pickings. The price paid for the mother of pearl was still relatively high. Torres Straight islanders became involved in the industry at all levels, from diving to owning luggers.

The pearling industry went into a massive decline in the 1960s as plastics usurped its traditional market. Pollution from an oil tanker, disease, and changes in the weather were all blamed for diminishing catches. Torres Straight islanders, meanwhile, left to find work on large construction and mining projects across tropical Northern Australia.

With the replacement of mother of pearl by plastics, Broome faced a depressed and uncertain future. The traditional pearling industry also received a setback in 1956 when a cultured pearl venture was formed under the name of Pearls Proprietary Limited. The influential Japanese pearl culture industry was about to be introduced.

Culturing pearls was no new thing. It had been attempted for thousands of years. Kokichi Mikimoto, a noodle vendor from Toba in southern Japan, produced the first consistent pearl crops. At Kuri Bay just north of Broome, Japanese scientists and technicians worked and produced the first round pearl in 1959.

With the development of the cultured pearl industry, and the takeover of this industry by Australian pearlers, divers, farmer and technicians, the pearling industry was again booming in the 1980s. Today there is only a small demand for live pearl shell, and that is used by the few Japanese/Australian pearl culture stations dotted around the north coast.

The pearl [1-3]

Pearls are formed inside the oyster by a secretion of calcium carbonate. They are of no practical value other than as an ornament or adornment. A pearl is the only gem perfect in its natural state, the only "live" gem found in nature. Other gems are formed from ancient inorganic matter and they require artificial treatment and faceting before they create their effect. The pearl is already perfect in nature. They have been referred to as "Moon Fire of the Sea" and "Necklaces of Death".

The Southern Cross pearl was so named because of the similarity to the crucifix of the 8 to 9 baroque pearls joined together. It now resides in the Vatican. It was originally sold by a Shiner Kelly for ten pounds and a bottle of rum.

The pearl oysters are hermaphrodites. In 30-40% of the population of *Pinctada maxima* oysters may spend 6-8 years as male and then change to female. It breeds by releasing spawn when the sea water temperature reaches about 29°C in the summer months. Fertilisation occurs in the open water. Larvae develop within 8 hours and after 3 weeks they settle on the bottom as spat. At this stage they are mobile and move until they find some suitable object, such as coral, shell or stone on which to settle.

The shells grow 35-80 mm in the first year, 80-140 mm in the second and by the time they are three years old the oysters have become mature shell, 170-200 mm across. They live for 20 years or more.

A flowing current is required to bring the organic detritus on which they feed, filtering it through their systems. They can be found from waters so shallow that they are exposed at low tide, to 80 m deep at the edge of the Continental shelf.

Australian pearls are marketed as "South Sea Pearls". *Pinctada maxima* is the largest of the world's 30 species of pearl oyster. Some have reached over 30 cm diameter, and over 5 kg weight. They grow in the "plankton soup" off the north west coast, about twice as rapidly as in other marine environments. The South Sea Pearls are from 9-16 mm diameter. Exceptional pearls may be as wide as 20 mm reaching values of $200,000.

Mother-of-pearl also came from *Pinctada maxima*, the biggest and best mother-of-pearl shell in the world. It is found from the Exmouth Gulf of Western Australia to the Torres Straits and northern tip of the Great Barrier Reef.

Cyclones cause a good deal of shell mortality in the shallow water beds. Oysters also go into shock when they are gathered by divers and moved from one locality to another. They may be damaged by bacterial infection and other diseases, especially if they are kept in confined quarters.

A natural pearl is found in one shell out of 5,000. Pearl cleaners, also called pearl doctors or fakers, take pearls with minor blemishes and skillfully remove the layers of defective skin, often producing a marketable product. At other times, huge pearls are skinned down layer by layer until they lay in husked pieces of lime on the table, the blemish continuing through the gem. This was the fate of the largest pearl ever found in Broome. It was a spectacular 264 grains weight. J E W Tilley took the gamble and whittled it away, to become the owner of a worthless pile of peelings, suitable only for the garbage.

One of the major factors causing shell growth in the north west of Australia is the phenomenal rise and fall of the tide, ranging from 6 m at Exmouth to 12 m at King Sound. The strong tidal currents supply rich marine food. The ideal ground is called "shell bottom". This is 20-30 cm of coral or stone fragments on sandstone or limestone. The pearl rich ground was often indicated by sea snakes and turtles on the warm surface, even in winter. Predators include octopus, stingrays and man.

For cultured pearls the oyster is operated on at 3-4 years. The foreign body implant is a small piece of sacrificial mantle from another oyster and a piece of the shell of a fresh water mussel, which has the best combination of colour and hardness. These come from the Mississippi and southern US rivers and 6,000 tons of mussel shell is exported to Japan each year. In Japan the mussel shells are cut and polished into tiny perfect spheres of various sizes suited to the variety of the oyster to be seeded. Culture success rate may be as high as 83% but only a few will create valuable round pearls. The others produce pearls of lesser quality or the mis-shaped pearl known as Baroque, or "nothing at all".

It is important not to let pearls dry out and that is why it is better to wear them than to store them. The exception is when someone is ill and perspiring heavily, as this is said to have "an acidic effect".

The wearer should only apply scent, deodorant or hair spray before to putting on the pearl. Otherwise these elements can damage the sheen. Dish washing detergent may also be harmful, and pearls are best protected from nail polish, tea or coffee spills or even the ring left by a glass of orange juice or champagne. If anything is spilled over the pearl it should be rinsed immediately in fresh water and dried with a soft clean cloth or chamois leather. It should never be a placed in plastic bag or airtight container. It should not be mixed with other jewelry.

The pearlers [1-5]

The attraction of pearls was obvious. Fortunes could be made, and a single pearl could do it. The pearlers were the ones that gambled on this fortune, and so were a very special breed of men.

The shelling industry derived its profits from mother-of-pearl, the top quality pearl (rarely), and the smaller and baroque pearls. The north-west settlement in 1872 encompassed 75 Europeans, 350 Aboriginal natives and a few Malays.

Pearlers were always strong individuals, distrusting of potential enemies, such as thieves, poachers, divers, deckhands, government officials and other pearlers. The rugged and colourful entrepreneurs of the pearling industry were not well tolerated or regulated by the governmental authorities, especially in the boom years. This is still so.

E. W Streeter, of Streeter and Company, London, was a traditional dealer in pearls and mother-of-pearl shell. He describes the pearlers as "a finer but rougher set of men it would be hard to meet. They are the products of a hard, dangerous but healthy life and there is among them a written code of honour that is seldom broken.......Drinking, gambling and fighting are the favourite recreations of this bronze and stalwart class. But ... the pearlers fought fair."

The pearlers, with their sailing fleet of "luggers" were stationed mainly at Broome, Western Australia.

The area is in the cyclone belt. The cyclone season is usually from December to April. The worst of these was on March 5th 1899, when 307 men from the pearling fleet were drowned in that one blow. There have been more than 100 cyclones since 1870. In 1875, 59 men were drowned. In 1877 there were 140 men drowned. In 1883, when Krakatoa erupted in Indonesia, a ten m tidal wave submerged and altered the shapes of many offshore islands. The eruption had the strength of 3,000 atom bombs.

In 1912, 150 people were drowned with no survivors from 1 passenger ship. Many luggers were lost

Figure 1. Luggers at low tide among the mangroves

at the same time. 50 men were drowned in 1908, 26 luggers and 40 men were lost in 1910.

A devastating cyclone struck in 1935 and 26 of the 29 pearling luggers were sunk off the Lacepedes and 141 men drowned. One survivor from the sunken luggers was able to swim for 2 days and nights before being washed up on Eighty Mile Beach. When divers returned to the Lacepedes patch in 1936 they could not work it because of the sharks. These had gorged themselves on human flesh in the 1935 disaster, and were too aggressive.

Government intervention and regulation was needed to restrict pearling to the non-cyclone season, now usually April-November.

Family dynasties of pearlers evolved. The Streeter and Male luggers were identified by their characteristic colourings, both above and below the water line. The war disrupted the pearling industry considerably. In 1946 Sam Male had 6 luggers operating and by 1956 the fleet had expanded to 42, most of them built in Broome.

The Torres Strait islands were the other traditional area for pearl, but there the boom/bust cycle was even more pronounced. Perhaps this was due to the local indigenous people taking over the industry; perhaps it reflected their reluctance to embrace the newer technologies.

Following World War I, Thursday Island was also booming, because when they went out and started to collect shell, they could get a ton of shell on deck a day, and they could get some in the shallows, up to 4 or 5 metres of water. Even the cook would go over the side with his swimming glass and collect shell alongside the divers. In the early 50's, they also collected a great deal of shell, just before the commercial downturn.

The Broome pearling lugger was a unique boat. It was 16-17 m in length, with a beam of about a third that. Deep keels drew 170-180 cm. There was always a silver coin under the foot of the foremast and they were still built as sailing vessels, although they became more and more dependent on engines. An important requirement was that they should be able to lie over on the mud when the tide was out, without damaging the keel.

Apart from the sea and its hazards, severe infections, scurvy, alcohol, greed, inter-racial conflict and the outback mentality ensured that only the hardy survived life as a pearler. The life was hard and the conditions frugal. One problem was the vermin. Cockroaches were about 5 cm long and thrived on the gristle of the reeking pearl shells in the hulls of the ships. The main reason for the pearlers leaving their boats to sleep ashore at Broome, was to avoid the cockroaches. They were more tolerant of the rats and lice.

For the first half of the 20th century, it was believed that only the Japanese had the expertise to run a successful industry, but now pearling in Australia is run entirely by Australians using the farm techniques which have been developed in this country.

By 1981 the luggers had radio, radar, depth sounders and improved crew conditions. Specially built pearling boats were designed. The use of oxygen had been incorporated for the divers to spend time at depth, to more effectively purge the nitrogen from their blood.

The Paspaley Pearling Company today harvests about 70% of the pearls that make up an industry worth $100-150 million a year for Australia. In the 1990s Paspaley was the largest pearl fishing operation in the world with a fleet of 6 ocean going ships and a multiplicity of smaller craft. The flag ship Paspaley III is a ultra-modern vessel of 650 tonnes.

The industry, by virtue of fishing for sustainable yields from the ocean and aquaculture style pearl farms, has embraced both technology and ecology. Not always has the evolution been voluntary, indeed the necessities of survival and the imposition of regulations have complemented each other in producing a robust and growing industry.

Divers and their equipment[1-5]

FREE (BREATH-HOLD) DIVERS

In the 1860's, Aboriginal men were initially used for diving. The women were employed for chipping and cleaning the shell, searching for pearls and being responsible for finding the day's food.

One of the new pearlers stated that "the most important part... is the picking up of niggers.... for pearling, after all, would never pay white labour".

Soon the skin diving Aboriginals extended into deeper water. The Aboriginals dived from dinghies. The men jumped in feet first, tucking the knees straight up to the chin. They then tumble turned and rapidly swam downwards. Some writers have credited them with diving to 18 m and staying under water for about 60 seconds. Most worked in the 5-8 m depth and seldom needed to go deeper. The Aboriginals were skilled swimmers.

When the shallow beds near the shore were exhausted they had the dinghies taken out to deeper water, to work from luggers. They would bring up 60 to 100 shells a day.

The demand for coastal Aboriginals to dive for pearl, rapidly outstripped the supply and "black birding" became common. As the divers had to live on board, when they returned to their families they would often find their women stolen or carried away, sometimes killed and their families scattered. Other times these divers would be landed hundreds of kilometres from their tribal grounds and it was impossible to return through an unfriendly and relatively foreign country.

It was then noted that the young women were able to remain underwater for longer periods than the men, and they allegedly possessed keener eye sight. There were many abuses and atrocities inflicted on the women, who were essentially imprisoned on the luggers.

In the 1870's Bishop Gibbley, at Lagrange Bay, wrote in his journal "When the natives gather at night I was surprised to hear the heart rending wail that went up from the crowd. It was related to the deaths of divers, black birded into the pearling boats....Aboriginal women were forced to dive in the last stages of pregnancy and divers whose fingers had been crushed by blows from heavy objects (probably a sculling oar) for clinging to the side of their dinghy too long between dives. Many of the divers were boys and girls, little more than children."

Governor Weld intervened with the Pearl Shell Fishery Regulations Act of 1875, as a result of which: Women were no longer allowed to be employed as divers; divers were not allowed to work in the cold weather months between April and October; diving depth was limited to 6 fathoms (11 m or 36 feet); they had to be signed on before a magistrate and returned at the end of the season to the place they had come from. The pearlers cried "ruin". That is when they commenced recruiting Koepangers from Timor and Malaya.

The loss from the industry of women divers, who were nearly as numerous as the men, resulted in a disastrous shortage of labour.

Thus Malay crews were used instead of Aboriginals and in late 1875 there were 989 Malays to 493 Aboriginals on the 57 vessels licensed out of the Roebuck port of Kossack, Western Australia. The Malays were not as hardy as the Aboriginals and many died.

One participant described his experiences on the pearling vessel *Emma* in 1884 as follows: "The Malays lived in the main hold on a platform of planks. The few white men, together with their provisions, lived in the small aftercabin. There were swarms of cockroaches on board. We carried 4 dinghies, each 16 feet (5 m) long, each with 4 oars and a conch shell for bailing. There were 8 divers and 1 white overseer. The divers dropped off the boat one by one, feet first, and turning when 5 or 6 feet underwater, swimming towards the bottom. Once they were all down I then let the boat drift with the tide on the surface to correspond with the movements of the divers who were swept along the coral bottoms by the tide till the first and then another appeared around the dinghy. They would then swim to the boat. Their rapid breathing gave evidence of the great exertion. After a few minutes rest the operation was repeated until sundown, when a return was made to the main vessel. This was usually some 3 to 4 miles back. Divers who did not bring sufficient shell were punished by being made to clean the oysters, while the others had their evening meal."

The tide swept the divers along the bottom at the rate of 3 or 4 or even 6 miles an hour. They had to be very astute in seeking and grabbing any shell within their reach. They had no goggles. A difficulty during the ascent was that if the diver released air from the lungs, the ascent was abruptly halted and he would then start to sink. Then the white man, or one of the natives directed by him, would plunge in and rescue the victim.

The Pearling Act of 1884 stipulated that no alien could own a boat or be issued a license for pearl shelling. This was to protect the white mans' interests, but was overcome when he illegally leased his vessel to Japanese, bringing to an end the era which had seen him dominate the industry.

HARD HAT (STANDARD DRESS) DIVERS

Japanese

In 1868 three vessels arrived, manned by South Sea Islanders, which did little to assist in the safety of the divers, as they brought with them the new German standard (compressed air) diving dress. The Seibe-Gorman diving suits were among the earliest used on the West Australian coast. The short air line prevented divers from moving any distance while the strong tides and currents unbalanced the men, resulting in many serious accidents.

The Pearling Act of 1875 specifically forbade skin diving between April and October, thus forcing them to dive in the warmer waters, from November to March but this was also the time of the dreaded cyclones. The introduction of the helmet enabled the pearlers to work the safer winter months and to lay up in the mangroves for overhaul and refit during the unpredictable summer cyclone season.

Acceptance of the "standard dress" and helmet diving, in 1884, resulted in the disappearance of Aboriginals as a major workforce from the fleet. They could not handle the technical complexity of the helmet and suit and they had an understandable dread of being shut-up inside the claustrophobic copper helmet. They had none of the boat handling skills of the Malays or the Japanese.

In 1884 only 2 vessels, the *Lily* and the *Emma*, were operating with helmet diving. By 1887 all but 2 of the 30 vessels were using helmet divers.

The first helmet divers were European, but very soon the divers of Manila and Japan took over. The latter came to dominate the diving industry. Folklore asserted a firm belief in the racial superiority of the Japanese, when it came to diving and detection of shell.

Hamaguchi, on 26th August 1915, described his typical diving activities. He used two suits of pyjamas of the finest flannel, each fitting tightly around the neck and ankles. Two pairs of thick woolen socks reaching up to the knees and an extra flannel, 18" x 49", wound around the abdomen. A large pair of heavy woolen drawers, reaching from the ankle to well above the waist, a heavy woolen sweater covered from the neck and wrists well down to the thighs. Two pairs of heavy woolen stockings came right up to his thighs and then the tough canvas diving dress covered his body and even enclosed the feet. The sleeve cuffs were greased, and of the finest rubber. They produced a very tight fit as he thrust his hands through them. A similar situation occurred around the neck. The great boots with the lead sole weighed 14 lbs. A copper corslet was screwed around the rubber collar, with butterfly nuts. The helmet was screwed on to this. The air line and the life line was separate, with the latter attached to the divers chest. The rope or lifeline was also a communication system. A series of rapid, frantic tugs indicated disaster and to "pull till the rope breaks".

The dive was to 18 fathoms (32 m or 108 ft). On reaching the bottom the signal would be given and the slack removed from the life line. Then the air pipe is called in, to produce just enough slack for the diver to work comfortably and safely. He would have to walk with the tide.

When two divers were underwater, the technique of speaking is by standing close together, touching helmets. With the air escape valve shut they could talk and hear each other. The length of conversation is determined by the associated inflation of the dress and the increasing buoyancy. By allowing air to escape they could come together again and resume conversation.

Sundays were always the traditional rest days and that was when the new divers would try out their skills in the harbour, equipment would be cleaned and maintained, and survival would be appreciated.

The whole equipment weighed over 100 kg but the diver normally drifted with the lugger, almost buoyant, his boots brushing the bottom with some slack line in his hand. When he sighted shell he would let out the slack. When he collected the shell, he would drop it in the bag clipped it to the end of his line and then collect the slack again.

From early 1890's until 1957 the majority of the divers and crew in Western Australia came from fishing villages along the 20 mile strip of coast line in the Wokayama Prefecture in Japan, south west of Tokyo. In season they hunted the whale, but otherwise lived by fishing and bartering. Tolerance to death by the sea, typhoons, etc. made them suitable applicants for pearling. In the 1890's many went to either Thursday Island or Broome.

They would work on the sea bed from dawn until dark. They experimented with the diving dress and, in the Torres Strait, soon chose to work only with a corslet and helmet. Each lugger had two corslets and as soon as one diver surfaced the helmet was removed and immediately screwed on to the waiting man to descend. The previous diver would then rest before returning to the bottom.

In time nearly half the divers and tenders were Japanese. Because of this a Royal Commission was held in 1897. By 1913 there were 1,166 Japanese employed in the pearling fleet, 634 Malays, 99 Koepangers, 7 Chinese and 1 South Sea Islander. The Japanese were never bettered as helmet divers and they were also excellent carpenters, engineers and crew, unlike most of the other nationalities.

In between World War I and World War II Oku was the chief diver and would take an average of 10 tons a year.

The last helmet diver worked out of Broome in 1975.

Europeans

In 1912, twelve ex-Royal Navy divers and tenders were brought from England to take over the diving from the Asians, whose presence conflicted with the "White Australia" policy in force at the time. William Webber, perhaps one of the world's most famous divers, headed the group. Before the season was over, Webber, the most reliable of all divers, was dead. Another was paralysed, one had suffered partial paralysis, and all had withdrawn from the pearling fleet. The Japanese and Malay divers, and their employers, were jubilant. The Navy divers felt bitter and betrayed. At the subsequent Royal Commission, one of the Navy divers stated that they had been sabotaged, and that they were often taken to areas where the shells were depleted. That may have been true, but the Asian diver had to raise eight times as much shell as the Englishman, for the same wage.

Nowry, the second in charge of the Royal Navy divers, recalled "We did well around the Banks group, but at depths I had never reached before, about 170 foot (51 m). I had a good shift and was back on deck, with the next run not being due for another 2 hours. My arms and shoulders began to ache with intense pain such as I had never experienced before. I went down 50 foot (15 m) or so and hung on by shot line. Gradually the pains left me, as the Malay skipper said they would. But I had diver's paralysis and could not walk. Six months in hospital and I was back on my feet again, feet that could not get me back to civilisation quick enough."

He subsequently died from decompression sickness in Victoria, testing out a new diving suit.

There was also a migration of Greek divers, in 1956. Unfortunately 2 weeks later the lugger that they were using came back carrying the body of Kristos Kondogiannis, the chief diver and head of the Greeks. The death was described by the coroner as "Asphyxia, due to the sudden damage to the lungs when the propeller cut the airline. The accident was caused when the lugger, proceeding at a very slow pace, was forced backwards by 3 heavy and unexpected waves, thus fouling the airline which was in its normal position protruding from the stern".

Although no evidence of carelessness or negligence was made, the Japanese knew that it would not have happened with a Japanese crew. The Greeks showed inexperience with the strong tides and drifts in the Broome area, so different from the Mediterranean where the tides are barely noticeable. After this tragedy the 8 remaining Greeks abandoned pearling.

SURFACE SUPPLY BREATHING APPARATUS (SSBA)

The scene changed worldwide in the 1960s. Working divers in other industries such as the abalone fishing, were using new equipment very successfully. SSBA still used air compressors on the surface, with air pumped down a line to a scuba-type regulator. The new divers used wet suits and flippers. It took far less time to prepare for a dive and they were infinitely more mobile than the lead-booted helmet divers. It also cost less.

Commander Batterham, RAN, spoke to Dale Chapman, a prominent Victorian diver, in 1971 and a trial was arranged with Australian divers. They first went to Broome and experienced the same mirth that greeted the English divers, years before. It was assumed that the "Australian Experiment" would end the same way as the "British Experiment".

The Japanese believed that the SSBA would not work as only a suit could allow them to spend the chilling hours underwater. It had taken them 90 years to perfect their system and why should they change now? No challenger had come near them for almost a century.

But these divers were different. They were Australian champion spear fishermen, most had been professional abalone divers and they were all young and fit. They had modern equipment. The first group included Alan Badger, Bruce Farley, Alan Nunn, Dale Chapman and John Monk. They started poorly and it did take them some months to modify the collection system. They changed the drift system, used weights and lift bags and by the end of the season their catch was greater than that of the Japanese.

One of the traditions was to have Sundays off, so that the crews could wash their clothes and visit other vessels. The Australians decided to break with this. As they were only out for 10 days or so on a neap tide, it did not seem logical to miss out on the good conditions by sailing back to Broome and wasting diving days.

In the 1972 season the Australians made a mockery of the Japanese catch figures. It was not that the individual divers who were better, it was the system and the gear. Nevertheless, the theory of Japanese diving supremacy was debunked. Australian divers had no difficulty in "seeing" pearl shells as well or better than the Europeans or Asians.

By this time the vessels had changed out of all recognition. They had deck houses for the steersman and helmsman, wheel steering instead of rope tackles and a tiller. Sails were seldom used and there were permanent awnings. Radar, echo sounders and modern radio equipment had taken over.

Alan Badger stated that pearl diving was never easy, and probably never will be. "We aim to be wet 500 minutes of the day, that's bottom time not just lurking around in a wet suit. The day begins before dawn and ends after sunset."

In the 1980's it is was no longer necessary to go to 35 or 45 m depth for the large shell. The 10-15 cm young shell required for pearl culture was plentiful at a depth of 18 m or less off the Eighty Mile Beach. Badger's log showed an average of 7.2 hours diving per man per day for the 103 days of the diving season.

Helmet divers had traditionally worked drifts below a moving lugger. Bruce Farley devised a system with multiple air lines, boom collection bags and weights, which would set the pattern for the future. The lugger drifted down wind or down tide, its speed controlled by a canvas drogue at the stern. The divers were towed a metre above the bottom, spaced out by wide booms on either side of the vessel, their depth controlled by a weight travelling just above the bottom. They breathed from surface supply hoses.

Ejiri and Takata, two very famous helmet divers, continued to dive until 1975 but by 1980 the remaining Japanese were using modern equipment identical to the Australians.

Most luggers at that stage (1981) were not using oxygen. This was introduced when they decided to extend into the deeper fields,again because of the universal fisherman's tendency to over exploit and deplete fishing stocks.

Divers then did 6-8 dives a day with a duration of no more than 40 minutes a drift. At the end of the first dive they purged for 5 minutes at 9 metres on oxygen, from a separate demand valve. By the final dive the purge time might be increased to as much as 20 minutes. The maximum safe working depth was considered to be 35 m, but they often went deeper.

In 1993 off the West Australian Coast, 74 pearl shell divers completed 21,452 dives and spent 15,000 hours underwater. Also more than 8,000 hours of diving were logged from 13 licensed pearl farms, turning and tending the shells.

The Australians had reclaimed their industry.

The dangers [1-10]

It was inevitable that many accidents would occur, related either to the environment or the equipment.

A recent survey[10] showed the relative incidence of diseases experienced by pearl divers over the 1988-91 seasons were DCS 45%, ear problems 15%, salt water aspiration syndrome 10%, marine animal injury 7% and respiratory infections 6%.

THE BENDS - DECOMPRESSION SICKNESS (DCS)

Early cases

On February 6th 1892 The Lancet published a letter by a naval surgeon, P W Bassett-Smith, aboard HMS PENGUIN, which was surveying the north-west coast of Australia, the centre of the pearl oyster fishery industry.[6] Several cases of "Diver's Paralysis" became known to him. He described a situation in which the, mostly Japanese divers, would spend many months a year at sea, diving from 10 to 25 fathoms (18-45 m or 60-150 ft) for periods of 4 to 5 hours per day.

He described the disorder as coming on rapidly but usually recovering completely. He also described a case of a 30 year old Japanese diver, who had worked at 32 fathoms (58 m or 192 ft), which was considered a dangerous depth, dying at sea after developing his divers' paralysis. He also described a previous case, with a far better outcome.

Dr Graham Blick,[7] the District Medical Officer in Broome, WA, from 1900 to 1908, looked after some 400 pearl divers, diving from 7 to 20 fathoms (13-36 m or 42-120 ft), but occasionally as deep as 25 fathoms (45 m or 150 ft). Diving occurred several days sail from port and he observed many serious and often fatal cases of "diver's paralysis".

Blick noted that most of the diving was carried out safely, by virtue of the very slow ascent rate to the surface, compared to divers elsewhere.

Nevertheless, not counting the "diver's rheumatics" (presumably musculoskeletal decompression sickness) he had seen approximately 200 cases of diver's paralysis, 60 dying and having postmortem examinations.

Of the 140 cases who did reach port alive, 11 subsequently died from renal infections with septicaemia and sometimes supervening meningitis. Most of the rest recovered, with only about 10% being permanently affected by slight paraesis, especially of the anterior muscles of the legs. The initial presentation of these patients was with paraplegia and an inability to urinate.

Although some patients had the paralysis on a number of occasions, clinically there was no subsequent extensive degeneration of the cord even though there was extensive degeneration in the postmortem cases.

He noted that with this form of paraplegia, nature was kinder than usual. He was astonished at the way apparently hopeless paraplegics could recover in the course of many months.

In some cases the paralysis of the bladder and loss of ability to micturate was practically the only symptom calling for attention. Some patients walked to the hospital asking for catheterisation. They often carried urinary catheters on the diving boats.

The usual history was that the divers had extended their exposure longer or deeper than customary, and/or that he had hurried to the surface. Soon after removing the diving dress the symptoms appeared, either gradually or suddenly. Deaths could occur within an hour or up to a day or two after the incident.

The 60 autopsies performed, all presumably many days after death, showed a "larger evolution of gasses and greater dissension of tissues than is the case with other bodies after equally sudden death". Almost invariably the heart, lungs and large veins were engorged with dark liquid blood. The spinal cord showed a characteristic "teased" appearance and minute haemorrhages were present, together with free blood in the dural canal. The thoracic viscera and large veins of the neck were engorged with dark liquid blood. Section of the brain was generally negative, although sometimes "the blood points seemed rather larger than usual". Only once was haemorrhage found in the brain, and this was a very small one in the internal capsule. Haemorrhages were found throughout the cord.

"Teasing" of the cord was meant to imply that the face of the section looked as if it had been stippled with a fine knife or needle, a semi-disintegrated appearance. It was nearly always associated with haemorrhage, of greater or lesser extent. Occasionally there were large haemorrhages practically cutting the cord in two and forming clots of more than an inch long.

He noted that the divers started working at about March and then there were practically no cases of paralysis before September and these continued then until the end of November, when the cases came in almost daily. One explanation for this was that they were working further out in the deeper water, having collected the shell from the shallower ones in the earlier part of the season.

DCS Statistics

Initially the depths were limited by the capacity of the hand driven air pumps, introduced in 1884. Even then, as the shell became depleted by over harvesting the divers were enticed to go deeper and stay longer, with the further development of "the diver's bends".

In 1890 in the rich Cygnet Bay area, divers had become more daring and were moving into deeper water than those in the Torres Strait. With the water from 19-24 fathoms (34.5-43.6 m or 114-144 ft) deep, there were unexpected depths and the bay became known as Graveyard. The *Bulletin* reported that it was a common sight to see a dead diver brought the surface and divested of his diving dress, so that another man could use it at once. On some boats the black flag is run up so often that no one takes any notice. One owner lost 8 men in 8 days.

In 1912 the Royal Navy brought with them the engine driven compressors, which replaced the hand pumps and allow deeper excursions. This directly led to the increased fatalities. The engine pumps allowed the divers to descend to 40 m (133 ft), where they found magnificent virgin beds of huge untouched shell. Then they reached 60 (200 ft), and then 80 m (264 ft).

The Japanese cemetery in Broome and the divers cemetery on Thursday Island have a forest of grave stones which tell their own story. From 1907 to 1917, 145 helmet divers died working out of Broome. In 1914 alone, 33

Figure 2. The Japanese cemetery, Broome.

divers died from divers' paralysis. Fourteen Japanese divers died on one patch of shell alone, the notorious Darnley Deeps. The Government closed the area, as being too dangerous, but divers would still sneak in and reach the rich shell beds. The total from all the Australian pearl ports from over the years may have reached 1,000. Most of the deaths were caused from the "bends".

In 1915 a Broome Pearlers Association report described a deplorable loss of life that had occurred from divers' paralysis, 21 men having died in that season. The reason for the reduction from 33 to 21 was because half the fleet were out of commission due to World War I. Two recompression chambers, one for each of the pearling areas, were gifts from 2 firms, Heineken and Company and Siebe Gorman Ltd. This was an attempt to reduce the death rate. The chambers not only saved many lives but prevented many men from spending their life as paraplegics.

One of Lou Marshall's divers set a grim record in the 1930's. He was brought up badly paralysed, and became unconscious. He was sent back to the bottom with a companion diver to work his exhaust valve and was nursed through the hours of darkness. He spent 36 hours underwater before he could be brought back on deck. Nevertheless the diver's life was saved.

In 1981 the death rate was down to 1, the lowest on record for over a hundred years.

Traditional treatments

The Japanese divers endurance was exceptional. In the 1980's two of the divers had become legends in their own time, Shoji Takata and Noritsugu Ejiri were both head men. The traditional diving that they performed was well in excess of the Royal Navy or US Navy tables.

Takata stated "We did 8 dives a day to 25 fathoms (45.5 m or 150 ft). We would spend about half our time on the bottom, and then come up slowly, spend about 10 minutes on deck between drifts, and then down again." They decompressed below the boat after each dive, and at the end of the day for about an hour below the lugger. The tenders would strip off the suit and the gear, and then a very important ritual followed. "We would sit for one hour. Sit very still. Not move an arm or a leg. Hardly even our eyelids. Just look over the sea." If at the end of that time the diver felt no twinges in his joints, he would cautiously raise himself to have his dinner, a welcome cigarette and perhaps a glass of port wine to keep out of the chills and the rheumatics. Divers were always cold at night, no matter how warm the water. As soon as he had eaten he would return to his bunk, dog tired. He would lay down, praying that he would not be wakened by the pains. "Usually the shoulder first, then you know." If the pain increased the diver would have to struggle back into the suit and hang underneath the lugger until the pains went and decompression was complete. Sometimes he would look forward to the next morning when he could resume his diving, and also get rid of the pain while he was underwater and under pressure.

Takata said, "I had the bends maybe 40 times. One time I had no feeling down my left side. No feeling in scalp, arm, leg, the whole of the left side of my body. That lasted maybe 2 years. I was all right. OK underwater though. My diving was not affected."

Ejiri, on the other hand, had never had a bend in his life. Most were afraid to dive with him because of his incredible endurance.

The Asian and Japanese divers often were not interested in the concept of staging, as they hated hanging from the boat, being jerked and tossed in their harness below the lugger, dangling in mid-water. Gradually the value of staging became evident. The old truculents retired, became crippled and were pensioned off, or were carried off to the graveyard.

A Thursday Island diver described the problem as follows: "When you are all anchored at night, and you hear a boat engine starting, you know some poor bugger has got the bends. They could hang him at night. They put him down at depth on the buoy anchor, he sits on it and we gradually stage him up."

"It was only shallow, 20-25 fathoms (36-45.5 m or 120-150 ft), and the first diver felt the air pressure wasn't coming through the airline properly, so he came up and he said to pull his brother up. I gave the signal, and instead of him coming up shortly, he just closed his clip. Once you close your clip in a dress, you come up like a balloon. And up he came. And as soon as we put him on deck he turned purple, and this is what they call heartcrush. He started vomiting and then became semi-unconscious. We tried to put him over the side again. We took him down, by putting him upright, and standing on his diving boots, as far as we can, and we leave him there. No sooner had we surfaced, when he came up too. We finally we got a bit of fishing line and put a clove hitch in his air clip, and that kept him down. We kept him, and we hanged him three days, and three nights."

"He just came to the surface to eat and drink now and again. The only thing he couldn't do was pass water. So we put the tube in and drew blood, so we had to bring him in to Thursday Island. We left him in the hospital in Thursday Island and went out to work at that neap. When we came back he was ready to come out with us again, to work".

Oxygen decompression

In recent years[3,8,10] the use of oxygen has greatly improved the divers capability of eliminating nitrogen from the fast tissues of the body, reducing the likelihood of severe decompression sickness. This, in turn, has resulted in divers sometimes extending the depths - but with the possible greater risk of dysbaric osteonecrosis ("bone rot").

By 1982 vast beds were discovered in 20 to 26 m (66 -87 ft). These were obviously the areas the Japanese used to work in. Alan Badger stated that the 1983 counterparts logged many hours in excess of those recommended by the dive tables. "We get by with careful decompression and by breathing straight oxygen for the last few minutes in the water." The use of oxygen has made a marked difference in keeping the older divers on the active list. Broome lies 10 hours of lugger travel from the pearling grounds and for a sick man this can be a lifetime. Badger stated "Its a hard decision to make, turning back to Broome when you are on a good shell, but sometimes it has to be done".

By the 1990's the industry had combined to form the Pearl Producers Association, and bought a recompression chamber installed at Broome Hospital for a cost of $180,000. By 1994 it was claimed that the decompression sickness had been reduced to an all time low. From divers in 1993 there were only 3 minor cases, all treated at sea. "We have not had to decompress a diver in the chamber since 1992" (David Appleby personal communication 1994).

OTHER DIVING ACCIDENTS

Many diving problems developed from contaminated air supply, entanglement of hoses, trauma from the boats and their propellers, entanglements between divers, etc.

Marine animals abounded and so did injuries from them. On November 21st 1993 Peter Richard Bisley was working on a pearl farm in 14 m (46 ft) of water at Roebuck Bay, when he was taken by a Tiger Shark. Although there was considerable alarm and amazement expressed at the time, there had been many such previous cases. Roebuck Bay had always been a bad place for shark accidents and numerous ones occurred there last century. There are also many other areas in which shark attacks occurred, but were often not documented in the medical literature.

In the Torres Straits the divers were more concerned with giant groupers than sharks.

In earlier days there were large number of deaths from crocodiles, in all three main areas, the North-West, Darwin and the Torres Straits. With increasing crocodile numbers and their ability to swim many miles from land, we can anticipate more in the future.

Even manta rays, gentle beasts with no malicious intent, would get hooked up on the air lines and cause accidents. Whales were sometimes a problem as they would tend to rub themselves against the air hose, possibly to remove barnacles.

Also present in the area were sea snakes and some injuries from these have been recorded. Stone fish proliferate throughout the area as do "dream fish". Stings are common and sometimes severe.

Other causes of death included cone shells, marine infections and coral cuts.

Perhaps the most worrisome and numerous injuries come from the jelly fish known as Irukandji (*Carukia barnesi*) and this has caused abandonment of many diving operations. The stings tend to be more common in the early part of the season, March-May. The severe abdominal pain and disorder of consciousness that occurs with these cases, makes them an acute medical emergency, with the potential of being fatal.

Acknowledgments

This history is a synopsis, with many verbatim quotes, of the documentation of three brilliant historians Mary Bain, Hugh Edwards and Ion Idriess.

The diving practices are also described by them, the Australian Broadcasting Commission programs on Thursday Island pearlers and the excellent physiology researchers who have learnt from the divers, Dr Hugh LeMessurier,[11] Dr Brian Hills[12] and Dr Robert Wong.[13-15]

The author's own visits to Thursday Island, Darwin and Broome between 1962 and1989, to socialise with the divers, both new and old, swap yarns and to dive the pearl grounds, were meant not only to collate information but also to collect traditional diving know-how. If, at the same time, he found a unique and priceless gem that would set him up for the rest of his life, then so be it.

Key Words

Decompression illness, deaths, history, occupational diving

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PEARL DIVING FROM BROOME

Robert M Wong

Abstract

Pearl diving in Australian waters began towards the end of 19th Century. Over the years the current mode of diving has evolved.[1] This paper traces the modifications to diving from drifting vessels (drift diving) which have led to the current practise in pearl diving in Broome.

Historical perspective

Broome, a town in Western Australia 2,600 km northwest of the city of Perth, is well known for its pearling industry. The areas fished are the seas off the Eighty Mile Beach down to Port Hedland. This area has large tidal variations. The mean high water spring tide is 9.4 m, mean low water spring tide is 1.1 m, while mean high water neap tide is 6.4 m and mean low water neap is 4.3 m.

For those with a limited aquaintance with the sea, neap tides are small tidal ranges which occur twice a month when the tide producing forces of the sun and moon are in opposition. Spring tides are large tides which occur when the sun and moon are acting in conjunction, around the time of full and new moon. The tidal range for both is measured from half tide level.

The colourful history of Broome and its divers is very well covered by a number of authors.[2-4] Some of the historical aspects of this article comes from H Edward's book "Port of Pearls" and is reproduced here with the author's permission.

Pearl fishing in Western Australia dates back as far as 1861 when the British colonists first noticed the necklaces made from pearl shells worn by the local Aboriginal population. The Mother of Pearl (*Pinctada maxima*) shells were obtained by breath-hold diving in Roebuck Bay, off Broome, by the indigenous population. The birth of the pearling industry in Western Australia was breath-hold diving around Broome. In the early days of the pearling industry, the local Aborigines were "engaged", with little choice, for breath-hold diving.

However, when compressed air diving, using a hand powered pump with a canvas suit and brass helmet, was introduced, the divers were brought in from afar. They were mainly Japanese, Malays, Koepangers (from Indonesia) and Arabs. It is believed that the first Japanese divers were brought to work in Port Darwin in 1884.[2] Nowadays days, the divers are mainly Caucasian Australians and New Zealanders.

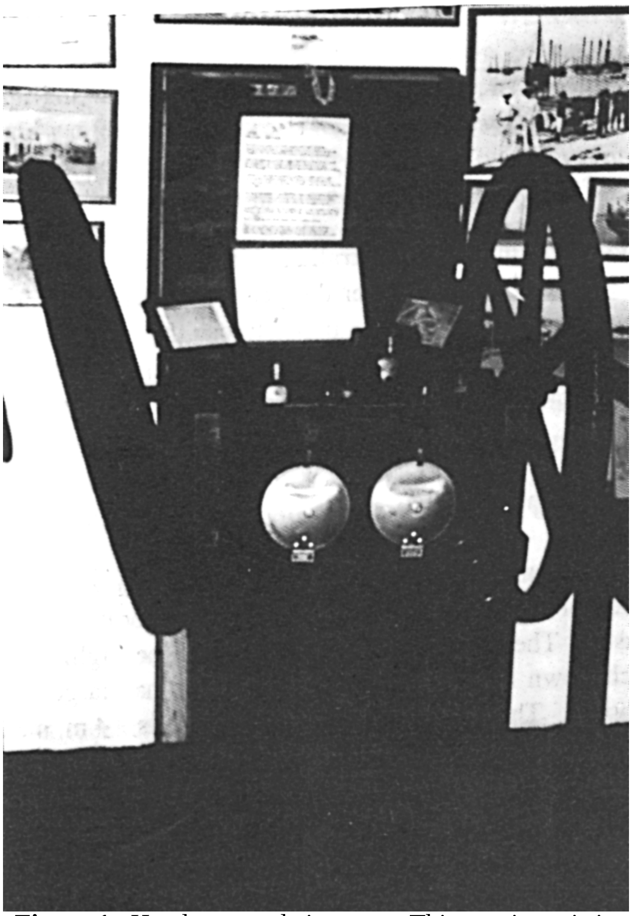

Figure 1. Hand powered air pump. This specimen is in the Broome museum

Compressed air diving was introduced to Broome in 1884. The depths achieved were limited by the ability, or more properly inability, of the pumps to provide sufficient air to the divers at depth.

It has to be stressed that in those early days, compressed air diving was extremely hazardous. Bert described cases of deaths and spinal cord decompression sickness (DCS) in Mediterranean sponge divers in 1868.[5] In Broome the divers also suffered death and permanent injuries, mainly from DCS but also from cyclones.

In 1892 Dr Bassett-Smith , a surgeon in the Royal Navy who visited Broome while on board HMS PENGUIN, published a case report of a death resulting from severe spinal cord decompression sickness in a diver after diving to 32 fathoms, 192 ft or 58 m (1 fathom=6 feet or 1.8 m).[6] Later Dr Graham Blick, a District Medical Officer in Broome from 1900-1908, reported that "diver's paralysis" was a common condition among divers and that no diver would consider his outfit complete without a soft catheter for bladder catherterisation in the event of spinal cord DCS.[7] The divers went to depths of 7 to 20 fathoms (12-36 m or 42-120 ft) sometimes even to 25 fathoms (45 m or 150 ft).

The dive profiles used were derived purely from trial and error. The early pearl divers had no knowledge of any decompression tables as these were not devloped until 1908, when Haldane's tables were produced for the Royal Navy.[8]

Attempts to introduce what is now conventional diving, with staged decompression using the Haldanian tables, were made in 1912 when 12 ex-Royal Navy divers and tenders arrived from England. They brought with them engine driven pumps to replace hand pumps. Before the end of that diving season, one of them was dead and another was paralysed. Eventually, the rest of the team left Broome. Diving depths and times reverted to the old technique of trial and error.

With the introduction of engine driven pumps, far greater diving depths were achieved, more divers developed DCS and more fatalities occurred. However, the number of dives undertaken is unknown so one cannot calculate the risk of death accepted by the pearl divers.

In 1913 Heinke and Co., who supplied the diving equipment used by the pearlers, donated a recompression chamber (RCC) to treat "diver's paralysis" (Fig 2). It was essentially a metal cylinder, without a porthole, into which the paralysed diver was put, pressurised and then slowly decompressed. That year 29 deaths were recorded and in 1914 the peak was reached with 33 deaths from diving, mostly from spinal cord DCS paralysis, infected bedsores and urinary tract infections.

Due to a combination of factors, among them the great distance from Perth, poor communications and lack of knowledge of how to dive safely, the pearl divers, out of necessity and self-preservation, evolved a system of diving techniques which was unique and worked well enough to contain the incidence of DCS to an "acceptable limit".

TABLE 1

DEATHS AMONG DIVERS IN THE BROOME PEARLING FLEET 1910 TO 1920

Year	Deaths
1910	11
1911	10
1912	9
1913	29
1914	33
1915	21
1916	19
1917	12
1918	1
1919	3
1920	4

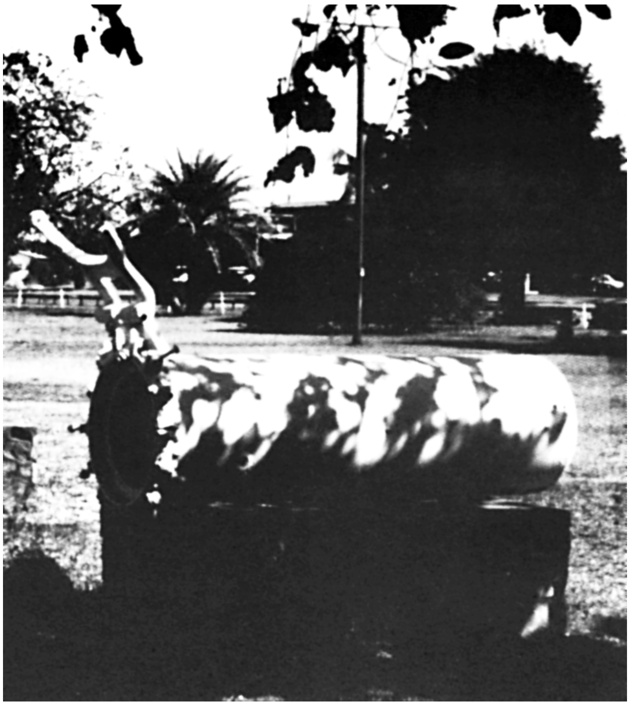

Figure 2. Heinke and Co recompression chamber on display in a Broome park some years ago.

These well tried, but dangerous, recipes were passed from generation to generation of divers and form the basis of the profiles now in use, which are merely refinements of those recipes which cost hundredst of lives and thousands of cases of DCS to develop.

Interviews with divers who dived in the 1950s, 1960s, 1970s and 1980s led to an appreciation of the development of the dive profiles. The decompression procedures remained essentially unchanged. The most significant change was the introduction of oxygen in decompression and its use in recompression at sea.

Diving in the 1950s and 1960s

Some of the personal experiences of the bends were perhaps not entirely accurate as memory fades with time. Nonetheless, the dive profiles described by the divers were consistent.

The ex-divers interviewed came from Japan as "try divers", basically they were on probation to test their suitability as divers. They worked as deck hands, and were taught to dive by the "Number 1 diver". They would dive occasionally or would replace one of the two divers when one of them was ill. This training lasted from 6 months to a year.

They had a concept of "strong" and "weak" divers. Strong and weak did not refer to physical strength, rather it was used to refer to the diver's ability to avoid DCS. It was a natural occurrence akin in some ways to the high or low

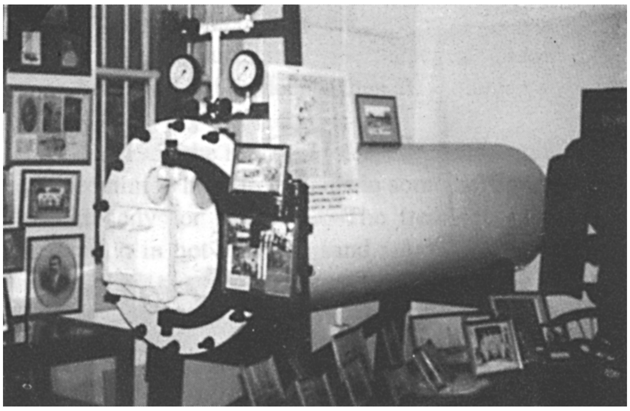

Figure 3. Heinke and Co recompression chamber restored and on display in the museum.

bubblers found in Doppler studies. The weak divers would need to stage after each dive and would ascend slower than the strong divers. It was said that some of the strong divers never got bent.

They dived for pearl shell from March to December and would be away from Broome for a minimum of 3 weeks at a time, diving every day of the week except Sunday, when they would have a day off. This was different from the days of Bassett-Smith in the 1880s and 1890s when the luggers were away for months at a time. The lugger usually carried only 2 divers and very rarely 3. Interestingly enough, they only dived in deep waters after August of each year and this coincided with the time when the divers got serious bends. At the beginning of the year, they only dived in shallow waters.

The luggers would fish in shallow waters, but if the shells were fished out, then they had to go to deeper waters. Also during Spring Tides, visibility in the shallow was poor, and they had to go deeper.

The Mode of Diving

Irrespective of depths, they dived from sunrise to sunset, about 12 hours in winter and 13 hours in summer.

SHALLOW WATERS

These were usually less than 10 fathoms (18 m or 60ft), but up to 12 fathoms (22 m or 72 ft). Bottom times were around 50 to 60 minutes. There was no staging in shallow waters. If the patch of ground had few oysters, the divers would surface after only 15 minutes. They ascended slowly, the rate being controlled by the diver adjusting the air flow into the helmet. With the expiratory valve setting unaltered increasing the air flow inflated the suit making the diver more buoyant.

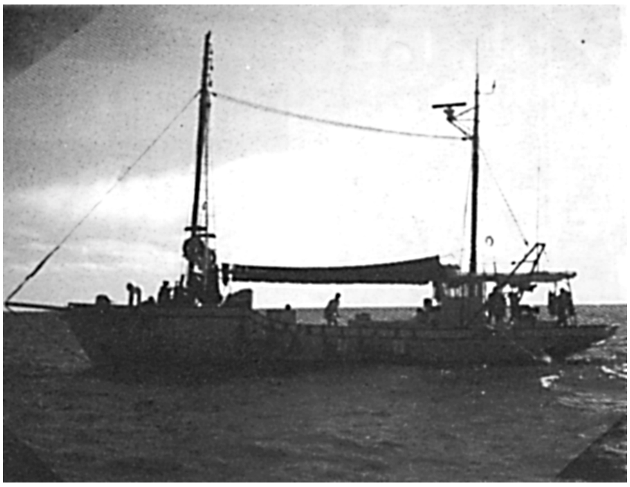

Figure 4. The last of the old pearling luggers.

As it usually took the lugger 15 to 20 minutes to turn around for another drift this time was the surface interval between dives whatever the depth.

MID-WATERS

At these depths, to about 15 fathoms (27 m or 90 ft), they used a shorter bottom time, usually around 45 minutes, but it could extend to an hour.

The ascent rate was slower than in shallow waters. The exact time is not known, as they wore neither depth gauges nor watches. The timing was kept by the tender on the lugger.

At this depth they would decompress after every dive, slowly ascending over about 3 minutes to 7 fathoms (13 m or 42 ft), approximately 2-3 fathoms per minute (3.6 to 5.5 m or 12-18 ft a minute). They spent 5 to 15 minutes at this depth and then took about 5 minutes to reach the surface (1.4 fathoms, 2.5 m or 8.5 ft a minute). The duration of staging was determined by Number 1 diver. The Japanese divers used to say that "a diver knows his body", meaning that if he ascended too quickly, he would know it, and if he did not stage, he would also know, presumably because he would suffer symptoms of DCS. The life line had markings at each fathom and the tender hit a gong, or made some other noise, to inform the diver that he had reached 7 fathoms (13 m or 42 ft) for decompression. Some of the "strong" divers would not bother with "staging" and would ascend faster. If the weaker divers follow suit, because of pride or embarrassment, they got bent.

At the end of the day, however, after the last dive, all divers would do a decompression stop. The depth was at 7-8 fathoms (13-15 m or 42-48 ft) for about an hour.

DEEP WATERS

They were careful to take 3-4 minutes to reach the seabed. At this depth, 15-25 fathoms (27-45 m or 90-150 ft) the bottom time was never longer than 40 minutes.

The ascent rate was slower than for the other 2 depth ranges. It took about 10 minutes to reach 7 fathoms (13 m or 42 ft) for their staging (1.8 fathoms, 3.3 m or 11 ft per minute). At the end of the day there was the usual one hour hang off at 7-8 fathoms (13-15 m or 42-48 ft).

Surface intervals were fixed by the time taken to get the lugger into position for the next drift, usually 10-20 minutes between dives.

After surfacing at the end of the day, there was a ritual in the undressing. The diver sat on deck and had the helmet and breast weight removed. He sat very still for about 20 minutes. If at that time he did not have symptoms of DCS, the corslet would be removed. He ate his dinner with his diving dress on. After dinner he sat motionless for another 20 minutes and, if all was well, then the dress would be removed and the diver went to bed, wearing his diving underwear and stockings. He pulled a blanket over himself and if he felt warm he knew that all was well. He would only then get changed. They obviously understood that post-dive exercise was inadvisable.

Decompression sickness and its management

Most of the older divers had suffered numerous episodes of DCS. They viewed musculo-skeletal DCS as an inconvenient and unavoidable occupational hazard. If the divers suffered pain during the night, they would get back into the water and hang off. They would go to the depth of relief and after half an hour or so start to ascend very slowly, usually taking all night. Interestingly enough, these hard hat divers' DCS tended to affect the knees, occasionally the elbows, but virtually never the shoulders. In deep waters spinal cord DCS was common.

Case Histories

CASE 1

Diver M, aged 63 in 1994, came to Broome in 1955 from Japan. He learned to dive from an old Japanese diver who had started diving long before the second World War. During his first year, he burst his tympanic membrane by too fast a descent to 9 fathoms (16 m or 54 ft). His apprenticeship took about 6 months.

In 1956, he dived daily to about 12 fathoms (21m or 72 ft), with a bottom time of about 50 to 60 minutes. The descent took about a minute. They dived for about 12 hours a day in winter and 13 hours a day in summer with 10-20 minutes between dives.

He suffered numerous episodes of musculo-skeletal DCS. This occurred usually after dinner when he lay down. Treatment of this kind of DCS was by recompression in water at depths of 7 fathoms (13 m or 42 ft). Duration varied from 1 or 2 hours to around 10 hours, depending on the level of pain and the response to the treatment.

He suffered 2 serious incidents of DCS. The first was in November 1956 after a dive in the deep waters, greater than 20 fathoms (36 m or 120 ft). He recalled that it was the middle of the day, and was definitely after lunch. Five minutes after surfacing he developed "tunnel vision" in his left eye. The periphery of the visual field started to darken and within minutes he had no vision in his left eye. Then he noticed an ache in the eyeball. He could not recall any other symptoms of note. There was no headache, no weakness, no numbness that he could remember. He was returned to 7 fathoms (13 m or 42 ft) and, after about 10 minutes, vision began to return. He remained at depth for 45 minutes and vision returned totally. He did not dive for the rest of that day, but dived again the next morning. He was adamant that there were no other associated symptoms.

Another incident was in September 1957. It was after the 8th dive of day 4 to depths of 23 fathoms (42 m or 138 ft). He recalled that about half an hour after dinner when he was lying down, he felt sick and nauseated and ready to vomit. He felt the top half of the body was numb, although he could use both arms. He managed to get on deck, his tender dressed him and he was returned to 23 fathoms (42 m or 138 ft). He thought that was about 8 p.m. As soon as he reached bottom, he started to ascend, about a foot (0.3 m) every 5 minutes or so. However, as he started to ascend, he felt a gripping pain inside his abdomen on the left side. He also felt difficulty breathing, as if a ball got stuck in his throat. The symptoms persisted for some 6 hours. He tried to ascend, but could not get above 20 fathoms (36 m or 120 ft), as the symptoms worsened when he tried.

About mid-day the following day, he was still at 20 fathoms. A nearby lugger, with a cousin of his on board, sailed alongside. After he had heard the story, the cousin told the tender to pull "M" up to 15 fathoms (27 m or 90 ft). He experienced a lot of pain on ascent. He spent another 4 hours at 15 fathoms (27 m or 90 ft), then the pain gradually subsided. When he attempted to ascend again, the pain returned. Nevertheless, he was hauled up to 7 fathoms (13 m or 42 ft), where he experienced a lot of pain. But after another 4 hours, the pain disappeared. Thirty six hours after the start of his treatment he surfaced. Feeling very weak, he was carried to his bunk. The lugger returned to Broome and he was taken to the hospital. No appropriate treatment was given. There was no recompression chamber in Broome. M was scared and he stayed ashore for a month. Then he returned to diving, however, he noted that he was fine if he only dived to 10 fathoms, if the depth was deeper, he would experience similar pain on surfacing. He persevered the following year, but could not go deeper than 10 fathoms (18 m).

In 1958, he returned to Japan. Some retired divers advised him to have treatments in some hot springs, which he did daily for 5 weeks. The treatment consisted of immersion in hot volcanic sand. A hole was dug in the coarse black sand and he was covered, except for his head, for 15 minutes. After 3 minutes the pain appeared, but it always subsided after 2 minutes. Religiously, he had this treatment. One day, he felt as if the pain from his abdomen had "come out of his body through his left leg and departed through his left big toe". This feeling happened daily for 2 weeks. After that he had no more pain. He remained in Japan until 1960 then he returned to Broome. However, when he dived deeper than 10 fathoms (18 m or 60 ft), the pain would return. Finally, he gave up diving and taught a young cousin to dive.

M now lives in Broome. When he gave up diving he worked with engines, now he works as a maintenance man. He appears to be fit and healthy. M has had long bone X-rays, but he does not know of any problems, although he is aware of divers with dysbaric osteonecrosis. He himself is fully mobile and has no problems with any of his joints. The only thing he admitted to on questioning was that he does have problems with noise discrimination, perhaps from the noise of the air inlet in his hard hat diving days or from working with engines.

CASE 2

The young cousin served his apprenticeship like M. He too suffered serious DCS affecting the spinal cord. This occurred in 1961 after diving in 15 fathoms (27 m or 90 ft). He was unable to walk. Similar in-water recompression was given and he was in water for 24 hours. There was no improvement. He was taken to hospital and transferred to Perth. No improvement was seen and he returned to Japan where he had hot springs treatment. Over time, he recovered slowly. In 1974, the cousin married and fathered 2 children.

CASE 3

Another retired diver, H came to Broome in the 1950s from Japan as a try diver. He was taught to dive by a diver called Hojo. H claims that he suffered 25 episodes of musculo-skeletal DCS each year. He, too, suffered a major bend that ended his diving career.

This serious DCS occurred in November 1960. He was diving off Port Hedland in waters between 19-23 fathoms (35-42 m or 114-138 ft). It was the third day of diving. He admits to missing his staging. Within 60 minutes of surfacing, he felt sick, with a strange sensation over his left side of his abdomen as if his intestines were being squeezed. When he tried to stand up, it felt as if someone had thrown ice cold water over the lower half of his body. Although he could stand, his legs would not move. He was carried to the ladder and lost consciousness, only to wake up when his feet touched the seabed. He felt alright at depth and stayed for half an hour. Then started to ascend at about 1 foot (0.3 m) at a time and paused for half an hour at each depth until he reached 7 fathoms (13 m or 42 ft). Although he had not finished his treatment, he surfaced around midnight to urinate as he did not like to urinate in his diving suit. At that time he had been in the water since 7 p.m. He was again returned to the seabed to repeat the decompression procedure, again with a slow ascent to 7-8 fathoms (13-14.5 m or 42-48 ft), eventually surfacing at 10 a.m. the next morning. He had had approximately 14 hours of in-water recompression. In the afternoon, someone gave him a cup of tea, and after one sip, he felt sick again with pain in his gut. At about 3 p.m., he was recompressed, surfacing at 5 a.m. the following day.

Unable to walk, he had to be carried to Port Hedland Hospital, where he remained for 3 or 4 days. T here was no appropriate treatment available. He was given some sedation and was discharged. Interestingly enough, he flew home to Broome rather than travel by road and remembered that in the air, he felt very sick again.

It took about one month before he started walking again. But it was another year before he regained enough strength to walk normally. He gave up diving after this episode of DCS. He remains in the pearling industry. The family business is conducted by his sons who are pearl divers.

During the 1950s and 60s, there were 4 deaths that the divers were aware of, unfortunately, no details were available and the divers could not remember very much. They remembered that one was a Japanese, who died from a “heart attack”, the others were Chinese, Malay and an Arab. They all died from serious DCS in deep waters and were dead when they surfaced.

Diving in 1970s and 1980s

The method of diving outlined continued in much the same fashion until the 1970s. This was the decade which saw major changes.

When the news of the success of abalone diving using the hookah system, instead of scuba, reached Broome it spelt the end of hard hat standard dress diving. Hookah is a surface supplied breathing apparatus (SSBA) using a compressor, pressurising a reservoir, to supply air to a wet suited diver, using a scuba second stage regulator on a long hose , who wears a mask covering nose and eyes.

In 1971 hookah diving was introduced to Broome where divers were still using the old fashioned hard hat.

The impetus for change came from Peter Cummings, who at the time was fleet manager of Pearls Pty Ltd (PPL), which in 1971 was the largest pearling company in Broome. Peter, who was an ex-Royal Australian Navy (RAN) officer, got in touch with a naval colleague, Commander Batterham, to get the help of some abalone divers. The first contact made was an ex-abalone diver, Dale Chapman, who enlisted Allan Stanley Badger and Bruno McKenna. Allan was a spearfishing champion and an abalone diver from New South Wales and Bruno was an abalone diver from Mallacoota in Victoria. These men arrived in Broome in April 1971.

Initially, these divers worked from the 60 ft (18 m) lugger *John Louis*, which Cummings, Chapman and David Dureau (a son of one of the owners of PPL) sailed down from the Torres Strait. The *John Louis* is now housed in the Darling Harbour Maritime Museum. The initial team consisted of Peter Cummings as skipper; Chapman, Badger and McKenna as divers; Frankie Bowie, a Torres Strait Islander, as engineer and David Dureau as deckhand.

The diving was done with the air hoses dangled over the sides of the lugger and when in motion, the divers were lifted off the seabed which made it very difficult to pick up shells. During the first months, they only managed to pick up about 16% of what the Japanese divers, who walked along the bottom, did. Not making much money, Bruno McKenna left Broome after about 6 weeks.

In 1971, the divers made use of SOS decompression meters (DCM), known at the RAN School of Underwater Medicine as “Bendomatics” because of the number of sport divers presenting with DCS who had used them. This was a gauge with a bladder inside where increased pressure forced gas through a ceramic filter simulating gas uptake. The dial showed green, safe to ascend, and red meaning into decompression time. The divers surfaced when the pointer came close to the red marking. They would stay on deck until the needle return to the black, theoretically degassed. It was common to dive to 18-21 m (60-70 ft) in 1972 and a lot of time was spent on the surface watching the DCMs. There was a lot of variation between DCMs, so the divers took an average reading! Eventually, after some 4 years, the divers considered the DCMs to be “too conservative and restrictive” and they stopped relying on them. Allan Badger could not recall any diver suffering any incidents of DCS using the DCMs with their system of average reading (average of the readings of the 4 DCMs after each dive).

Diving for pearl oysters was very secretive and competitive and the Japanese divers would not disclose their secrets.

The manager of PPL in Broome, Alby Ross recruited two men who had a lot of experience in pearl

Figure 5. Tender of hard hat diver on outrigger platform.

diving operations working as tenders on board Japanese pearling luggers. One of these was Jimmy Hunter, an Aborigine, the other was Guy Williams, a Torres Strait Islander. They had learned a lot about the way the Japanese dived.

After lengthy discussions, Chapman and Badger wanted to use shot lines with lead weights and work ropes and drogue to slow the lugger. They also wanted some kind of outrigger (boom) to separate the divers when drifting. Cummings was not prepared to spend the money for the modifications and had also said that a drogue was out of the question. Cummings, being an ex-naval officer, did not take kindly to being told what to do by his men, so there was some conflict. When Cummings unexpectedly returned to Melbourne on business, the divers managed to get what they wanted.

Most of the major changes in pearl diving occurred in 1971-72. The divers "acquired" the outriggers from the Japanese luggers which were lying around in the yards of PPL. These outriggers were wooden booms which had small wooden platforms at the distal end of them on which the Japanese tenders used to sit to tend to the life and air lines of the divers (Fig 5). Badger calls them "Japanese verandahs".

From the outriggers, these new style divers rigged shotlines, with lead weights on the lower end, from the shot lines were work ropes which trailed along the seabed. The original work ropes were only 6 m (20 ft) long, which was too short for effective pearl collecting. Furthermore there were no neck bags to put the oysters in, although they had abalone bags which they placed on the shotlines.

In June 1971, some 2 months after the PPL team started, Bruce Farley, an abalone diver from South Australia, arrived in Broome to work for the Brown family in the oyster farm in Cygnet Bay. Farley brought with him his abalone runabout and diving gear intending to use it for shell collection. He discovered that his gear was

Figure 6. The Cornelius at low tide. She is now used for touring in Broome waters.

unsuitable and started to use the Brown family's lugger.

As the months passed Chapman and Badger would discuss the various diving techniques, in the local pub, with Farley who mentioned the use of "neck bags". After this, Badger made use of all the available equipment and techniques. The result was that the catch improved dramatically, reaching a catch rate equal to that of the Japanese. At the end of their first year, they added pulleys to the end of the outriggers for the shot lines.

By 1972, these ingenious divers had replaced the wooden booms with longer steel pipes designed and welded by Alan Nunn of Newcastle, a boiler maker and spearfisherman, who could make up whatever gear the divers needed. He was recruited by Allan Badger. Dale Chapman also recruited John Monk of Melbourne, a hard working abalone diver and spearfisherman.

When Chapman and Badger arrived in Broome, the divers went to sea for a month at a time as they did in the 50s and 60s. They dived every day except Sunday, but no diving was done during spring tides. However they did not return to Broome, but sailed to Cape Bossut near La Grange Bay to lay up for a week of fishing and resting.

Badger thought that was a waste of time and decided to return to Broome during the spring tides. The management of PPL was displeased by this practice, but in time, everyone followed suit. This is now standard practice.

The Australian way of diving, hookah diving, became common practice in 1972 and even Japanese divers started to adopt the technique. By 1975, the last hard hat diver had retired and the entire industry used hookah. Chapman had by then became a contractor and entered into the business side of pearl diving, while the rest of them became subcontractors.

Use of oxygen in decompression

Badger had numerous incidents of DCS. He spoke to his friend Rick Poole from ProDive in Coogee about his mode of diving. Rick introduced him to two salvage divers, one of whom was Bill Fitzgerald who suggested, in 1976, to Badger that he might try oxygen at 9 m (30 ft) for decompression. He used non-static rubber hose and AGA full-face mask for this procedure.

The use of oxygen for decompression was kept very much a secret. Badger started using oxygen for only 5 minutes at the end of the day but gradually the amount was increased to 30 minutes at a time depending on the depth of the dives. He did not use oxygen between dives. His technique was noted by others, yet because of the secrecy surrounding this practice, no one knew what he was doing. However as he could hear engines being started up in the night to put divers in the water for recompression as cases of DCS continued to occur on other luggers, Badger felt obliged, for humanitarian reasons, to divulge his secret technique and told others about his technique of oxygen decompression in the water.

In time, Badger was asked by Alec Myer, the managing director of PPL to teach the Japanese divers in the use of oxygen in decompression. Badger wrote a 5 page document explaining the reasons and technique. Farley learned the technique and developed his own system and applied it after some drift dives during the day as well as at the end of the day.

Ascent rate

Initially when hookah was used in the industry, the standard rate of ascent of the USN Decompression Table was adopted and this continued for about 4 years. Badger made the observation that divers who ascended slowly did not seem to get DCS, particularly the old hard hat divers who were accustomed to a slow rate of ascent. Furthermore, his previous experience as an abalone diver had convinced him that a slow rate of ascent was safer and after some deliberation, he advocated a slow rate of ascent, hand over hand on the shot rope. This was not adopted universally within the pearling industry. The Japanese who switched over to hookah also ascended slowly but had no specific timing, but it was faster than hand over hand.

Development of the deep profiles (28-37 m)

Since the hard hat diving days of the sixties deep waters had not been dived. In 1981 a new patch of ground was discovered with large shells at depths of 28-35 m. Initially, the divers were not sure how to dive to this depth using the new equipment, except that it should be done with great care, because of the serious DCS symptoms which had affected the old hard hat divers in this depth range. However when using the USN Decompression Tables they could not achieve the desired number of dives, so a differemt way of diving had to be devised.

The only people with any experience of diving these depths were the Japanese divers, but they were very secretive about their diving techniques. However one Japanese head diver, Takata, was prepared to talk about the various techniques with Badger.

Initially, when diving in waters deeper than 30 m, Badger emulated the Japanese and did 8 dives with 30 minutes bottom time in the day. The ascent scent rate was slow, hand over hand on the shot rope, with a decompression stop at 9 m (30 ft) for 5 minutes followed by a slow ascent to the surface. The ascent from the bottom took about 20 minutes. The surface interval was to be no more than 20 minutes, as he had observed that longer surface intervals would produce DCS cases. This technique produced a significant amount of DCS which caused Badger to reduce the number of drift dives from 8 to 7 a day. After drift 7 all the divers would decompress on oxygen. The decompression procedure would take 3 hours (1.5 hours on air and1.5 hours on oxygen). They had 4 divers in the water at the same time. They decompressed in pairs, one on air and the other on oxygen, for 30 minutes then the divers would switch breathing gases. Each gas was on a separate line with a separate regulator. This technique was a secret between 1979 and 1981. This mode of diving formed the basis of the susequent “non-rotational” dive schedules.

Badger experimented with oxygen between dives and found that divers still suffered from DCS if the ascent rate was too fast, irrespective of oxygen usage. He decided upon a slow ascent rate and made use of oxygen decompression only at the end of the day after the last drift. He gave up the use of oxygen between drifts. He believed, as did the Japanese, that post dive physical exertion was detrimental, so his divers did not clean shells after their dives. With different opinions and experiences the various key figures developed their own diving schedules, all aimed at maximising bottom time in the daylight hours.

Badger also believed that each diver has his own decompression time. Some of the younger and fitter divers could get away with little or no decompression, whereas he felt that he needed more and more decompression time, especially as he got older.

Farley and Nunn, on the other hand, developed their own system and decided to use 2 teams of divers, thus saw developing the “rotational schedules”. Instead of having a fixed 20 minute surface interval, the rotational schedules had surface intervals from 60 minutes upwards, depending on the depths of the dives. The drift dives were 35 minutes each. The rate of ascent used was also slow and oxygen was used in decompression between drifts as well as at the end of the day. Decompression was initially on oxygen at 12 m (40 ft) followed by air at 3 m (10 ft). Surprisingly no convulsions, which would have almost certainly led to drowning, were reported. During the 1980s the oxygen stop was changed to 9 m (30 ft) but even as late as 1987 at least one company regularly decompressed divers at 11 m (36 ft) on oxygen.

When on deck, the divers would clean pearl shells. Farley’s method of provicing oxygen was to turn a switch on board the vessel which would deliver oxygen instead of air to the diver’s regulator. Badger believed that there was an inherent danger in this because a diver could be switched to oxygen while at depth.

Treatment of DCS with in water oxygen

Until Badger experimented with oxygen the industry, on the whole, treated DCS with in water recompression using air. Farley suffered numerous episodes of DCS. His treatment initially was to return to the depth of dive then ascended slowly to 9 m (30 ft) for 30 minutes and then to 3 m (10 ft) for 60 minutes. Badger suffered as many as 42 episodes of DCS, affecting his hips and elbows. His first experience of DCS was a rash, initially he tried oxygen using an OxyViva on deck, and in his words, “it was a waste of time”. He successful treated himself with in water oxygen recompression at 9 m (30 ft). He used a full face mask as he felt the safety of voice communication a necessity. From his experience, he worked out that if pain disappeared within 3 minutes, then 30 minutes of oxygen was adequate. However, if pain lasted longer than 3-5 minutes, then he would need 1 hour of oxygen. None of his divers, who were considerably younger than himself, needed more than an hour of oxygen. Badger himself needed more oxygen and he tried a combination of air and oxygen, with 30 minutes each.

Thus, the diving revolution for pearling started in Broome in 1971, with different developments by the few individuals. Despite the secrecy surrounding the changes, in time, the new techniques were adopted by the industry. From the 1970s to 1990, the techniques of diving were as varied as the number of pearling companies, but most adopted the slow rate of ascent. Decompression technique was variable, especially with the use of oxygen. Various companies used a combination of air and oxygen decompressions. Nonetheless, they shared some common features.

Profiles of the 1980s

The profiles below came from the largest pearling company of the time, therefore could be considered as typical. There were only a few companies, all diving to profiles very similar to the ones described below with only minor variations.

As in the hard hat diving days, pearl diving was still divided into shallow, mid and deep waters. Surface interval was of no consequence being related to the time taken to get into position for the next drift dive. The profiles were determined by shell quantity and availability at the dive sites. Nevertheless, they would still dive from sunrise to sunset.

The profiles below are divided into shallow, mid and deep waters. But the depth range around 21-28 m (70-93 ft) was not covered. This was because the pearlers had learned from experience that there were virutually no shells in that depth range, the shells were either in shallow waters or in deep waters, therefore experience in 21-28 m (70-93 ft) was very limited.

SHALLOW WATERS LESS THAN 40 FEET (12 M).

Bottom time was dependent on the quantity of shells on the seabed. The divers might stay as long as 2 hours. If the bottom time was 2 hours, then there would only be 4 dives per day. If shells were scarce at a particular patch, the divers would surface. The total number of dives and bottom time was therefore dictated by shell availability. They dived fbetween 4 dives and 14 dives a day at this depth. The ascent rate was slow, hand over hand on the shot rope, perhaps at 6-9 m (20-30 ft) a minute. In these shallow waters, no decompression was called for.

The divers also adhered to the rule of no hard physical work after diving. They used to dive for 7 consecutive days during the neap tides.

MID-WATERS AROUND 50-65 FEET (15-20 M).

Again the profiles were dependent on shell quantities. Bottom time was more than 20 minutes and less than 60 minutes. The ascent rate was slower than in shallow waters. They also stopped diving an hour before sunset in this depth range.

The first decompression stop was before lunch, at 3 m (10 ft) for 10 minutes. This depth of decompression stop was borrowed from the US Navy Tables. The divers would use the pearl diving profiles, but add what they thought was good or appropriate from the USN Tables. If the tides were strong, another 10 minute at 3 m (10 ft) decompression stop would be done in mid-afternoon. At the end of the day, decompression was at 3-5 m (10-15 ft) for 15-20 minutes.

Surface intervals were 10-40 minutes dependent on shell availability and the weather. Visibility was another important factor. A south-westerly wind and rising tides could make conditions rough and another decompression stop would be added in mid-afternoon.

During the decompression stop, if the wind was strong and the tides were large, the boat would rock which would make decompression stops difficult. The divers devised a method to counteract this. They tied a metre long rope to the shot line, the diver either tied the end of this rope around his body, or made a large loop where the diver could sit (Bosun's chair) during decompression. This method minimises the up and down movement of the diver.

DEEP WATERS BETWEEN 29 AND 37 M (97 AND 122 FT), AVERAGE OF 33-34 M (110-113 FT).

This depth range had not been dived since the 1960s because shells were plentiful in the shallower ranges. In 1981 due to a high mortality rate (some 90%) among the oysters, the shell quota was lifted and pearlers were allowed to dive all year. A new patch of oysters was discovered at a depth in excess of 28 m (93 ft), so the deep water range was dived again. Previously, adequate shells had been found in shallower waters. In 1981, oxygen was adopted generally for decompression within the industry and also conventional decompression tables were studied, adopted and modified. Oxygen was first used for decompression in these deep dives (notwithstanding Badger's secret experiments with the use of oxygen since 1976).

In this range, the bottom time was strictly adhered to and was to be 30 minutes.

The initial ascent rate from depth was slow, but at a rate faster than 6-9 m (20-30 ft) a minute used in the 12 m (40 ft) dives. The divers used this ascent rate to about 15 m (50 ft) then they slowed the ascent rate to 9 m (30 ft) where they switched to oxygen. They breathed oxygen for 5 minutes after the first dive and, empirically, an extra 5 minutes was added after each dive. Therefore the decompression stops were 5 mins for the first dive, 10 mins for the third, 15 mins for the fourth, 20 mins for the fifth and 30 minutes after the last dive.

Surface interval was again not taken into consideration. However, this depended on who the skipper and head diver were and whether they were diving to the rotational schedules or the non-rotational schedules. Everyone was interested in achieving the maximum bottom time during the daylight hours. They paid attention to the ascent rate which was to be slow. They had learned from experience that a fast rate of ascent caused DCS. Descent to depth was to be fast, as they believed a fast rate of descent would break up bubbles.

Some divers interviewed in the 1980s indicated that it was common to be tired, moody and irritable while at sea. It appeared that "niggles" were more common in the winter months. They were treated with either Panadol or with in-water oxygen recompression. The sites of pain tended to be the elbows and shoulders and hardly ever affected the lower limbs as in the hard hat diving days.

CASE 4

DA worked as a diver in the pearling Industry between 1977-1989. He was taught to dive by friends. Later, he obtained commercial qualifications in Newcastle, so he is also well versed in the conventional mode of diving. DA suffered about 12 to 15 epiosodes of DCS affecting mainly his left knee. Other joints such as shoulders and hip had also been involved. He indicated that all these DCS occurred after diving in deep waters. He never had any incidents from shallow waters diving.

During his diving career, he could not recall any serious incidents of DCS in the industry apart from one grossly obese diver who suffered spinal DCS after diving at the 18 m (60 ft) range. That diver was transferred to Perth for treatment.

Treatment of Decompression Sickness

Virtually all cases have been treated with in-water oxygen recompression since the introduction of oxygen to the industry. Oxygen was used to recompress at 9 m (30 ft) . The patient stayed at 9 m (30 ft) for 30 minutes and if they were improved, they would surface. However, if there were still symptoms, they would stay an extra 15 minutes. The ascent took from 15 to 20 minutes, about 2 m (6.3 ft) a minute. The number of cases so treated are not known as no records were kept. The yearly total was estimated to be around 30 to 40 incidents of niggles.

In the 1980s, a number of cases of DCS were treated in the RAN facilities near Perth. These were more serious cases where either in-water oxygen recompression was unsuitable or did not relieve symptoms. However, they were virtually all from oyster farm divers. Until recently this group of workers was not covered under the Pearling Act and were not required to have a medical examination

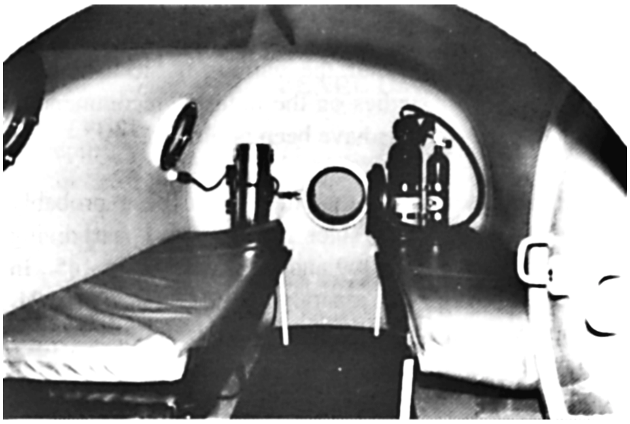

Figure 7. Inside the new Broome recompression chamber.

for compressed air diving. Until the late eighties, medical examinations were performed in accordance with the requirements of the Western Australian Pearling Act of 1912. The Medical Form was inadequate for the medical examinations of divers, which were performed largely by practitioners with no training in dfiving medicine.

In 1987, the pearlers formed an association called the Licensed Pearl Producers Association but each company still dived to its own profiles. It was not until 1990 that the new Pearl Producers Association Inc. agreed to dive to a set of profiles produced by the association and printed in their Code of Practice[1] and a recompression chamber was purchased (Figure 7).

Discussion

The pearl diving of bygone days shows that it was possible to do repetitive and multi-day diving, albeit at a high price. The incidence of DCS was not accurately recorded, but the technique used indicated that the following factors were important in avoiding DCS.

1 a slow rate of ascent,
2 the importance of decompression stops,
3 the depth of decompression stops, at 7-8 fathoms (13-14.5 m or 42-48 ft),
4 surface intervals were considered of little importance but have caused many problems in deep dives,
5 avoidance of post-dive exercise,
6 the use of oxygen to aid decompression, which was introduced in 1981 for use within the industry, although experimented with in 1976 by Badger.

These various factors used to improve safety in pearl diving are discussed in another paper.[1]

Acknowledgments

I would like to thank all those who have provided information used in this paper, especially members of the pearling industry, the Pearl Producers Association Inc. WA, pearl divers past and present and the R&D Corporation, Fisheries Department, Western Australia.

Key Words

Deaths, decompression illness, history, hyperbaric facilities, occupational diving, oxygen, tables.

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PEARLS FROM THE DEEP

A STUDY OF AUSTRALIAN PEARL DIVING 1988-1991

Carl Edmonds

Abstract

Pearl divers are a unique diving group. It remains a fairly hazardous occupation, but much less so than in the past. A survey covering four seasons (1988-91) of pearl diving has been conducted. In 1991 decompression sickness (DCS) was the dominant medical disorder (45%), followed by ear problems in 15%, salt water aspiration in 10% and others less than 10% each. The decompression profiles are discussed in relation to the DCS incidence. Decompression and treatment experience with oxygen is described, and the relevance of this to diving physiology is noted.

Background

The excitement of pearl diving lies not only in its product, but also in its mystique.

Since the papers of Bassett-Smith and Blick,[1,2] the superb documentation of historians such as Idriess,[3] Edwards,[4,5] and Bain[6] have excited the adventurers, entrepreneurs, divers and pirates.

The exceptional dives that these men appear to have performed have led to various research approaches, including those of Le Messurier and Hills,[7-9] who derived interesting and innovative concepts and questioned the conventional knowledge of decompression.

Factual information regarding the actual diving performed by the pearl diver, and its sequelae, is not readily obtained. Secrecy and paranoia have bedevilled researchers looking for facts. There is no paucity of fantasy, and each investigator group has its own perspective, depending on whose story is heard. The parable of various blind men independently trying to describe an elephant after only touching one part, is germane.

Recently Wong[10] and his co-workers have rekindled the fascination with this occupational diving group. Their interest involves both the practical diving capabilities and research projects attempting to elucidate an explanation for the relative low incidence of DCS, despite the diving exposures extending far beyond the limits acceptable by the conventional diving manuals.

The history of the Western Australian pearl divers is discussed elsewhere.[11] Analysis of the actual diving exposures, computation of the various tissue saturation levels and Doppler studies on the industry recommended decompression protocols have been published.[12-14]

It has been stated that there have been probably about 1,000 diving deaths since 1883[4,5] when pearl diving commenced. Between 1909 and 1917 there were 145. In 1914, 33 died from diver's paralysis and in 1915, only 21. This improvement was attributed to safer diving practice, but paralleled the reduced diver numbers which accompanied World War 1. A salutary reminder to question all statistics from the industry.

The "official figures for 1993" from Broome[4] claim that there were no deaths reported and only three cases of DCS, all successfully treated with underwater oxygen, amongst the 74 divers. During that time the Broome divers were said to have performed 21,452 dives, with approximately 15,000 hours underwater and averaging 290 dives per diver, per year.

There were approximately 100 divers in the Broome/Darwin area, during 1988-91, with approximately a 3:1 ratio. It varies somewhat each year, depending on commercial decisions.

Methodology

This present report is a documentation of a sample of pearl diving activities carried out during the years 1988-1991 in two areas.[15] It includes a report on the DCS incidence and the use of oxygen in decompression and underwater recompression therapy. The first three years involved pearling from Broome, and the last year from Darwin.

The information was obtained from diver log books and not from the official "boat logs". The reasons for this were three fold. Firstly the boat logs are not fully documented, either as regards diving profiles or accidents. Secondly, it is much more difficult to obtain the boat logs from the pearling industry, than it is to obtain divers' logs. Thirdly, the diving logs documented the exact durations on oxygen.

Also, the diving logs had a great deal of interesting information, such as clinical details of accidents, marine animal behaviour, etc. Boat logs were used to clarify and verify some data when it appeared to be conflicting.

The presence of DCS was noted by the statements in the log books indicating this, and verified by checking the extended oxygen decompression times employed for treatment.

TABLE 1

PEARL DIVER DCS STATISTICS 1988-1991 (10% SAMPLE)

Depth m	Diver days	Average dives per day	Total underwater time (average)	0_2 time (average)	DCS numbers	DCS % diver days
45-54	140	4.4	152	96	19	13.6%
35-44	406	4.4	210	80	27	6.7%
25-34	322	4.7	285	73	7	2.2%
15-24	511	8.0	406	9	2	0.4%
10-14	455	8.3	444	-	?1	0.2%

Totals = 1,834 diver days, 11,776 dives, 56 DCS, 1 medevac. This sample represents approximately 10% of the pearl divers 1988-91.

Results

During the 4 years 1988-1991, extending over 4 pearl diving seasons, there were a total of 1,834 days dived by these open ocean shell divers. It comprised 11,776 dives, averaging 6.4 dives per day. The divers were exposed to depths between 10 and 54 m (Table 1).

The boats would "drift", usually carrying 8 divers at a time, collecting shell. At the end of the drift the boat would return and then carry out another drift. For the shallower depths there would be more dives per day, and a much longer bottom time. For depths over 23 m there would be a limit of 5 dives per day. The divers tended to use oxygen decompression towards the end of the day and/or following deep dives. The Broome profiles and their analyses are described elsewhere.[12-14]

The oxygen was always used at a fixed depth of 9 m (Table 2). The average duration on oxygen was 70 minutes per day, with a range of 10-150 minutes. Oxygen was used on 1,064 diver days (with an average of 5.6 dives per day). In accordance with the pearl diving recommendations at the time, it was much more likely to be used on the last dive of the day than the previous ones, and if it was used on the previous dives then the oxygen amount would be increased with subsequent ones.

An extrapolation from the survey would suggest that there had been over 10,000 diving days with oxygen, for either decompression or DCS treatment. There were no oxygen hits during this time, and none since.[14]

If a diver developed DCS, then he would often be treated for this either immediately, on oxygen, underwater, or following the next dive (he would have had another shell-collecting dive and that would be followed by an extended oxygen decompression regime).

TABLE 2

OXYGEN DECOMPRESSION AT 9 m

Duration O_2 mins/day(average)	Diver days	Maximum depth (m)	Underwater hours	Dives number
120-150(138)	147	43.3	3.24	4.95
90-149 (95)	147	37.3	4.26	4.81
60-89 (75)	420	34.2	4.65	4.83
30-59 (37)	147	29.5	5.05	5.67
10-29 (16)	203	22.2	6.48	8.0

This represents approximately 10% of the pearl divers 1988-91.

Like the abalone divers before them,[10] the pearl divers have modified the oxygen underwater treatment regime, but not in the same direction. Their consistent routine is to employ oxygen for 30 minutes at 9 m, extended if symptoms persist, and then ascend at a relatively fast rate, 3 m per minute.

The cases of DCS were of interest. Of the 56 cases recorded, only one required medevac to a chamber. All the others were treated effectively and successfully with an abbreviated underwater oxygen regime.

All DCS cases occurred at sea and treatments were usually given within 30 minutes, either:

a receiving oxygen at 9 m for 30 minutes; or

b recompressing on air for the next routine dive, to a depth approximating the original dive, and then being given supplementary oxygen at 9 m after the dive.

One interesting observation was made. No matter how serious the decompression case was, no matter how painful or disabling the symptoms, it was always recorded as "niggles". The reason for this is given by the divers themselves. Had the designation "DCS" been made, then the diver would have been required to miss all further diving on that, and possibly the following, day. Thus there was a strong financial inducement to ensure this did not happen, and in doing so a whole new concept of "niggles" evolved.

The incidence of injury, accident or illness was recorded, but there can be no assurance of these records being comprehensive. They demonstrated a preponderance of DCS, in 45%, followed by ear disorders, (barotrauma, infections, vertigo) in 15%, salt water a spiration was well recognised by this group and comprised 10% of the accidents noted. All other causes comprise less than 10% each (See Table 3).

Only 7% of the illnesses were probably not related to diving, and were often a recurrence of previous medical conditions. The marine animal injuries were mainly fish and irukandji stings, although they did include a sea snake bite, whale entanglement, and a stone fish sting.

Deviations from customary diving practice

Also of interest are the deviations from customary diving practice, which may have important implications.

1 The slow ascent time, being 5 m per minute to 21 m, then 3 m per minute to the surface(See Table 4).

2 Not all dives were carried out reducing the depth with each repetitive dive. On the contrary, 41% of the dives increased in depth during the day, 39% decreased depth and 20% were relatively flat. In making these calculations the dives were grouped in 2 metre increments of depth to determine whether the profile was either increasing in depth, decreasing in depth or remaining flat.

3 The rapid return to diving after DCS. Except for the diver who required medevac, most divers continued to dive on that or the next day. Most (49/55) without any more problems.

4 The underwater oxygen treatment was different from that previously recorded.[15] As all the cases were treated rapidly, either immediately or following the next drift dive, it is possible that less oxygen was required.

By extrapolation of this sample to the remainder of the Broome and Darwin fleets, we can presume a DCS case load of over 500 cases treated underwater on oxygen over the 4 seasons studied. During that time there was not one incident of an oxygen "hit" (convulsion) on the treated divers, and nor on those who were using oxygen for decompression.

TABLE 3

DISTRIBUTION OF 125 PEARL DIVER ACCIDENTS

DCS	56	45%
"Ear" barotrauma, infections vertigo	18	15%
Salt water aspiration syndrome	12	10%
Marine animal injury	8	7%
Respiratory infections	7	6%
"Sinus" barotrauma, infections	6	5%
Previous disorders	6	5%
Pulmonary barotrauma	2	-
Near-drowning	1	-
Others 9	7%	

This represents approximately 10% of the pearl divers 1988-91.

TABLE 4

PEARL DIVING ASCENT RATES

Ascent rates after an air dive

3 m/minute shallower than 21 m

5 m/minute deeper than 21m

Oxygen decompression ascent times

3 m/minute between 9 m and the surface

Oxygen decompression stops at

9 m for variable times

Discussion

These divers well exceed the limits normally imposed on most other commercial divers, both as regards the repetitive dive exposures and the amount of oxygen used.

They do not comply with the requirements to have shallower depths with each repetitive dive. However each dive is not much different in depth from the previous one.

They also do not comply with the usual multi-day dive rules of having one day rest for every three days diving. On the contrary, they dive throughout the neap tide, and this determines not only their initial depth but the consecutive depths of each dive. They dive on consecutive days during those tides.

They could not be said to "acclimatise", as in fact they do the opposite. They spend some weeks absent from diving and then return immediately to a full diving program without work up.

The rapid exposure to underwater oxygen treatment may be the reason why the treatment appears to be more effective in the pearl divers than it is in most other diving situations. Certainly with the delayed cases that we treated in the RAN School of Underwater Medicine, the ascent rate had to be much slower, 12 minutes per metre for some of the cases.[15]

The reasons why these divers can reduce the expected consequences of DCS, could be explained in a number of ways.

1 The very slow ascents could well have an influence in reducing the likelihood of lung over pressure accidents causing air emboli. It would also be expected to reduce the likelihood of bubbles developing[16] at least in the fast tissues. Multi-level diving is not performed and there is only one ascent per dive.

2 The use of oxygen at 9 m after most dives of 20 m and greater, and at the end of the day with shallower dives (13-19 m), will reduce bubble formation and DCS.[17] With increasing depths, certainly in excess of 20 m, there was a considerable reduction in the hours of exposure and an escalation in oxygen consumption.

3 Even though there are between 5 and 10 dives per day, the surface interval is so short that insufficient time may be available for maximal bubble development after the earlier dives, before being recompressed by the subsequent dives. This is especially so with the shallower non-oxygen dives with 8-10 drifts/day. Whether this would be an effective way of reducing gas nuclei is not known, but could be one factor.

4 The majority of these dives would not be considered deep by recreational diving standards (less than 30 m in experienced divers). Although bubble production may be more rapid in deeper dives, thereby reducing the latent period or tolerable surface interval, these are the very dives in which oxygen decompression is used, thus reducing the likelihood of fast tissue bubble formation.[18]

5 The divers age, physical fitness and warm water diving might well be factors in reducing the DCS incidence. Most of the divers are young, very fit males, who do not usually stay in the industry very long. This is in contra-distinction to the old pearl divers who, because of their experience in the use of hard hat equipment and shell gathering, stayed in it for many years or most of their life, whichever came first.

Because of the above, there should be no automatic extrapolation of the pearl divers decompression regimes and their use of oxygen decompression, to other diving groups.

As regards their underwater oxygen treatments, we have no idea how this treatment influences the development of dysbaric osteonecrosis, either positively or negatively.

There is every reason to believe that the nitrogen build up in the slower tissues is excessive, and this could lead, on theoretical grounds, to an increased incidence of dysbaric osteonecrosis. The disorder is frequently seen amongst this occupational group, but no medical survey to determine its actual incidence has yet been reported.

Oxygen toxicity may be a problem. There is a large amount of oxygen exposure over 1-5 dives per day, but we have no concept as to the short-term cumulative effect of this. Thus a diver may use oxygen on his second last dive, but whether this contributes to any oxygen toxicity for the last dive of the day, after breathing air for 1-2 hours, is not known. The degree of long-term oxygen toxicity, if any, still needs to be assessed.

The value of the oxygen is evident in the capability to undertake such dive profiles and not cause more deaths.

The dive protocols used by the pearl diving industry have always been in a state of flux, and have also varied somewhat over the last few years. It is therefore not now (1992-95) exactly the same as it was during the 1988-91 survey period.[13] This fact is used to allay criticism of the current decompression regimes, as it always has been.

In conclusion it does appear that pearl diving remains a somewhat hazardous occupation, but much less so than in the past. Pearl divers' profiles and treatment regimes are potential gems for the diving medical community.

Key Words

Decompression illness, occupational diving, oxygen, tables.

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WESTERN AUSTRALIAN PEARL DIVERS' DRIFT DIVING

Robert M Wong

Abstract

This is a report on pearl diving out of Broome, in Western Australia, from 1991 to 1994. The mode of diving in earlier days has been reported elsewhere.[1]

Despite popular misconception and the "cow-boy" image perceived by conventional commercial divers, the incidence of decompression illness (DCI) amongst the pearl divers has been less than 0.01% and the type of DCI has been confined to the musculo-skeletal system.

The reasons for this low incidence of DCI are discussed and has been reported elsewhere.[2] It is believed that the contributing factors are:-

a slow rate of ascent;
b appropriate depth of decompression;
c use of oxygen in decompression;
d suitable between dive (surface) intervals.

Pearling in Western Australia

The pearling industry of Western Australia now employs some 600 people. Of these, 142 are divers (based on the records of medical examinations conducted in 1994) and only 90 or so of these are pearl divers engaged in drift diving. The others are pearl farm divers.

The drift divers harvest wild oysters (*Pinctada maxima*) which are then seeded by highly skilled technicians and placed on panels and immersed in water in pearl farms. The farm divers attend to these oysters, since 1985 they have dived according to the USN Dive Tables.

Pearl divers

Unlike the past, when most of the divers were Japanese, Malays and Koepangers, nowadays virtually all are Caucasian Australians and New Zealanders.

Divers usually enter the industry as a qualified recreational diver holding the Open water certificate or higher. The industry has an induction course conducted by its Safety Officer and Chamber Operator who is an ex-pearl diver. All potential pearl divers have to pass the course before they are accepted into the Industry. Most work initially in the farm sector, while a smaller number are employed as drift divers.

Figure 1. Drift divers getting ready for a dive.

The drift divers are well paid. They receive a retainer plus $3-$5 per shell collected, so there is competition among the divers to do drift diving.

All divers are required to undergo an annual Diving Medical Examination in accordance with the Australian Standard for Occupational Diving AS2299,[3] which includes a long bone survey.

The average age of the pearl divers was 27.7 years in 1994, with a range of 18 to 48 (Table 1). The younger and the older divers are mainly farm divers.

The stay of a diver in the industry varies. Those who do not collect many shells, so not making much money, tend to leave the industry after about 3 years, while others who are successful divers tend to stay on, a 10 year stay as a diver is not uncommon. Some stay in the industry to become skippers of pearling vessels or managers of pearl farms and some join the companies as administrative or managerial staff.

Of the 142 divers, 18% admitted to having experienced DCI. Of those with more than 5 years of pearl diving experience, 34% have experienced DCI, whereas 6% of those with less than 5 years experience in the Industry had suffered DCI. Most experienced DCI while diving on the farms or in other industries and not from drift diving.

TABLE 1

AGES OF WESTERN AUSTRALIAN PEARL DIVERS IN 1994

Age in years	**Percentage**
under 20	6%
20 - 24	20%
25 - 29	41%
30 - 34	22%
over 35	11%

Drift diving season

The season starts in February each year and usually ends by August. From November to January weather is cyclonic and unsuitable for drift diving. As is common in the northern parts of Australia, Broome is subject to large tidal variations, and the divers only dive during the neap tides, which have an average variation of up to 6.5 m. During the spring tides, aside from the larger tidal variations and fast movement of water, the visibility is poor and makes pearl diving a nearly impossible task, necessitating divers going to deeper waters.

Pearling vessels

The vessels are usually 25 metres long; either custom built or converted from trawlers. They all have a drogue at the stern to retard the speed of the drift. On either side near the stern are hydraulic booms from which gas (air and oxygen) hoses and weighted lines (shot lines) are suspended (Figure 2). Work lines run from the shot lines and drag behind them.

Mode of diving

The aim of the drift diving profiles is to achieve maximum bottom time in a 12 hour daylight working day.

As shown in Figure 3, the divers hang on to the work lines (drag ropes) and drift along the seabed to pick up oysters which they put into their neck bags. When the neck bags are filled, they go forward towards the shot line at the front of the drag rope and empty the catch into large net bags which are then floated with compressed air to the surface and emptied onto the deck of the vessel.

At the end of each drift, the divers surface slowly by coming up the shot rope hand over hand and decompress in accordance with the particular profiles in use. They then rest on deck while the vessel turns around to sail against the tide and then turns to drift again with the tide.

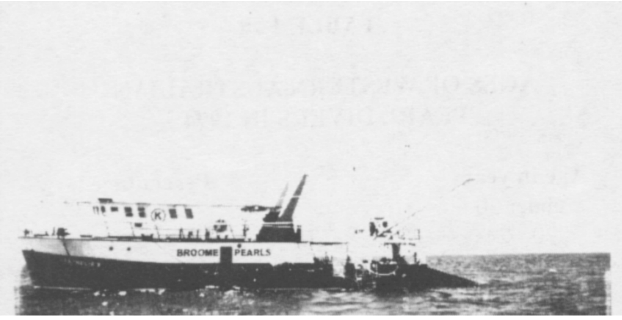


Figure 2. Modern Pearl fishing boat

The current mode of diving is a refinement of the technique handed down over the years from the turn of the century. It involves repetitive dives of up to 10 dives a day and multi-day diving for up to 8 consecutive days. Due to the tidal variations, diving frequently involves doing the deep dive in the middle of the day or at the end of the day. This pattern of diving is considered to be of high risk in conventional diving. The pearl divers profiles are not based on any scientific calculations, they dive in that manner because the profiles had worked for them over the years and they had developed faith in the profiles. A previous scientific analysis by Le Messurier and Hills[4] was based on the Okinawan divers operating around the Torres Strait where deep dives to depths of 45 fathoms (82 m or 270 ft) (1 fathom is 6 feet) were performed . These investigators noted the deep decompression stops used (for dives deeper than 35 fathoms (63 m or 210 ft), staging was done at 30, 23-25, 15 and 7 fathoms (54, 42-45, 27 and 12 m or 180, 138-150, 90 and 42 ft)) and the slow rate of ascent of 25 ft/minute. Of the 468 dives studied, 31 cases of bends were recorded (6.6%), and 29 of those had dived deeper than 35 fathoms, nonetheless, the symptoms were mainly joint and skeletal pains.

Fishing area

Pearl diving is done off the coast of Broome, Chart 324 - Lacepede Islands and Bedout Islet, usually in areas some 9-11 hours steaming time south west of the township. Some areas north in the Lacepede Channels and another area just west of the township are also fished. There are areas which are some 16 hours away, but these are seldom fished nowadays.

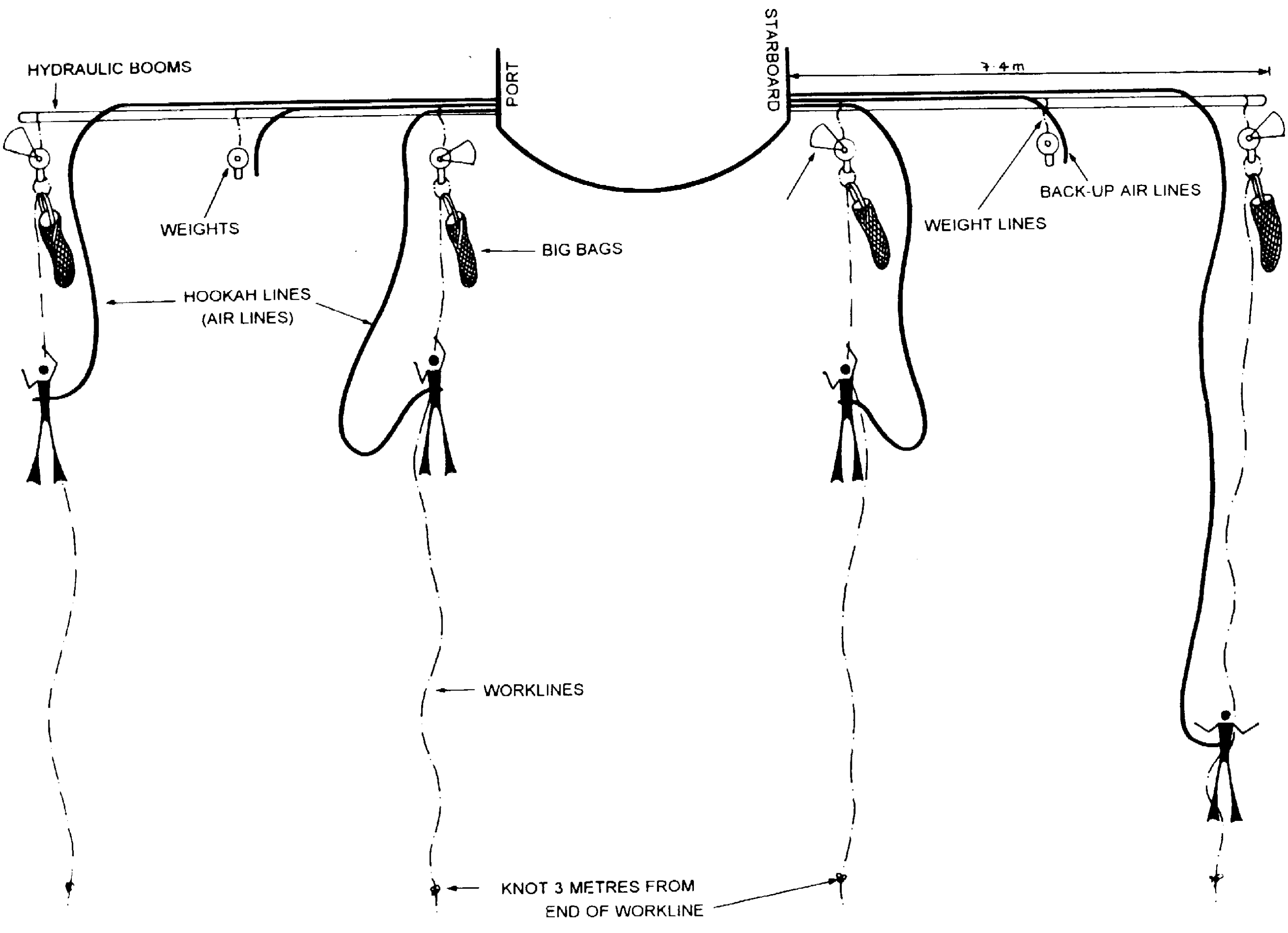


Figure 3. Plan view of pearl fishing operation

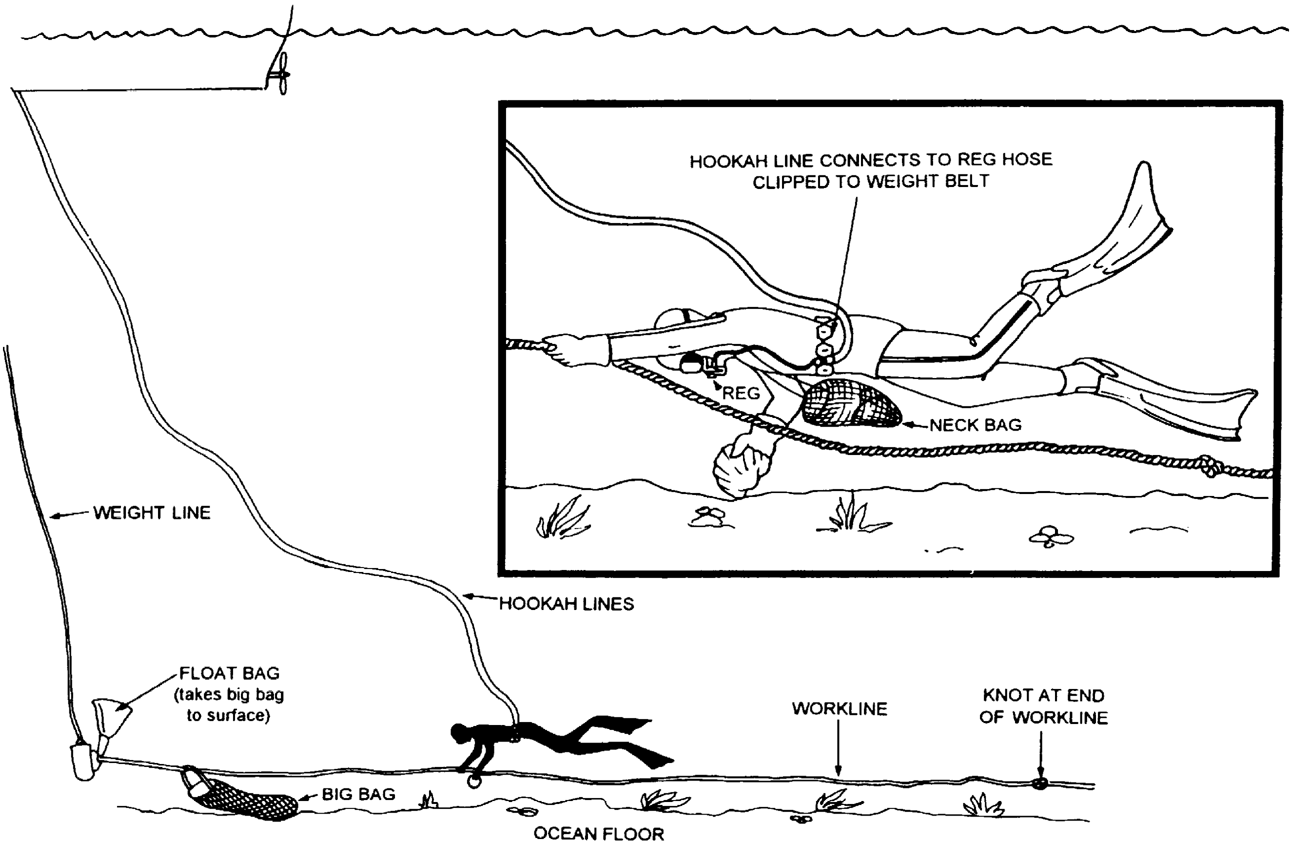


Figure 4 . Side view of pearl fishing operation.

Unlike the past, thanks to improved communications and transport, injured divers could be retrieved by 2 seaplanes based in Broome.

Climatic conditions

The climatic conditions are tropical. There are essentially 2 seasons, the dry with a temperature range of 28-30°C and humidity of 44%. The wet season has temperature of 33-34°C and humidity of 54 -75%.

Tides

As is common to the northern parts of Australia, Broome is subjected to large tidal variations. During spring tides, the maximum water depth range is from -0.1 m to 9.3 m; whereas, during neap tides, minimum water depth range is from 3.8 m to 5.6 m. (Mean high water spring - 9.4 m; mean low water spring - 1.1 m; mean high water neap - 6.4 m; mean low water neap - 4.3 m).

Water temperature

The temperature varies from 32°C in summer months to 18°C in winter months.

Drift diving dive schedules

There were 13 pearling companies each with their own drift diving profiles. In 1990, under the umbrella of the Pearl Producers Association Inc. (PPA), they agreed to dive to a "fixed common schedule" as printed in their Code of Practice. In 1991 all divers from all companies dived to similar schedules. In the same year, a recompression chamber was purchased by the PPA and donated to the Health Department of WA. It is located in the Broome District Hospital. The same year Doppler ultrasound equipment was purchased to initiate a study of the diving profiles.[5]

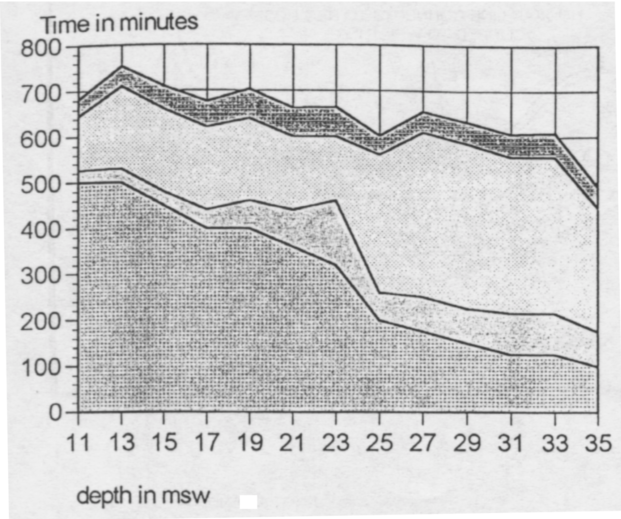
The pearl divers still speak of shallow water, mid-water and deep-water diving as in the old days.[1] But examination of the profiles will reveal that there are 2 types of dive schedules.[5]

1 Non-rotational profiles for depths less than 23 m;
2 Rotational profiles for depths deeper than 23 m and up to 35 m.

The pearl divers from Broome, as agreed by all members of the PPA, no longer dive deeper than 35 m. At the time of writing February 1996), it is not possible to dive to 23 m with the non-rotational procedure. Most companies use the rotational technique for this depth.

FIG 5

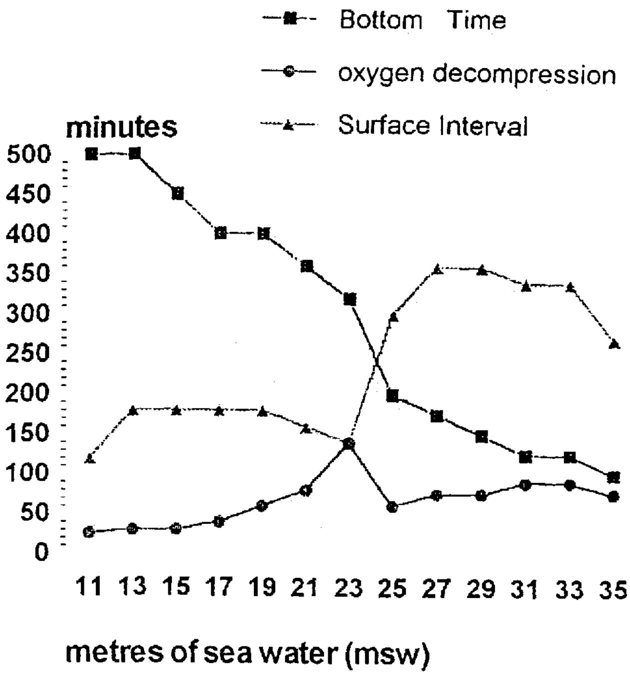
PPA PROFILES 11-35 m SHOWING TOTAL WORKING TIME



From the bottom of the graph the shaded areas represent bottom time, oxygen decompression, surface interval, and ascent times.

FIG 6

PPA PROFILES 11-35 m TIMES ON BOTTOM, OXYGEN DECOMPRESSION AND SURFACE INTERVALS.



Non-rotational profiles means that each diver dives every dive of the profile. For dives of up to 13 m, the aim is to achieve a maximum bottom time of 500 minutes for the day. With increasing depths, the bottom time decreases accordingly in an empirical fashion e.g. 400 minutes for 19 m. Figure 5 shows the relationship of bottom time, oxygen decompression time, surface interval and ascent time of each dive schedule. All decompression stops are done on oxygen at 9 m, except for the 11 m profile where decompression is at 6 m. Up to the 19 m profile, decompression stops are only done on every other dive. Surface intervals for the non- rotational profiles are 15 minutes for the 11 m profile and 20 minutes for the other profiles. Each profile consists of 10 dives except for the 21 m one which only has nine and the 23 m one which has 8.

Rotational profiles are schedules deeper than 23 m and involve 2 teams of divers. With these profiles, each diver dives every second dive. Every dive requires a decompression stop.

The rotational profiles (deeper than 23 m) have variable surface intervals, increasing with each dive so that for the 35 m profile, surface intervals range from 80 minutes after the first dive to 100 minutes after the 3rd dive. From 23 to 33 m the profiles have five dives but the35 m profile only has four dives. Figure 6 shows the PPA schedules where oxygen time increases empirically as the depth of the dive increases and surface intervals remain reasonably constant, accepting that the non-rotational and rotational profiles have different surface intervals.

The original ascent rate for deep water was set at 5 m/minute to 21 m. From 21 m to the surface, the ascent rate was pegged at 3 m/minute. After decompression at 9 m, the ascent rate was slower, 0.3-0.5 m/minute.

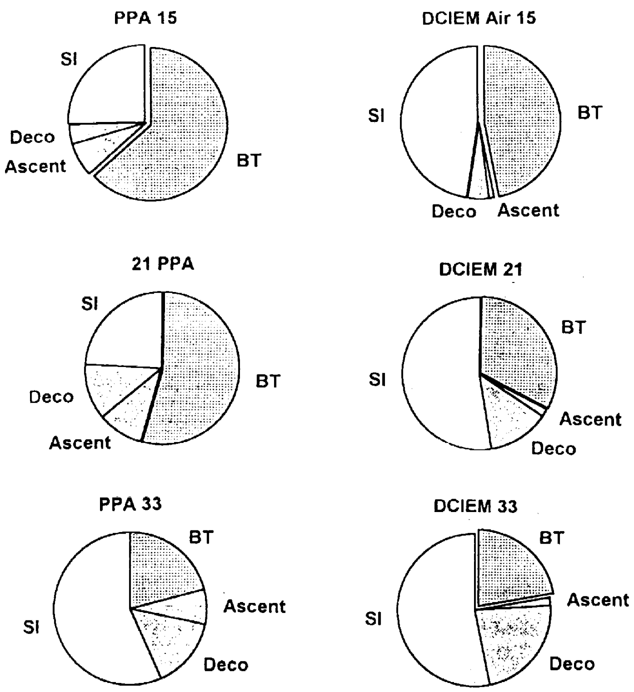
Originally, decompression was not required for the 11 m profile. For the 13 m profile, decompression was on air at 5 m. The other profiles call for decompression stops on oxygen at 9 m, but not for every dive in the shallower profiles.

With modifications of the profiles, the ascent rate was changed to a uniform rate of 3 m/minute for all depths of dives. Decompression stops were also introduced to all depth profiles.

Figure 7 and Table 2 show the comparison of the DCIEM Decompression Tables with the PPA profiles. The pie-graphs shown are not identical in times, they represent what could be achieved in a 12 hour working day using the respective profiles. It can be seen that the PPA profiles allow for more bottom time at the 11 m and 21 m depths. The 33 m profile shown was calculated using the same bottom time for both the PPA and the DCIEM Tables. It is interesting to note that the time taken for the slow ascent rate of the PPA schedules together with their staging time

FIG 7

COMPARISON OF PPA PROFILES TIMES AND DCIEM TABLES



The three pairs of pie charts show total of bottom time, ascent time, decompression time and surface intervals for depths of 15 , 21 and 35 m for PPA and DCIEM schedules.

(decompression time) are comparable to the required decompression time of the DCIEM Decompression Table.

Decompression illness and its management

Before 1990, dive profiles varied from company to company. There was no uniformity in the profiles. The incidence of DCI was not accurately known. Most cases were treated at sea by in water recompression on oxygen, some also used air. Only serious cases which did not respond were referred to conventional treatment in Perth.

Current dive profiles

The dive profiles are constantly being modified to improve diving safety.[5] The modifications of the profiles are discussed elsewhere.

It can be seen that the 1994 profiles are quite different from those printed in the Code of Practice.[5]

TABLE 2

COMPARISON OF PPA PROFILES AND DCIEM TABLES AT 15, 21 AND 33 m

Table	Depth (m)	Bottom time	Total time
PPA	15	450	710
DCIEM	15	315	672
PPA	21	360	663
DCIEM	21	240	738
PPA	33	125	700
DCIEM	33	125	562

Medical problems affecting the pearl divers

Apart from DCI, other problems include marine animal stings, salt water aspiration, ear and sinus baro-trauma.

Acknowledgments

I would like to thank all those who have provided information used in this paper, especially members of the pearling industry, the Pearl Producers Association Inc. WA, pearl divers and the R&D Corporation, Fisheries Department, Western Australia.

Key Words

Decompression illness, occupational diving, oxygen, tables.

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DOPPLER STUDIES ON THE DIVE SCHEDULES OF THE PEARL DIVERS OF BROOME

Robert M Wong

Introduction

Before 1990 the drift divers of the 13 pearling companies working out of Broome all dived using the methods described in another paper but with individual variations, such as the rate of ascent, frequency and depth of decompression stops and surface intervals.[1]

In 1989 three divers died. 2 were pearl farm divers, who died from carbon monoxide poisoning, while the other was a drift diver, the cause of whose death was undetermined.

Because of the fatalities, an inquest was held in Broome, the coroner, in passing his findings recommended that the pearl divers either adhere to conventional decompression tables, or if they were to dive to their own schedules, then a study had to be conducted to assess the relative safety of their mode of diving. With such a recommendation and under the scrutiny of the Department of Occupational Health Safety and Welfare (Worksafe WA), the members of the Pearl Producers Association got together and produced an agreed set of profiles (Appendix 1), that they would adhere to, for examination. Also they accepted the recommendation that a recompression chamber (RCC) should be purchased and be located in Broome. The RCC was installed in 1991 (Fig 1).

The Director of Fisheries of the time asked me to put forward a research proposal for consideration. Although the dive profiles of the pearl divers do not follow any conventional calculations, the pearlers strongly believed that the profiles were safe. I thought that the best way was to test the profiles using the Doppler technique to assess the relative decompression stress of the profiles.

Objectives of the study

Five objectives were set down in the study application.

1 To determine whether any significant problem exists with regard to decompression sickness arising from the diving schedules and practices currently (1990) in use by the pearl divers of Broome.

2 To document the actual dive profile using depth and time recorders.

3 To determine the bubble score using the Doppler technique in evaluation of the profiles.

4 To determine the incidence of decompression sickness and its manifestations.

5 To document any long term health effects.

The Research and Development Corporation of the Fisheries Department accepted the objectives and adopted the strategy that the study was to :-

assess the relative safety of the PPA drift diving profiles as set out in the Code of Practice;

and modify the "stressful profiles" to achieve a higher level of safety.

With the acceptance of the project, the Doppler equipment was purchased (Figure 2) and a Doppler technician was appointed.

Methods

The pearl divers profiles were tested using the Doppler ultrasound technique in accordance with the DCIEM's Kisman-Masurel protocol[2,3] in the RCC and at sea. In the past, the end point of testing a decompression procedure was an incident of DCI. Since the advent of the Doppler, an arbitrary bubble grade can be chosen as the end-point, so avoiding subjecting divers to DCI.

Essentially, if a profile has more than 50% of divers showing bubble grades greater than grade II, grades range from 0 (no bubbles) to IV, then the profile is considered as stressful and associated with a higher risk of DCI. It is also known that some divers are "high bubblers" whilst some are "low bubblers". It is accepted also that the Doppler technique has certain disadvantages, as it only identifies moving bubbles and only certain vessels are available for study.

Chamber Trials

Two divers at a time are tested in the recompression chamber. These divers are volunteer pearl divers who have given informed consent to the trials and have been approved by the Safety Committee of the PPA. The RCC trials can only be done after the pearling season of each year, because during the season there are no divers to be found. Even after the season, divers are reluctant to sit in the RCC despite a $200 daily financial inducement. All the dives are dived to the maximum depth and to the maximum time of the square profile as stated in the Code of Practice of the Pearls Producers Association Inc. (Appendix 1). Doppler is done on both divers after each dive and at the end of the day, half hourly for 2 hours and for a total of 8 days, which approximates the period of the

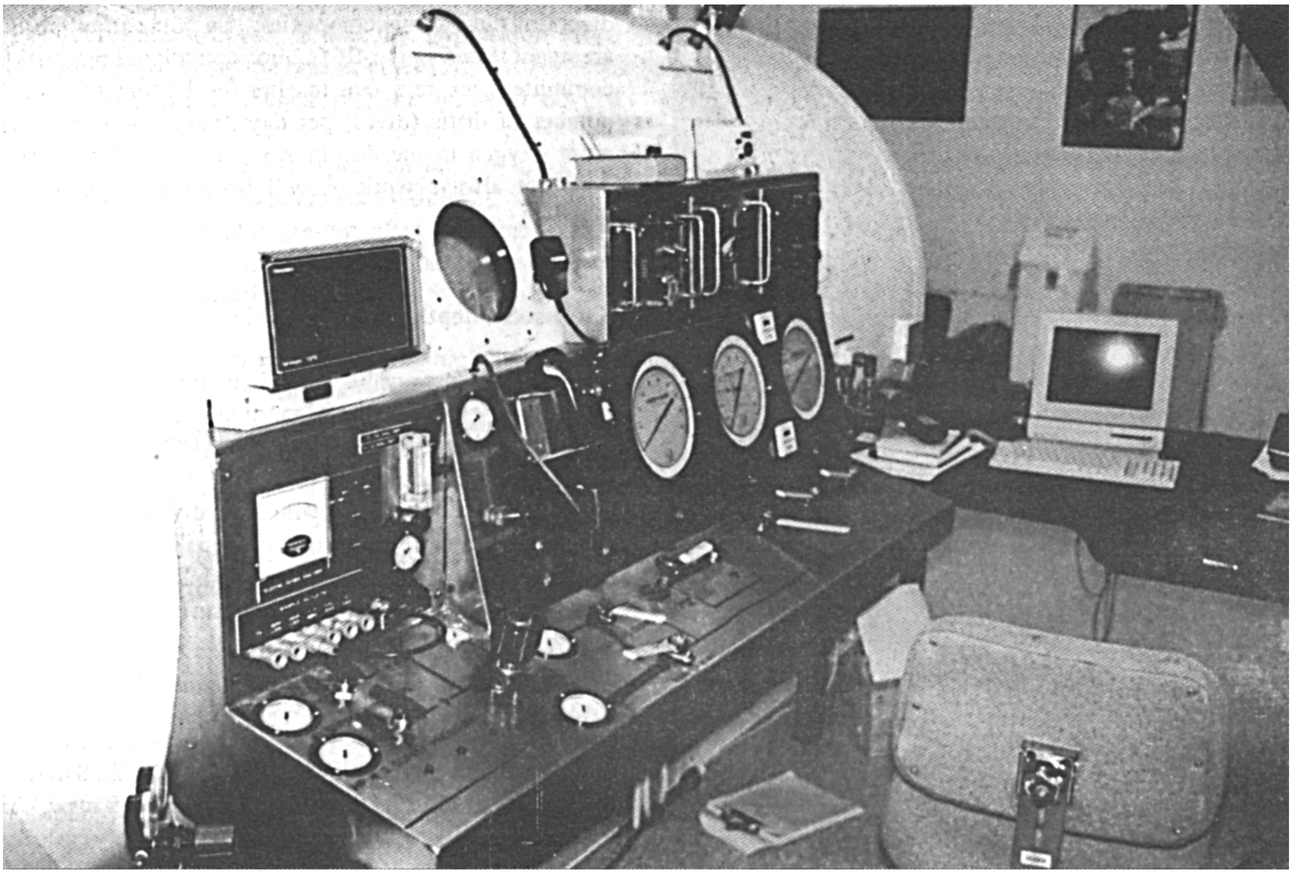


Figure 1. Side view of Broome recompression chamber

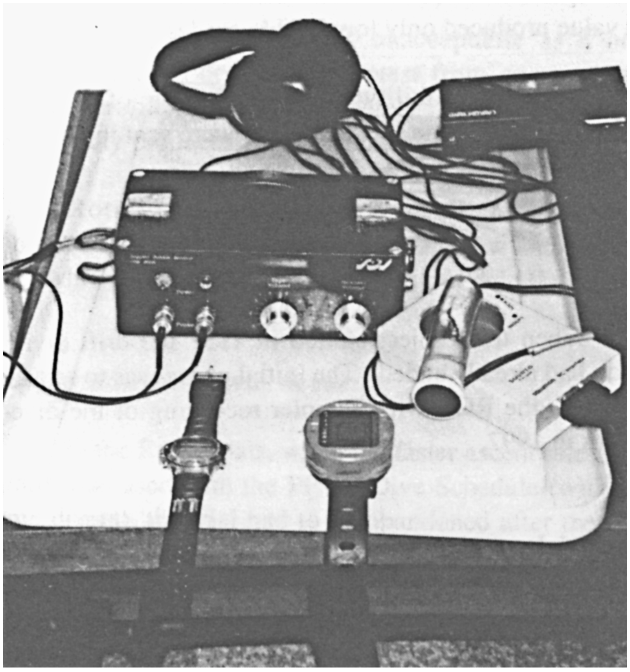


Figure 2. Equipment for Doppler monitoring. Showing chest probe, Suunto depth recorder, Hyperaqualand depth/time recording watch, tape recorder and ear phones.

neap tide. Any profiles which showed high bubble grades were modified or abandoned.

Doppler studies of the RCC trials showed that bubbles tended to peak after 60 to 120 minutes. In the non-rotational profiles when the surface interval is only 20 minutes, the bubble grading gives little indication as to the severity of the stress of that particular profile. This only becomes apparent at the end of the day.

As it is believed that one of the contributing factors for the relative safety of the pearl diving profiles is the slow rate of ascent, the effects of different ascent rates, the 3 m/min ascent rate of the pearl divers' profiles and the faster ascent rate of 15 m/min, were compared.

The various dive schedules of the PPA Profiles were tested employing the same pairs of divers whenever possible.

There are limitations to the RCC trials in that the test subjects (pearl divers volunteers) are reluctant to perform any physical work. It is accepted that gas exchange in dry and the immersed state is different,[6,7] nonetheless, it gives some indication as to the

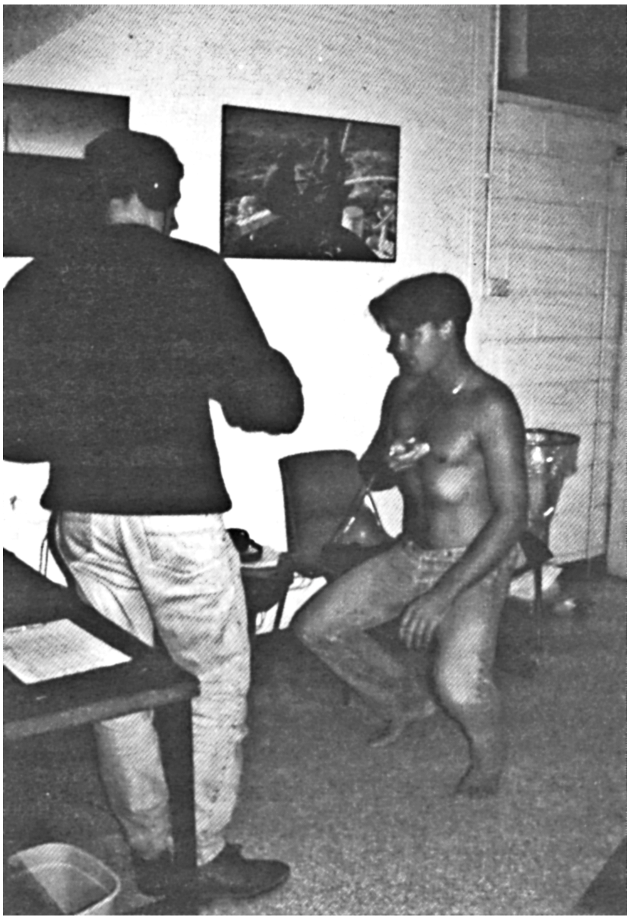


Figure 3. Doppler equipment being used. The volunteer is doing knees bends as controlled excercise to provoke bubbling.

decompression stress of the profiles. Any profiles which give rise to grade III bubbles consistently are rejected and modified.

Modification of the profiles

The profiles are of two types, non-rotational and rotational.[4] Non-rotational profiles are those where the divers dive every dive with a short surface interval of 20 minutes and decompression is done only after every other dive. The rotational profiles are those where the divers dive al;ternate dives and there is a decompression stop with oxygen after each dive.

When the profiles are found to be stressful, the information is communicated to the Profile Sub-Committee, consisting of the Chairman of the PPA and representatives of the various companies. The profiles are reviewed by the committee, taking into consideration the operational requirements and their experiences with the profiles at sea, they would then modify the profiles accordingly. Proposals for modifications of profiles are also discussed by the Safety Committee, consisting of the Safety and Training Officer of the PPA and the senior divers of the various companies. Such modified profiles are again tested in the RCC. For operational reasons, the committees are reluctant to alter the bottom time or the number of drifts (dives) per day, they would rather add more oxygen to the decompression stops. This method does not always work as will be discussed in another paper.[5]

Safe ascent depth (SAD) analysis

When testing the profiles in the RCC, they were also analysed with the Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) safe ascent depth (SAD) model to establish a SAD for the specific profile. SAD is a depth at which the diver should be after the hyperbaric exposure of depth and time and decompression stops and that one should not go shallower than that depth, i.e. one should only surface when the SAD is zero.

The initial analysis of the SADs showed high values for the non-rotational profiles, with values as high as 4.02 m for the 23 msw profile, 3.51 m for 21 msw, 2.78 m for 19 msw, 2.30 m for 17 msw and 1.69 m for 15 msw. The rotational profiles produced more satisfactory values, a SAD of 0.46 m for 35 msw, 0.18 m for 33 m, 0.6 m for 31 msw, 0.33 m for 29 msw, 0.47 m for 27 msw and 1.04 m for 25 msw.

Those profiles which showed a SAD greater than 1.46 m were modified. This arbitrary figure was chosen from experience with the field work and the RCC trials as this value produced only low bubble grades.

Due to variability of interpretation of Doppler scores,[8] initially some selected tapes were sent to DCIEM for verification.

Results

When this project started in 1991 the drift diving season had already ended. The initial phase was to test the profiles in the RCC with Doppler recording of the dived profiles in 1992.

RCC Trials

The trials showed a general pattern.

All the PPA profiles produced bubbles.

All divers showed bubbles on all trials.

Non-rotational profiles were more stressful than the rotational profiles.

Decompression stops were useful in the prevention of high bubble grades.

Increasing oxygen in the decompression stops assisted in lowering the bubble grades.

Bubble grades tended to peak between 60-120 minutes after a dive.

Bubble grades tended to peak on day 4 of the diving and remain virtually unchanged till day 8.

Bubbles were still present after 12 hours. They started to disappear after 17 to 19 hours depending on the stress of the profile.

Some of the early RCC trials with high SAD values of the non-rotational profiles produced symptoms of DCS in some divers. The committee modified the profiles by arbitrarily increasing the decompression stops as they did in the old pearling days.

Profiles are rejected if they consistently show grade III bubbles in both divers of a trial.

Profiles are considered as acceptable only if they have grade II bubbles or less. The 1994 PPA dive schedules (Appendix 2) generally produce grade II bubbles or less.

Non-rotational profiles have been tested from 3 to 7 times. All of them have been modified because of high bubble grades. The shallower profiles 13 msw; 15 msw; 17 msw have all been modified and re-tested at least 3 times, they are considered as "acceptable" at present. The 19 msw and 21 msw need further modifications, because in 1992-1995 six of the 9 cases of DCS were from these depth ranges.

The 23 msw profile is unacceptable as a non-rotational profile despite the protest from one company that this profile has been used safely at sea. This profile consistently produces very high bubble grades.

Rotational profiles were all tested once. Modifications were made to profiles 25 msw and 35 msw after which they all produced bubbles of grade II+ or less.

Doppler scores and ascent rate

In the RCC trials, when the faster ascent rate of 15 m/min was used with the PPA's Dive Schedule (with the same divers), the trial had to be abandoned after the first day due to high bubble scores (III+). With the slow rate of ascent of 3 m/min, the trial was successfully completed over the 8 days.

The preliminary studies with various trials using different ascent rates indicated that the faster ascent rate produces a higher bubble grade which tends to persist longer. Testing the 17 msw profile with the slow ascent of 3 msw/min, only grade II bubbles were recorded, which dropped to grade I by 60 minutes and disappeared within 90 minutes. But when using the 15 msw/min ascent, grade III bubbles were observed at 30 minutes, which dropped to grade II at 60 minutes. At 3 hours grade I bubbles were still being recorded.

Preliminary analysis of data from the RCC trials

Due to individual variability in bubbling, a block design was used, with divers as blocks. It was to test divers at a number of depths to estimate their propensity to bubble. Ordinal logistic regression was used to estimate the probabilities of not exceeding grade II. For the 11 msw, 13 msw and 15 msw profiles, the estimated probabilities of not exceeding grade II are well above 50%. Other PPA profiles have yet to be tested to produce enough data for analysis.

Unexpected termination of a dive schedule

What might happen should a dive schedule (non-rotational profile) be terminated before the end of the day? This had been considered but had not been tested formally.

However, during one of the trials of the non-rotational profiles, the compressor of the RCC failed and the trial had to be abandoned after dive 3 of the 3rd day. Usually with the non-rotational trials, the surface intervals being 20 minutes, the bubble grade did not rise above I or II-. The short surface interval perhaps limits the growth of bubbles. However, with this particular incident, the bubble grade rose to III+ after 90 minutes.

Field testing

One diver is chosen as the "test subject". Doppler scoring is done on the test subject pre-dive, after each dive and at the end of the day he is tested half hourly for 2 hours. The rest of the divers are only tested at the end of the day. All studies are done daily for the duration of the diving trip, usually referred to as the neap tide by the industry, which is usually 8 days. Divers are quite reluctant to be tested because they are usually tired at the end of the day and incentives had to be given. Initially, the dive profiles were recorded with a locally built depth-time recorder, unfortunately this was unreliable and difficult to calibrate. So the diving depths were initially recorded by the echo-sounder of the fishing vessel (having taken into consideration the depth of the echo-sounder from the surface of the water) in combination with a Suunto dive computer. This was unsatisfactory. Fortunately, towards the end of 1994, Citizen Hyperaqualand watches became available. These can log the dive profiles at 3 seconds intervals.

Figure 4 shows the number of dives performed at each depth in the years 1991 to 1994. The number of dives vary from year to year depending on the abundance of wild oysters over the fishing grounds. Each company is allocated a fixed quota of oysters each year.

Decompression illness

Table 1 shows the number of cases of DCI and the number of dives each year. The 1991 dives were dived in accordance with the profiles printed in the Code of Practice of the Pearl Producers Association Inc. of Western Australia (Appendix 1) before modification of the profiles. In that year there were 11 cases of DCI, 2 of whom had neurological symptoms. Appendix 2 shows the profiles used in 1994 where a lot more decompression stops were added.

In 1992 and 1993, there were 4 and 3 cases respectively and all had musculo-skeletal symptoms. There were no recorded cases in 1994 and two in 1995. Review of the DCI cases showed that the depths of dives which caused DCI symptoms were mainly from depths around 18-21 m. Appendix 3 details the DCI cases from 1992-1995. Figure 5 gives the dives and depths for 1992-1995 when the revised schedules were in use.

Bubble grades

Despite profile modifications, the Doppler scoring in the field work has not changed substantially from 1992 to 1994 (going from II+ to II- at equivalent depths). This is probably due to the divers not adhering to the prescribed rate of ascent.

The pre-dive bubble grade (12 hours out of the water) shows an average of I+ for both the non-rotational and rotational profiles.

For the non-rotational profiles the bubble grades tended to peak on day 3, with an average grade of II- at the end of the day. However, on day 4, they dropped down to grade I+ and remained at I+ to day 8. With the rotational profiles, the grades reached II- on day 2 and remained virtually unchanged till day 8.

Since it takes an average of 60 minutes for the bubble grade to reach a maximum, it is not surprising that for the non-rotational profiles, with their short surface intervals, the grades were all below II, with an average grade of I+.

For the rotational profiles, the bubble grade tended to rise around dive 3 with an average grade of II-. This applies to RCC studies and to the limited number of field studies.

FIGURE 4

PEARL FISHING DIVES 1991-1994

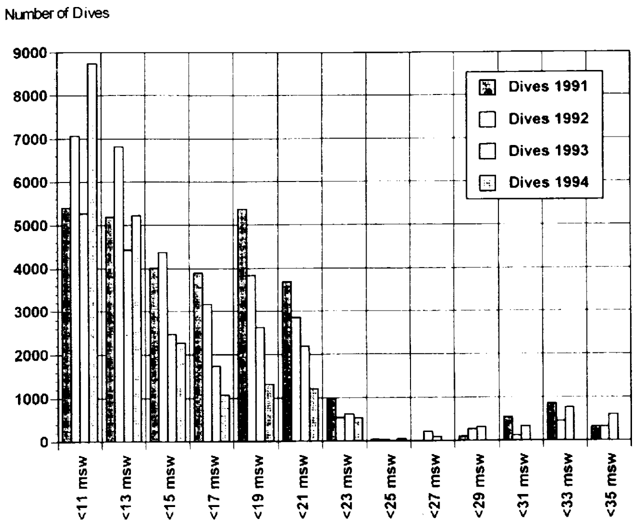


TABLE 1

DCI AND DIVES 1991-1995

Year	Dives	DCI Cases	DCI Incidence
1991	30,402	11	0.036%
1992	30,095	4	0.013%
1993	21,452	3	0.013%
1994	20,436	0	0.000%
1995	18,974	2	0.010%

Sea trials

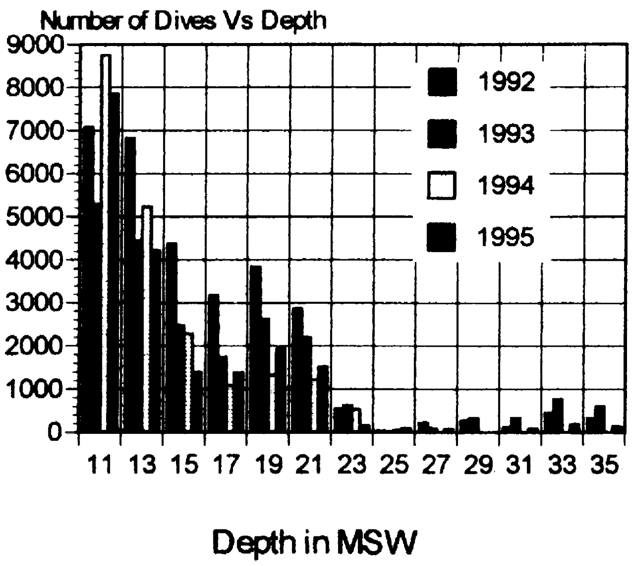
The bubble scores recorded at sea represent only a small percentage of the dives. With only one research assistant the studies done are limited by the availability of the pearling vessels and the depth dived by the divers of that vessel. The preference is to dive in shallow waters, but if the shell availability is low or if the visibility is poor then the divers are forced to go to deeper waters.

The divers were asked to grade their level of workload as light, average or heavy. Most were graded as average or light.

There were 8 diving trips monitored in 1992. The Doppler recordings showed an average reading of grade II, with grade III- on trip 8 when the diving depths were around 33.65 msw (Table 2). The ascent rate of the divers were faster than the 3 m/min dictated by the Code of

FIGURE 5

PEARL FISHING DIVES 1992-1995



Practice, particularly in trip 5 when it was recorded as 9.7 m/min.

There were only 5 trips monitored in 1993 and the recordings were done in the shallow waters. Workload was again graded as average, while trips 2 and 4 were graded as light. (Table 3). The ascent rate departed from the prescribed 3 m/min. The average recorded rate was 3.7, 6.3, 4.4, 4.3 and 10.2 m/min on the five trips.

Six trips were monitored in 1994, again they were in shallow waters, and the workload was graded as average (Table 4). The ascent rates used by the divers were faster than prescribed.

Bubble grades in RCC and at sea

Initially, when the profiles were tested in the RCC and in the field, the bubble grades at sea were lower than that in the RCC. The reason was that all the profiles tested in the RCC were dived to the maximum depth and time in accordance with the Code of Practice. At sea, however, depths were variable (so not producing a square dive profile) and not necessarily to the same depth for every dive or every dive.

When the modified profiles were applied to the field work, there was a tendency for the bubble grade to fall, this however did not continue in 1994. On analysis, it was discovered that the divers had adopted a faster rate of ascent, perhaps because of the shallower depths dived. This faster ascent rate could account for the rise in bubble grades.

TABLE 2
BUBBLE GRADES AND MEDIAN DEPTHS ON 8 DIVING TRIPS IN 1992

Trip	Bubble grades	Median Depth
1	II+	19.55
2	II-	15.35
3	II-	11.9
4	II+	12.2
5	II+	13.0
6	II+	13.1
7	II+	30.5
8	III-	33.65

TABLE 3
BUBBLE GRADES AND MEDIAN DEPTHS ON 5 DIVING TRIPS IN 1993

Trip	Bubble grades	Median Depth
1	II-	14.2
2	I+	10.10
3	II-	10.83
4	I+	10.93
5	II-	12.1

TABLE 4
BUBBLE GRADES AND MEDIAN DEPTHS ON 6 DIVING TRIPS IN 1994

Trip	Bubble grades	Median Depth
1	II-	
2	II-	11.9
3	II-	11.5
4	II-	11.8
5	II-	12.0
6	II-	12.3

Over the 3 years a decreasing number of divers complied with the PPA's ascent rate. The percentage of divers who ascended under 6 m/min changed from 80.30% in 1992 to 75.20% in 1993 and to 63.30% in 1994.

Discussion

By using Doppler bubble monitoring in the RCC we have been able to identify diving profiles which produced DCI and those which produced high bubble grades when using a 3 m/min ascent rate.

The use of the Doppler technique has been most useful in identifying the stressful profiles of the PPA's

TABLE 5

RECORDED ASCENT RATES 1992-1994

Ascent rate	1992	1993	1994
< 3 m/min	34.4%	28.6%	18.7%
< 6 m/min	45.9%	46.5%	44.7%
< 9 m/min	8.6%	10.6%	19.6%
> 9 m/min	11.1%	14.3%	17.0%

Profiles as stated in the Code of Practice. The modifications, although empirical as was done in the bygone days, show that it is possible to dive to the new profiles safely as the end of the day Doppler score usually lies around the grade I or II, which is perhaps due to the longer decompression time used for the final dive.

However it has been difficult to persuade divers to use the slow 3 m/min ascent rate. We have shown in the RCC trials that a 15 m/min ascent rate markedly increases the production of bubbles. The general increase in ascent rates used by the divers (Table 5) may make the profiles less safe than they can be.

Acknowledgments

I would like to thank all those who have provided information used in this paper, especially members of the pearling industry, the Pearl Producers Association Inc. WA, pearl divers past and present and the R&D Corporation, Fisheries Department, Western Australia.

Key words

Bubbles, occupational diving, oxygen, hyperbaric research, tables.

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APPENDIX 1

PEARL PRODUCERS ASSOCIATION
MAXIMUM LIMIT DIVE PROFILE

ADOPTED 1991

NO ROTATION

DEPTH (Maximum)	BOTTOM TIME (Maximum)	ASCENT RATE	SURFACE INTERVAL	No of DIVES or MAX BOTTOM TIME	DECOMPRESSION
0- 11	90 mins	3 m/min	Min 15 mins Min Accumulated Surface Intervals 135 mins	Max bottom time for the day 500 min	Not required
11- 13	60 mins	3 m/min	Min 20 mins	Limit of 500 mins	10 mins on air at 5 m at end of day. Then 3 m/min to surface ascending on air.
13- 15	45 mins	3 m/min	20 min	Limit of 400 mins	10 mins on O_2 at 9 m at end of day. Then 3 m/min to surface ascending on O_2.
15- 17	40 mins	3 m/min	20 mins	Limit of 400 mins	10 min on O_2 at 9 m at end of day. Then 2 minutes/metre ascending on O_2 at end of day.
17- 19	40 mins	3 m/min	20 mins	Limit of 400 mins	5 mins on O_2 at 9 m after the 5th drift. 15 mins on O_2 at 9 m at end of day. Then 2 minutes/metre ascending on O_2 at end of day.
19- 21	40 mins	3 m/min	20 mins	Limit of 360 mins	5 mins on O_2 at 9 m after the 5th drift (then ascending at 3 m/min on O2). 15 min on O_2 at 9 m at the end of the day then ascending on O_2 at 2 minutes/metre.
21- 23	40 mins	3 m/min	20 mins	Limit of 360 mins	10 mins on O_2 at 9 m after the 5th drift (then ascending at 3 m/min on O_2. 20 min on O_2 at 9 m after the last drift ascending on O_2 at 3 minutes/metre.

ROTATING 2 TEAM ROTATING SYSTEM

DEPTH (Maximum)	BOTTOM TIME (Maximum)	ASCENT RATE	SURFACE INTERVAL	No of DIVES or MAX BOTTOM TIME	DECOMPRESSION
23- 25	40 mins	5 m/min to 21 m then 3 m/min to stage point at 9 m.	After D1 = 60 mins D2 = 70 mins D3 = 80 mins D4 = 90 mins	5 per team	D1 = air ascent to surface at 3 m/min. D2 = 5 min on O_2 D3 = 10 min on O2 D4 = 15 min on O_2 D5 = 20 min on O_2 (D2 - D5 then ascent on O_2 at 3 m/min.)
25 - 27	35 mins	5 m/min to 21 m then 3 m/min to 9 m.	After D1 = 60 mins D2 = 70 mins D3 = 80 mins D4 = 90 mins	5 per team	D1 = 5 min on O_2 D2 = 10 min on O_2 D3 = 15 min on O_2 D4 = 20 min on O_2 D5 = 25 min on O2 (D1 - D5 then ascending to surface on O_2 at 3m/min.)
27 - 29	30 mins	5 m/min to 21 m then 3 m/min to 9 m.	After D1 = 60 mins D2 = 70 mins D3 = 80 mins D4 = 90 mins	5 max per team	D1 = 5 min on O_2 D2 = 10 min on O_2 D3 = 15 min on O_2 D4 = 20 min on O_2 D5 = 25 min on O_2 (D1 - D5 then ascending ascending to surface at 3m/min.)
29- 31	25 mins	5 m/min to 21 m then 3 m/min to 9 m.	After D1 = 70 mins D2 = 80 mins D3 = 90 mins D4 = 100 mins	5 max per team	D1 = 5 min on O_2 D2 = 10 min on O_2 D3 = 20 min on O_2 D4 = 25 min on O_2 D5 = 30 min on O_2 (D2 - D5 then ascending to surface on O_2 at 3m/min.)
31 - 33	25 mins	5 m/min to 21 m then 3 m/min to 9 m.	After D1 = 70 mins D2 = 80 mins D3 = 90 mins D4 = 100 mins	5 max per team	D1 = 5 min on O_2 D2 = 10 min on O_2 D3 = 20 min on O_2 D4 = 25 min on O_2 D5 = 30 min on O_2 (D1 - D5 then ascending to surface on O_2 at 3m/min.)
33 - 35	25 mins	5 m/min to 21 m then 3 m/min to 9 m.	After D1 = 80 mins D2 = 90 mins D3 = 100 mins	4 max per team	D1 = 10 min on O_2 D2 = 15 min on O_2 D3 = 20 min on O_2 D4 = 25 min on O_2 (D1 - D5 then ascending to surface on O_2 at 3m/min.)

ROTATING SYSTEM 4 IN 2 OUT'

DEPTH (Maximum)	BOTTOM TIME Maximum	ASCENT RATE	SURFACE INTERVAL	No of DIVES or MAX BOTTOM TIME	DECOMPRESSION
19- 21	40 mins	3 m/min	20 mins SI 90 mins SI Rotating sequence	8	10 mins on O_2 at 9 m then ascending with O_2 at 3 m/min after the last dive.
21-23	40 mins	3 m/min	20 mins 90 mins Rotating sequence	8	15 min on O_2 at 9 m then ascending with O_2 at 3 m/min after the last dive.

NOTE:

This dive profile is the maximum recommended times with an ascent rate of 3 metres/minute from 21 metres. (Below 21 metres ascending at 5 metres/min.) The profile is to be used when conditions are ideal and if necessary the profile associated with the next 2 m interval when conditions are less than ideal (for example ,when considering the fitness of the diver, weather conditions, visibility, prevalence of stingers and the experience of crew).

Three zones have been marked as:-
(1) Deeper than 23 m
(2} 15 m to 23 m
(3) 0 to 15 m

If you propose to move from a shallower to a deeper zone you should do the full decompression stop for that day before moving to the deeper zone. Once .you have moved to another zone, then you should observe the full decompression stop at the end of the day for whatever zone you have moved into.

If you move from a deeper to a shallower zone. at the end of the day decompression would be that of the deeper zone. Skippers must allow for transducer position on ship's hull when determining depth.

5.2 INDUSTRY DRIFT DIVE PROFILES

5.2.1 All Industry Drift Diving will be to these Profiles or more conservative versions that have been approved by the Safety Committee and the PPA.

5.2.2 The Skipper and Head Diver at the site of dive is responsible for determining the dive profile to be employed.

5.2.3 The accompanying divers are responsible for checking the designated prolife.

5.2.4 All divers are responsible for maintaining of the designated dive profile.

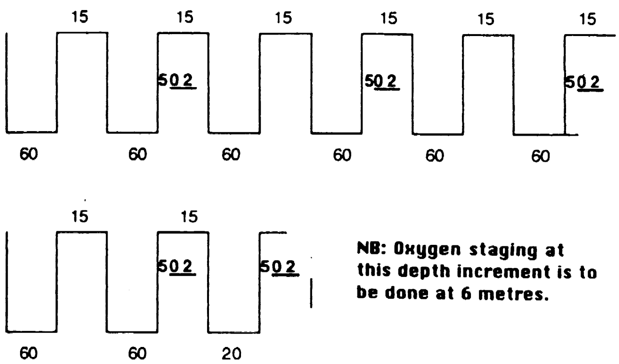
5-2.5 It is essential that each diver is fully aware of the decompression sequence prior to the dive as underwater visibility may be poor and Head Diver supervision may be limited.

APPENDIX 2

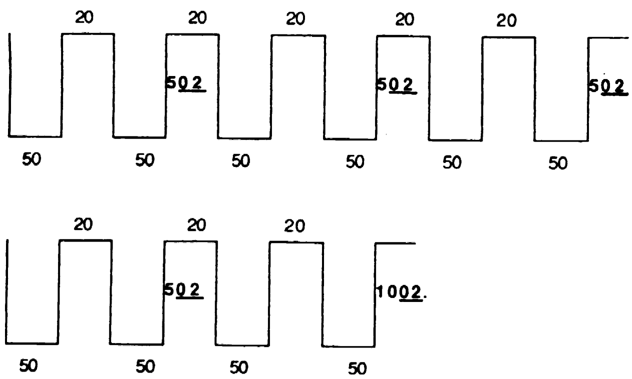
DRIFT DIVE PROFILES 1994
NO ROTATION

Ascent rates 3 m/min. Decompression stops on O_2 at 9 m and ascending.
O2 = oxygen, **5** = 5 minutes, **10** = 10 minutes etc.

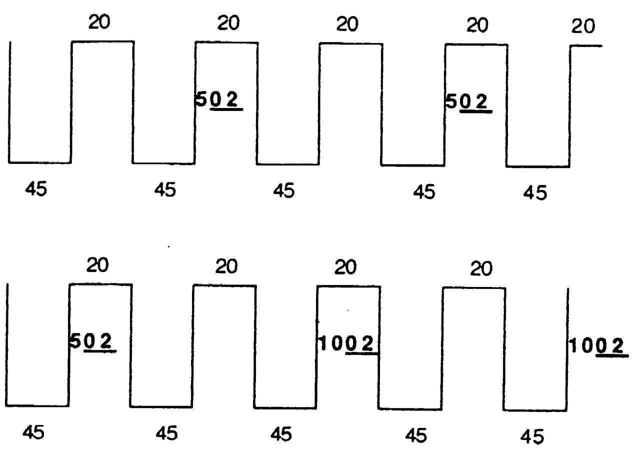
0-11 metres max BT 500 mins. 10 dives max.



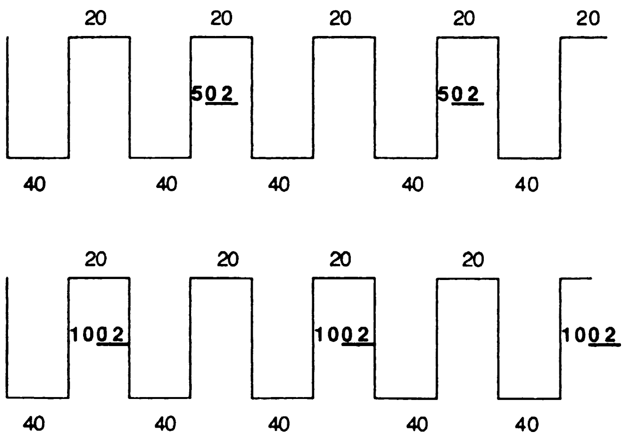
11-13 metres 500 min/day. 10 dives max.



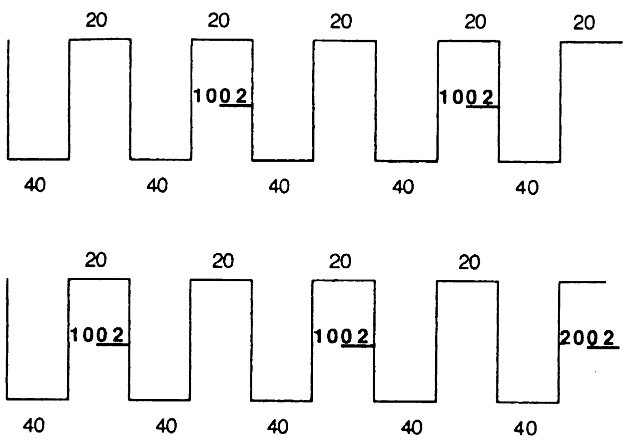
13-15 metres 450 min/day 10 dives max.



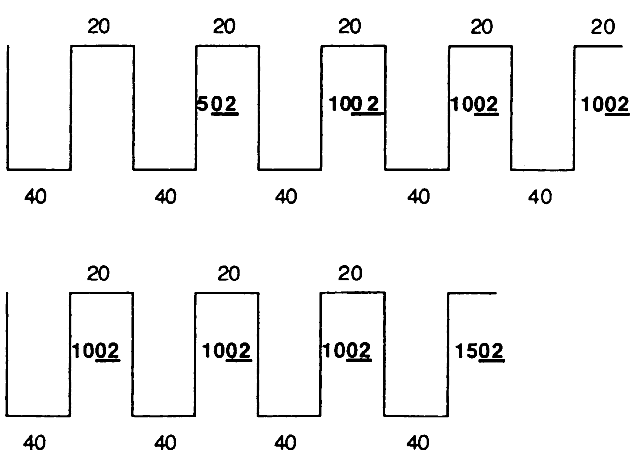
15-17 metres 400 min/day 10 dives max.



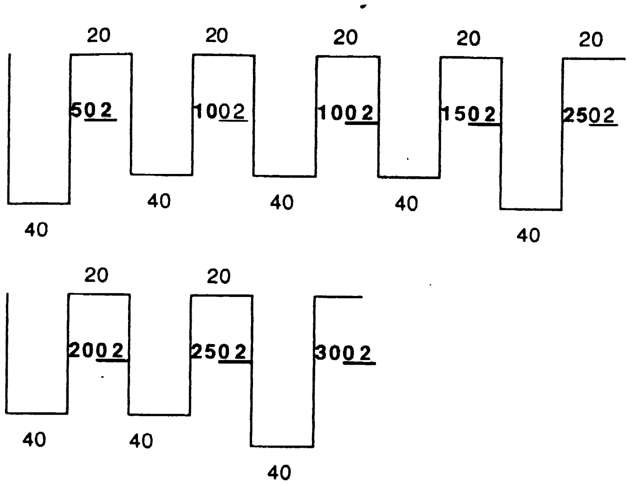
17-19 metres 400 min/day 10 dives max.



19-21 metres 360 min/day 9 dives max.



21-23 metres 320 min/day 8 dives max.



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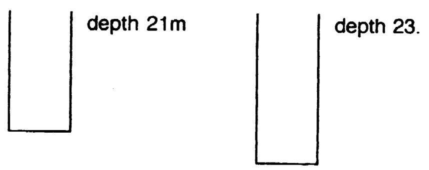
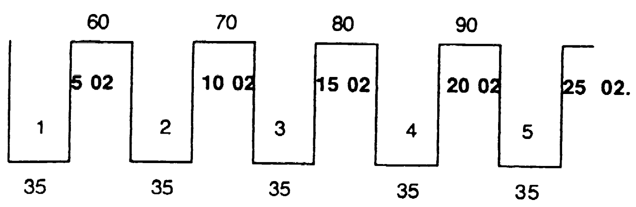


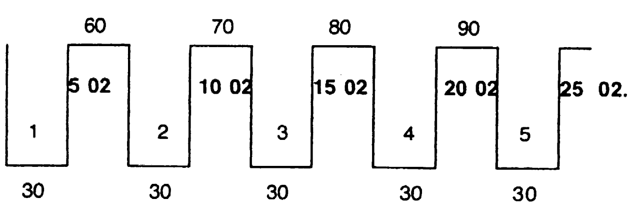
Footnote: When diving this profile flexibility to O_2 times must be used in relation to tidal variation. i.e. The above profile is an example only of how to apply O_2 times. If, for example, depths nearing 23 m are dived at times differing from the above profile, then the greater O_2 times will need to follow the greater depths.

ROTATION

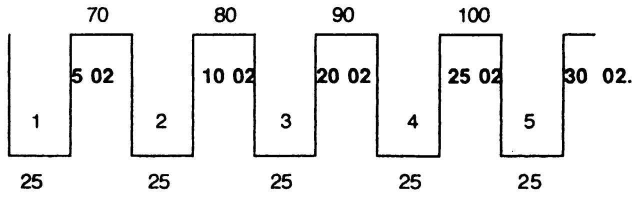
25-27 metres



27—29 metres

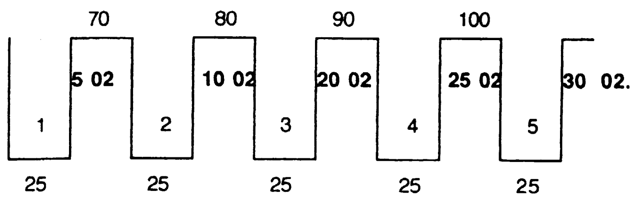


29-31 metres

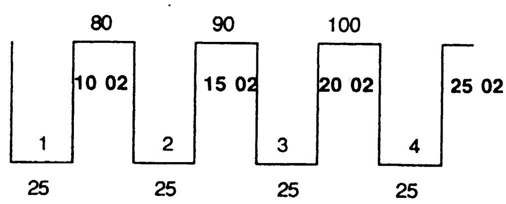


NB: ALL ASCENT RATES ARE 5 METRES/ MINUTE TO 21 METRES AND 3 METRES/ MINUTE TO 9 METRES.

31-33 metres



33-35 metres



NB: This dive profile is the maximum recommended times with an ascent rate of 3 metres/minute from 21 metres. (Below 21 metres ascending at 5 metres/min.) The profile is to be used when conditions are ideal and if necessary the profile associated with the next 2 m interval when conditions are less than ideal. e.g. when considering the fitness of the diver, weather conditions, visibility, prevalence of stingers and the experience of crew.

Three zones are marked as:-
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(3) 0 to 15 m

If you propose to move from a shallower to a deeper zone you should do the full decompression stop for that day before moving to the deeper zone. Once .you have moved to another zone, then you should observe the full decompression stop at the end of the day for whatever zone you have moved into.

If you move from a deeper to a shallower zone. at the end of the day decompression would be that of the deeper zone.

Skippers must allow for transducer position on ship's hull when determining depth.

APPENDIX 3

DCI CASES

In 1991, all the dives were performed in accordance with the original Code of Practice of the Pearl Producers Association Inc. There were 11 cases of DCI. From 1992 onwards, the profiles were modified as a consequence of the results of Doppler studies.

TABLE 1

TOTAL DIVES AT VARIOUS DEPTHS 1992-1995

Depth in m	Year 1992	1993	1994	1995
11	7,075	5,269	8,742	7,842
13	6,821	4,428	5,226	4,215
15	4,373	2,470	2,274	1,383
17	3,168	1,738	1,080	1,380
19	3,835	2,642	1,320	1,926
21	2,856	2,189	1,212	1,518
23	547	621	534	144
25	35	12	48	88
27	220	88	0	78
29	269	316	0	0
31	118	332	0	88
33	455	764	0	188
35	323	600	0	124
Total	30,095	21,469	20,436	18,974
DCI	4	3	0	2
Incidence	0.013%	0.013%	0.00%	0.010%

All the cases from 1992 onwards presented with musculo-skeletal symptoms. Table 1 gives the number of dives, number of DCI cases and incidence. Of the nine cases of DCI in 1992-1995 four (44%) occured at 21 m, two (22%) at 19 m and one at 13 m, at 17 m and at 33 m. Details of the 1992- 1995 cases are given below.

Case 92/1
28/2/92. DCI affected the left knee on dive 1 on day 3 of a 5 day diving trip, the third of the year. Depth 19 m.

Case 92/2
28/3/92. DCI affected the right wrist on dive 9 on day 4 of a 7 day trip. Depth 21 m.

Case 92/3
9/4/92. DCI affected shoulders after dive 7 of 9 dives on day 1 of first diving trip of the year. Depth of dive 20 m.

Case 92/4
23/5/92. DCI affecting right shoulder and elbow after 8 dives on day 4 of a 10 day trip, the fourth for the year. Depth 13 m.

Case 93/1
16/1/93. After 8 dives on day 3 of diving. Depth 21 m.

Case 93/2
16/2/93. After 9 dives on day 1 of diving. Depth 18 m.

Case 93/3
30/3/ 93. After 5 dives on day 4 of diving. Depth 33 m.

Case 95/1
12/3/95. After 9 dives on day 4 of diving. Depth 20 m.

Case 95/2
13/5/95. After 8 dives on day 8 of diving of an 8 day diving trip. Depth 16 m.

HOW SAFE IS PEARL DIVING?

Robert M Wong

Abstract

The pearl divers of Broome, in Western Australia, perform repetitive and multi-day diving and yet they have an overall incidence of decompression illness of 0.01%. This paper discusses the reasons why.

Introduction

On initial inspection of the pearl divers dive profiles,[1] one could be excused for thinking that the profiles are unworkable, because the mode of diving have **inadequate decompressions** and **inadequate surface intervals** when compared with the conventional decompression tables.

Moreover, they appear to violate all the current recognised risk factors as they require more than 3 repetitive dives per day, multi-day diving for more than 4 consecutive days, deep dives to more than 30 m and diving from deep to shallow on occasions.

Notwithstanding the above, their overall incidence of decompression illness (DCI) among the pearl divers is less than 0.01% and, for the past four years, the clinical manifestation has been confined to musculo-skeletal symptoms only.

Current data on repetitive and multi-day diving

It is well known that repetitive dives and multi-day diving cause problems and run a high risk of DCI. This has been demonstrated both clinically and in experiments. A number of papers have presented theoretical reasons for such risks. The "critical diameter model" or "arterial emboli model" suggests that bubbles are trapped in the lungs during normal decompression and with repetitive diving the recompression of the next dive may allow bubbles to pass across to the arterial side causing serious neurological DCI.[2,3]

The existence of this transmission has been demonstrated in mice and in guinea pigs.[4] It has also been shown that there was central movement of bubbles formed in the periphery by the compression phase of a repeat dive.[5] Showers of bubbles could be seen ascending the inferior vena cava during the compression phase of the second dive and bubbles were observed in the aorta during the second decompression. Therefore, an ill judged repeat dive not only could give rise to an increased likelihood of DCI but may also result in far more severe symptoms.[6]

While it is convenient to accept the arterial emboli model, it has to be pointed out that Francis et al.[7] injected air into spinal arteries in dogs and found the emboli to be distributed in the grey matter rather than the white matter where spinal lesions are typically seen.

Other experimental evidence also showed that repetitive diving was a reliable means of producing spinal DCS in goats and dogs.[8,9]

Imbert et al.[10] indicated that the currently available data suggest that the risk of Type II decompression sickness (DCS) decreases as the surface intervals increase and also that the arterial emboli model successfully permitted correlation of Type II DCS occurrences with depth changes or recompressions. Nevertheless, after 6 hours, it appears that recompression at the beginning of the second dive no longer produces arterial bubbles.

It has long been recognised that sports divers who perform repetitive and multi-day diving have a high incidence of neurological DCI.[11] Information on risk and incidence is scarce, however, by applying the method of maximum likelihood to repetitive air dives using the DCIEM Sport Diving Tables for a two-dive profile, it is estimated that the probability to be around 1.1% to 3.2%.[12]

Notwithstanding the above theoretical and experimental evidence of harm caused by repetitive diving, the pearl divers appear to do this with no incidence of neurological DCI.

Since the pearl divers continuously "break the rules" of conventional diving, why then are they not prone to DCI just like everyone else? Why is it that they have an incidence of less than 0.01% and are confined to musculo-skeletal symptoms?

In practice, the acceptable risk of DCI has been quoted as US Navy divers 3-4%, Caisson workers 2%, Commercial divers 0.1-0.5% and the space shuttle as 6%.[13]

Pearl divers of Broome

Despite their unconventional way of diving, it appears that the pearl divers of Broome dive reasonably safely.

The success of the profiles could be due to a number of factors which are different from the conventional decompression tables.

These are a slow rate of ascent, an appropriate depth of the decompression stop, the use of oxygen in decompression, suitable interdive intervals and perhaps acclimatisation.

Is there an optimum rate of ascent?

Dr M Foley wrote at the time of construction of the bridge at Argenteuil over the Seine in 1861 that he considered the rate of decompression to be unimportant. He thought that one minute per atmosphere was enough.[14] However, most scientists at the time believed that a slower decompression should be followed.

In diving, unlike caisson work, there appears to be some very different opinions. From the historical perspective, Haldanian practice used an ascent rate of 25 ft/min (7.6 m/min).[15] Haldanian "staged decompression" was challenged by Sir Leonard Hill,[16] who advocated a slow bleed approach of uniform decompression, a technique in use by the pearl divers. A study of the pearl divers in Torres Strait led to the thermodynamic approach advocated by Brian Hills.[17]

Although it has generally been accepted in the diving community that the "standard ascent rate" of air diving ought to be 60 ft/min or 18 msw/min., supporting evidence is wanting. The 1952 issue of Bureau of Ships Diving Manual NAVSHIPS 250-880 stated that the ascent rate was not to exceed 25 ft/min. Commander Doug Fane USN, wanted his "frogmen" to ascent at 100 ft/min or greater. As a compromise between the "frogmen" and the standard hard hat divers that 60 ft/min came into being. (US Navy Air decompression tables 1958).[18] The new USN decompression tables (1993) have been modified to a 30 ft/min ascent rate.

Most air decompression tables concentrate on the depth and duration of the decompression stops as well as the duration of the surface intervals. The ascent rate is given less attention.

A survey of various dive tables shows that the recommended ascent rates vary. The USN and PADI use 60 ft/min (18 m/min). The Swiss (Bühlmann/Hahn) tables use 10-15 m/min to 6 m, then 6 m/min to the surface. Huggins uses 40 ft/min (12 m/min) to 20 ft (6 m) then 20 ft/min (6 m/min) to the surface, in addition a three minute stop at 20 ft (6 m) is required for dives deeper than 60 fsw (18 m). The DCIEM tables use 18 m/min (± 3 m/min). The Royal Navy uses 20 m/min while the Bassett tables have 10 m/min as the ascent rate.

If the ascent rate is too slow, there is a penalty of added bottom time. For instance, the DCIEM table states that if the ascent rate is less than 15 m/min and if delay starts deeper than half the maximum depth of the dive the time delay is added to the bottom time and the diver is required to decompress in accordance with the new bottom time; if however, the delay starts shallower than half the maximum depth of the dive, then the delay is added to stop time of the next stop. If no stop is required, then the diver has to stop at 3 m for the time of the delay. Similar rules are applied to the USN decompression tables where the rate is less than 60 ft/min (18 m/min) and the depth of 50 ft (15 m).

Is slower better?

The size of bubbles is determined by degree of saturation and the rate of pressure reduction (ascent). Therefore, a slow ascent has the advantage of maintaining the micronuclei under pressure but has the disadvantage of slowing diffusion from the tissue.

Lewis, using the US Navy's 6 compartment model as a basis of calculation, showed that by halving the ascent rate from 60 ft/min (18 m/min) to 30 ft/min (9 m/min) is the equivalent of 0.8 minutes of decompression stop at 15 ft (4.5 m) when diving to the USN's no-decompression limits.[19] Wienke considers safety stops of 2-4 minutes are easier and more efficient than slowing the ascent rate.[20]

Hamilton while agreeing that slowing the ascent rate decreases the incidence of DCI, points out that a slower ascent rate results in a penalty of bottom time.[21] He considers that a short stop is slightly more beneficial than a slow ascent rate and does not increase the dive time as much.

Yount, using the varying permeability (VP) model as a basis for calculation, considers that there is no minimum rate of ascent.[22] Van Liew considers that the slower the ascent the better.[23]

Smith implanted Doppler cuffs around the inferior vena cava in 2 goats.[24] He chamber dived the goats to 220 fsw (66 m or 660 kPa) for 20 minutes and compared the results of using the USN Decompression Procedure (Exceptional Exposure Table) and a 2 phase linear decompression with 30 ft/min (9 m/min) ascent rate to 80 fsw (24 m), then ascent at 2 ft/min (0.6 m/min) to the surface. With the latter incidence of precordial bubbles was greatly reduced.

It was stated by Vann that in 60 dives using a variety of decompression profiles, venous bubbles were nearly abolished by reduced ascent rates and deeper initial decompression.[25]

Mano, using gelatine gel experiments, demonstrated that as the ascent rate decreased, the number of bubbles also decreased. He further demonstrated that the optimum rate of decompression was 9 msw/min (30 ft/m).[26]

Rapid ascent to the surface may generate bubbles of a diameter small enough to cross the lungs,[27] and that repetitive diving with short surface intervals and yo-yo diving could be expected to produce arterial bubbles.

However, it has also been stated that a carefully planned sequence of repeat dives may have a lower than expected incidence of symptoms because the nuclei are consumed and the number of bubbles decreases and that dives must be conducted in decreasing severity.[19]

Daniels has calculated that if decompression in a saturation dive was slowed by 25 times, then bubble formation could be avoided.[28]

Evans and Walder demonstrated that hydrostatic treatment of *Cragnon cragnon* could reduce the extent of bubble formation on subsequent decompression and postulated the existence of micronuclei.[29] Other workers using other models indicated that bubble formation within tissue is initiated as micronuclei and that they are pressure sensitive.[30] Daniels et al. have investigated and confirmed the effect of hydrostatic pressure on the common shrimp *Cragnon cragnon* and that regeneration of micronuclei does occur.[31]

Brubbak noted that, in saturation dives, there were more bubbles formed during the first than the second ascent. This was postulated to be due to consumption of the micronuclei during the first ascent and inadequate time for subsequent regeneration.[32]

From the practical viewpoint, Zannini reported that the Italian commercial divers now routinely use 10 m/min ascent rate and reported no incidence of DCS in over 24,000 dives at depths ranging from 10 to 50 m.[33]

Koch modified USN treatment table 6 by slowing the ascent from 18 msw to 9 msw and reported a dramatic reduction of recurrence of symptoms (personal communication 1992).

The ascent rates of therapeutic tables vary greatly.[34] USN 6 uses 1 fsw/min (0.3 m/min) while USN 1 uses 20 fsw/min, 10 f/min and 6 f/min (6, 3 and 1.8 m/min). RN 71 uses 60 m/h at depth, then 6 m/min to 0.5 m/min towards the surface, while COMEX Cx 30 requires 5 mins/m to 2 mins/m.

Since we assume that, in DCI, bubbles are the offending agent the rationale for treatment, in simplistic terms, is to recompress the bubbles and use a breathing gas that would cause the bubbles to shrink by creating a large diffusion gradient, then use an ascent rate(s) that does not encourage bubbles to grow on decompression. As it is generally accepted that after a compressed air dive bubbles are formed on most decompressions,[35] especially with repetitive dives and multi-day diving, one should logically consider a slow rate of ascent to avoid bubble formation. Perhaps, this was the rationale and the lesson learnt by the pearl divers in developing their profiles from their personal experience of trial and error over the past 100 years.

A slow rate of ascent, apart from decreasing the risks of pulmonary barotrauma and its sequelae, does appear to shift the type of DCI from neurological to musculo-skeletal symptoms, (in the same manner as in saturation diving where it is uncommon to have symptoms affecting the spinal cord) and therefore confer a degree of safety for repetitive diving.

Analysis of DCI incidents at the Royal Australian Navy (RAN) Submarine Escape Training Facility, HMAS STIRLING, revealed that 7 (54%) of the 13 instructors suffered DCI when exposed to multiple and rapid ascents (buoyant and hooded ascents) from depths of between 18 and 22 msw. (Loxton personal communication).

Depth of decompression stops

Pilmanis showed the effectiveness of a decompression stop in reducing bubble numbers. A 2 minute stop at 10 ft (6 m) after a 100 ft (30 m) dive for 25 minutes (USN no-decompression limit) produced a dramatic drop, by more than 5 fold in the first 15 minutes, in bubble numbers when compared with a direct ascent to the surface (Fig. 1). It was suggested that short “safety stops” could be beneficial in reducing the occurrence of “silent bubbles” in divers using the limits of the USN no-decompression Tables.[36]

While there is consensus regarding the benefits of a decompression stop, there are varying opinions about the optimum depth of decompression.

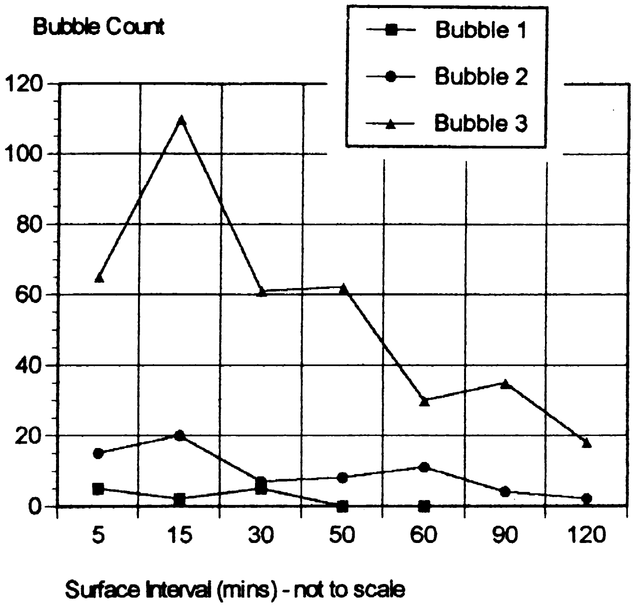
The decompression tables of the USN and RN have decompression stops at 3 m, 6 m, 9 m and 12 m, whereas RNPL/BSAC have stops at 5 m and 10 m.

Le Messurier and Hills studied hard hat divers in Torres Strait and found that they surfaced directly from 33 -44 ft (10-13 m) and decompressed in about 2/3 of the time required by a USN table.[37] The pearl divers from Broome also chose to decompress at a greater depth than the standard decompression tables, they staged at 7-8 fathoms (13-14 m or 42-48 ft) on air. Nowadays, they use 9 m on oxygen.

Kindwall reported that Behnke felt that the USN decompression stops were too shallow.[38] It has been demonstrated by Kindwall et al. that more gas can be eliminated at 50 fsw (15 m) than at 10 fsw (3 m) in a given amount of time.[39] Hills has also shown that goats can be decompressed in a shorter time period without DCI symptoms if the 20 fsw (6 m) and 30 fsw (9 m) stops were prolonged instead of coming to 10 fsw (3 m) for the final stop.[40] As stated above, Mano has demonstrated, with his gelatine model ,that the most effective first stop was at 9 msw.[26]

FIGURE 1

PILMANIS EXPERIMENTS ON ASCENT PROCEDURES



All dives were to 100 ft (30 m) for 15 minutes.
Bubble 1 had decompression for 1 minute at 20ft (6 m) and 4 minutes at 10 ft (3 m).
Bubble 2 had decompression for 2 minutes at 10 ft (3 m).
Bubble 3 was a direct ascent to the surface.

Trials in the UK indicated that when decompression stops were done at 6 msw rather than 3 msw, the incidence of DCI dropped by some 40%.[41] It appears that deeper in-water stops are beneficial for elimination of inert gas. Further, inert gas elimination is more effective without bubble formation, because the effective half time for elimination of gas in a bubble is greater than for the elimination of dissolved gas.[25] It is known that dissolved and free gases within tissues do not behave in the same manner.

From this evidence the slow rate of ascent and the 9 msw decompression stop chosen by the pearl divers might well be the optimal way for their mode of diving.

Oxygen decompression

Oxygen decompression was used as early as 1917 in the recovery of gold from the sunken "Laurentic" when oxygen was given immediately after surfacing from the sea.[42]

The investigations by the Admiralty Committee on Deep Diving in 1930 subjected divers to partial pressures of oxygen of 1.7 to 2.27 ATA, and it was noted that the divers showed confusion and amnesia as well as unreliable and unpredictable behaviour. They attributed these symptoms to raised tension of oxygen; psychological factors or indeed increased tension of nitrogen. The "Damant Tables" using oxygen for decompression from 60 fsw (18 m) upwards (in the dry) were adopted by the Royal Navy in 1932. Despite the experiment in 1933 in which 2 RN Officers (Damant and Phillips) breathed oxygen at 4 ATA in a RCC and convulsed in 18 and 13 minutes respectively, the lesson of oxygen toxicity did not register. The USN introduced in-water oxygen decompression from 60 fsw (9 m) in 1942 and the Royal Navy followed suit.[42]

It is well known that hyperbaric oxygen could give rise to CNS oxygen toxicity. The toxic effects of hyperbaric oxygenation had been amply demonstrated by Bert using dogs, rats and other animals.[14]

It was known also that breathing oxygen deeper than 33 fsw (10 m) underwater was dangerous and that any oxygen stops should be in a chamber and with an attendant. But Behnke in 1946 felt that it was safe to decompress on oxygen at 40-60 fsw (12-18 m) provided the divers were at *complete rest.* This practice finally ceased when there were a number of cases of acute oxygen poisoning at 60 fsw (18 m).[42]

In spite of the above, there are some well-known and respected decompression tables that make use of oxygen in decompression such as DCIEM, COMEX, French Navy, Duke University etc. In the UK sector of the North Sea, oxygen is not administered at depths greater than 40 fsw, and some Dutch companies limit oxygen breathing to 9 msw, in a wet bell.[42] Imbert indicated that COMEX has 2 types of oxygen decompression tables, one at 6 msw for a surface demand regulator, and a 12 msw table for use in a wet bell.[43] He indicated further that from the COMEX data bank, there were some 5,600 dives using 12 msw oxygen decompression with more than 30 minutes of oxygen breathing, suggesting that it is a "safe" procedure. However a few cases of toxicity were recorded, but these were found to be due to errors in procedure such as sending the wrong gas to the diver.

It must be remembered that the navies of the world use oxygen diving with rebreathing sets for clandestine operations to avoid the tell-tale bubbles. The Royal Navy employs a 8 m (26 ft) limit for **swimming** oxygen divers.[44] The USN allows oxygen dives to 30 ft (9 m) for up to 80 minutes.[45] The RAN allows a maximum depth of dive to 10 m (33 ft) and underwater swimming to a maximum depth of 8 m (26 ft).[46] Nonetheless, central nervous system (CNS) oxygen toxicity with convulsions have been reported at 25 fsw (7.5 msw) after 72 minutes.[47] These were "working dives". A second series[48] conducted by the same authors, with no convulsions at 25 ft (7.5 m), gave rise to the official USN depth time limits of oxygen diving of 4 hours maximum at 25 ft (7.5 m), 80 minutes at 30 ft (9 m), 25 minutes at 35 ft (10.5 m), 15 minutes at 40 ft (12 m) and 10 minutes at 50 ft (15 m).

It has been stated by Donald[42] that rest does not give the remarkable protection from oxygen poisoning underwater as has been claimed, but the comparative tolerance at rest and on exercise at 30-50 ft underwater has not been fully studied since the Royal Navy series in 1945.

The Draft Standard of AS2299-1992[49] specifically prohibits the breathing of oxygen under water on the basis of risks of "fatal underwater toxicity reaction". It did not specify the depth nor the duration of oxygen breathing.

Notwithstanding the above, there are obvious advantages in the use of oxygen. In the Haldanian model, it was assumed that inert gas was dissolved. It is known that on decompression, bubbles are formed and that the faster the rate of ascent, the more bubbles are formed. The elimination of dissolved gas and bubbles have totally different gas kinetics. Oxygen creates a large diffusion gradient for elimination of bubbles. Hence, one could hypothesise that the pearl divers "slow rate of ascent" would eliminate a large proportion of inert gas and the bubbles which are formed are either removed or reduce in size because of the large diffusion gradient generated by the breathing of oxygen.

It has been claimed that oxygen decreases decompression time by 30% to 50% depending on the depths of the dives.[50] The French Navy considers the use of oxygen reduces decompression time by 30% at all depth ranges.[51] Imbert and Bontoux,[50] using the French air decompression tables with in-water oxygen decompression, indicated that oxygen decompression not only saves decompression time but also has the effect of decreasing the incidence of DCI to 2-3 times lower than with air decompression for dives of the same depths and bottom times.

Fife et al.[52] reported the successful use of oxygen decompression in 7,500 dives, ranging in depths of 50-60 m (166-200 ft), in the excavation of a Bronze Age Shipwreck. There were 3 cases of DCI with no incidence of oxygen toxicity. The decompression tables used were modified USN tables as well as Duke University tables with oxygen introduced at 20 and 10 ft (6 and 3 m).

Furthermore, oxygen might confer other safety benefits. Dysbaric osteonecrosis (DON) is a well known occupational hazard for divers and caisson workers. Kindwall reported that ever since the Germans and the French introduced the use of oxygen in decompression for caisson workers, there have not been any cases of DON.[38] It is not known whether oxygen decompression confers the same degree of safety to the divers.

It has to be borne in mind however, that experimental data has demonstrated that animal fat cells enlarge when exposed to increased partial pressures of oxygen and this could play an important role in the cause of DON.[53] However, it has not been reported that the divers of the armed forces of the world who use oxygen rebreathing sets have a high incidence of DON.

Although CNS oxygen toxicity is a recognised hazard, since the introduction of oxygen in decompression in the pearling industry in 1981, there has not been a single incident of CNS oxygen toxicity.

Long term use of oxygen also raises doubt of pulmonary toxicity. Sterk and Schrier suggested that long term exposure in the order of 400-500 UPTD (Units of Pulmonary Toxic Dose) each day could be a risk.[54] Nonetheless, Donald, with his extensive experience with the RN divers using oxygen, considers that cumulative effects are most unlikely.[42] The experience with the pearl divers so far indicate that Donald was right.

Suitable interdive interval (surface interval)

It is assumed that on surfacing after compressed air diving inert gas is eliminated, it is also known that elimination of inert gas is not the mirror image of uptake, it takes longer. Based on this assumption, for repetitive diving, increasingly longer surface intervals are required after each dive. However, the exact time for elimination of inert gas is unknown. Various figures have been quoted,[13] Rogers (PADI Recreational Dive Planner) assumes 6 hours,[55] the French Navy requires 8 hours, the USN says 12 hours and the DCIEM tables need 18 hours.

When the various mathematical models are used to calculate the decompression requirements for various dives, the results are quite different for different tables. For instance the no-decompression limits for a dive to 18 m (60 ft) and to 40 m (120 ft) are shown in Table 1.

Similarly, different results are obtained for repetitive dives, for instance after a dive to 30 m for 10 mins and a surface interval of 2 hours 30 minutes, a repetitive dive to 15 msw will give widely differing results (Table 2).

The calculations for repetitive diving exposures, which rely on the concept of compartments and half times for elimination of inert gas, are based, at best, on a premise which needs proof. The Haldanian model employs a number of compartments in parallel, varying from 6 for the USN to 16 for the Bühlmann tables, the DCIEM model uses compartments in series and the diffusion model uses a slab concept. Furthermore, elimination of inert gas is not the mirror image of uptake, it is slower. It may not be exponential, it could be linear or could be a combination of the two.

TABLE 1

NO-DECOMPRESSION LIMITS FOR DIVES TO 18 AND 40 M

Table	18 m	40 m
RN	60 mins	9 mins
USN	60 mins	10 mins
RNPL	57 mins	11 mins
Bassett	50 mins	5 mins
DCIEM	50 mins	5 mins

TABLE 2

REPLETITIVE DIVE AVAILABLE AFTER A DIVE TO 30 M FOR 10 MINS AND A SURFACE INTERVAL OF 2 HOURS 30 MINUTES

Table	Dive
RN	10 min
RNPL	15 min
USN	79 min
Bassett	49 min
DCIEM	55 min

An optimum surface interval for repetitive diving?

Western Australian pearl divers of bygone days had their surface intervals dictated by the time needed for the lugger to turn around, sail up current and get into position for the next dive, this was 10 to 40 minutes and a natural occurrence of their daily work. Nevertheless, there are examples where surface intervals do play a part in the safety of the divers.

In the experiments with *Cragnon cragnon* ,[31] it was found that pressure pre-treatment can eliminate bubble formation after subatmospheric decompression. It was also found that regeneration of bubbles does occur after a half-time of 8-10 hours and the effect of pre-treatment was not evident after 24 hours. If dives were performed in rapid succession, then micronuclei could have been consumed and therefore not cause any problems.

In Taravana,[56] a condition akin to DCI, that affected breath-hold pearl divers of the Tuamoto Archipelago in the South Pacific, it was found that prolonging the surface interval from their usual 3-4 minutes to 10 minutes made the phenomenon of Taravana rare. These were not compressed air dives, so the inert gas load would be much lower, and 10 minutes might be all that was required to eliminate all the extra inert gas.

Yo-yo diving has long been considered a risk factor, however, a study of the Scottish fish farm divers by Shields et al.[57] has refuted this allegation, but the number of surface excursions was less than 10. Another study by Parker et al.[58] using the USN Probabilistic Decompression Model showed that the risk of DCI in yo-yo diving does increase especially if a large number of descents (more than 10) are made. A surface interval of approximately 5 minutes resulted in the highest estimated probability of DCS [P(DCS)] and longer surface intervals (10-120 min) provided intermediate estimates. A surface interval of 0 min (immediate return to depth) provides the lowest estimate of P(DCS).

For the technique of surface decompression, where the diver ascends rapidly to the surface, from either the bottom or a stop, and is then recompressed to 3 m deeper in the RCC, the DCIEM surface decompression tables allow a maximum time of 7 minutes to reach the required pressure. The pearl divers' technique could be viewed in a similar light in that they surface and are recompressed within 20 minutes to a depth of the previous dive. The difference is that they ascend slowly (producing fewer bubbles) to a 9 m stop using oxygen, so eliminating bubbles which are formed, and use a fixed surface interval of 20 minutes. This method does not explain the success of diving in deeper depths than 25 m where the schedules are more akin to the conventional profiles, with a longer surface interval after each dive.

The safe surface interval before flying after diving varies depending on the type of dive, which can range from no-decompression dives though decompression dives, repetitive and multi-day dives to saturation dives. Opinion also varies regarding flying after treatment of DCI. Currently, there is no consensus. Essentially, the relative safety of the surface interval depends very much on the adequacy of the decompression. If the decompression is inadequate, then theoretically, large number of asymptomatic bubbles could be generated which could lead to symptoms on altitude exposure.[59]

Reflecting on the old hard hat diving days, the pearl divers used to ignore surface intervals. The time spent between drift dives on deck was dependent on the time it took the old luggers to sail against the tide and to swing around to drift again. That short surface interval appeared to be adequate in shallower waters, however, when they dived in deep waters, the incidence of DCI rose.

With the current PPA Profiles, the Non-rotational profiles all have 20 minute (11 msw has only 15 minutes) surface intervals. This applies to depths from 13 m to 23 m. However it is not possible to dive the 23 msw profile to the number of dives allowed by the original Code of Practice of the PPA. The 19 msw and 21 msw profiles are also high risk.

When one views the hyperbaric stress of each dive expressed as PrT (P=absolute pressure, rT= square root of time in minutes of bottom time), it appears that the product PrT should not exceed the value of 17 for repetitive diving when the surface interval is limited to 20 minutes (Fig 2)

In simplistic terms, it seems as if the body can tolerate a certain amount of supersaturation after a dive (perhaps this is the limit of supersaturation of the fast compartments, but the slow compartments dictate how much surface interval is required) and provided that some elimination of inert gas is permitted between dives to buffer the additive effect of the next dive's increase in inert gas load, if this is not too high; the situation could be tolerated. However, once the limit is exceeded, such as when PrT is greater than 17, the short surface interval of 20 minutes becomes inadequate, the slow compartments are gradually being filled up with each repetitive dive and become super-saturated on surfacing which would lead to symptoms of DCI. This simplistic view has not taken into consideration that short surface intervals do limit the growth in size of bubbles. The risk of DCI could perhaps be avoided if the subsequent slow ascent rate is very, very slow and that the decompression stop is very, very long. It is interesting that the pearl divers have learned by trial and error that longer surface intervals were required when diving to depths of over 23 m. Preliminary testing of the high stress profiles appear to be promising when the PrT value is reduced. By reducing the bottom time of the 23 msw profile from 40 minutes to 25 minutes, the bubble grades are reduced to an acceptable level.

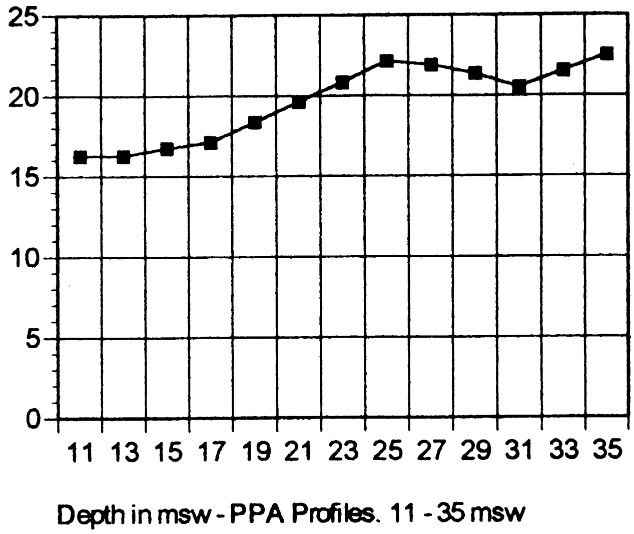
This phenomenon of high PrT with short surface interval is also observable in conventional diving. Among the DCI cases who presented to the RAN for treatment, there is a group who appeared to be refractory to treatment and had dive profiles with the repetitive group (RG) designated as E and F in the DCIEM Standard Air Tables (Loxton personal communication).

On examination of the repetitive factors/surface intervals table, table 4 of the DCIEM Standard Air Tables, it is allowable to do repetitive dives with short surface intervals. In RGs A to F, one could have short surface intervals of 15 to 30 minutes. From group G onwards, longer surface intervals are required, with a minimum of 30 minutes for group G and a minimum of 3 hours for group M. The bottom times required for dives to fall into the E and F groups need to be 50 minutes for 15 m, 40 minutes for 18 msw etc. These will give PrT values of 17 to 18.5 for the group E dives (from depths of 18 to 36 m). For dives that fall into repetitive dive group F, the PrT values range from 18.62 to 20.57 (Table 3). For a 21 msw dive, the PrT value ranges from 9.8 for Group A to 31 for Group N. Group E and F have values of 18.34 and 19.61 respectively, with permissible surface intervals of 15 to 30 minutes (Table 4).

From the foregoing, it appears that there is a minimum tolerable surface interval for different modes of

FIGURE 2

PrT OF PPA PROFILES DIVED AS WRITTEN



Bottom times of PPA Profiles

Depth in m	Bottom time of each dive	Number of dives
11	60	10
13	50	10
15	45	10
17	40	10
19	40	10
21	40	9
23	40	8
25	40	5
27	35	5
29	30	5
31	25	5
33	25	5
35	25	4

TABLE 3

REPETITIVE DIVE GROUPS E AND F WITH PrT VALUES

Depth	Bottom Time		PrT value	
in msw	Group E	Group F	Group E	Group F
15	50	60	17. 68	19.34
18	40	50	17. 7	19.8
21	35	40	18.34	19.61
24	25	30	17	18.62
27	25	30	18. 5	20.27
33	0	20	0	19.23
36	15	20	17.82	20.57

TABLE 4

REPETITIVE DIVE GROUPS FOR 21 msw DIVES AND PrT VALUES

Repetitive Group	Bottom Time	PrT value
A	10	9.8
B	20	13.86
C	25	15.5
D	30	16.98
E	35	18.34
F	40	19.61
G	50	21.92
H	60	24.01
J	70	25.94
K	80	27.72
M	90	29.41
N	100	31.0

diving, the period depends on the hyperbaric stress of the dive(s) and the subsequent adequacy of decompression. Nevertheless, there appears to be a "safe period of grace" after surfacing before sufficient number of bubbles are formed and grow in size to cause symptoms.

If the recompression is rapid enough, little harm would befall the diver provided that the subsequent decompression is adequate, as illustrated by the practice of surface decompression.

The effects of surface interval on the pearl divers profiles are under investigation. Preliminary testing shows that when a stressful profile is modified by reducing the PrT, the short 20 minute surface interval is feasible. Unfortunately, the PrT values are not additive, and no prediction could be made.

From the RCC trials of the Pearl Diving Profiles, the pre-dive bubble grades were invariably Grade I- to Grade I+ after a 12 hour break),[60] indicating the presence of moving bubbles, suggesting that inert gas elimination takes longer than 12 hours with their mode of diving. After about 17 to 19 hours, the Doppler score was generally 0. The testing is continuing.

Acclimatisation

It has been suggested that acclimatisation is a factor in preventing DCI. This is highly unlikely because the divers dive daily for the duration of the neap tide then return to shore for a week. When they dive again, the depth could be deeper. Also it is known that acclimatisation is depth specific and that caisson workers lose this advantage after even a week-end off.[61] The pearl divers do not dive during the spring tides.

If acclimatisation is a factor, then one would expect the bubble grades to decrease at the end of the diving trip. If however, multi-day diving is a high risk factor, then one would expect to see rising bubble grades towards the end of the trip. In reality, bubble grades stay reasonably constant.

Long term health

The long term health effects of this mode of diving are not known. The divers have an annual medical examination, in accordance with AS2299. So far these have not demonstrated any overt impairment. No formal psychological assessment has yet been instituted. The common medical problems such as salt water aspiration, marine animal stings and hearing problems will be the subject of another report.

From the diving records, 43% of the divers commenced diving before 1990, 33% between 1990 and 1993 and 24% started diving in 1994.

Dysbaric osteonecrosis

Dysbaric osteonecrosis was recognised in tunnel workers in 1912, but only in 1942 was it accepted as a condition that affected divers.[62]

Studies on naval divers and commercial divers have shown a lesion in 5 to 7% in Navy divers and 4.8% (in 1979) in commercial divers.[63-65] These divers dived to conventional and experimental profiles.

Ohta and Matsunaga reported that 50.5% of Japanese diving fishermen had radiological lesions and juxta-articular lesions were seen only in those who had dived deeper than 20 m and had over 5 years of experience.[66] The age range was from 16 to over 50. The incidence increased with age, particularly over the age of 30 and in those with over 10 years of diving experience.

Kawashima also demonstrated a high incidence of DON in Japanese divers who dived to unconventional profiles, and particularly to depths in excess of 30 m.[67] 54.4% of divers with more than 5 years of experience were affected. The divers were aged between 16 and 64.

It is known in the past that there are a number of pearl divers who have DON. However, since the introduction of AS2299 diving medical in 1990, no new cases have been detected in divers with less than 5 years' experience in the industry. This covers the period since the adoption of uniform diving profiles by the PPA and the four years of diving the modified profiles. Modification of profiles is on going. All radiographs are performed at Royal Perth Hospital or the Broome District Hospital. Any suspicious lesions are investigated and followed up. A medical registry was started in 1990 which includes a survey of all long bone X-rays. It is interesting that despite the unconventional profiles of the pearl divers, there has not been an overwhelming incidence of DON seen in the Japanese divers. Perhaps, oxygen breathing decompression provides a protective effect or perhaps the onset of DON takes much longer.

At the end of 1995, there have been 2 cases of dysbaric osteonecrosis reported. These 2 divers had started diving in the pearling industry in the 1980s when the use of profiles were not uniform and the usage of oxygen for decompression was haphazard.

The pearl divers dive profiles are being tested continuously and their mode of diving is being documented for further study.

Summary

The dive schedules of the Western Australian pearl divers are based on years of experience and are all "dived" profiles. Despite the fact that their mode of diving does not conform to the current decompression models and mathematical calculations, they nevertheless "invented" a mode of diving which is "safe" or at least with an acceptable DCI rate. They have manipulated all the diving variables, bottom time, surface interval, ascent rate, depth of decompression, to their advantage and to the limit. It is however, not recommended that non-pearl divers adopt such mode of diving.

In common with previous investigation, the profiles share the slow ascent rate and the deep decompression stop of other pearl divers.

One can hypothesise that the mode of diving which afforded relatively safe diving for the pearl divers appears to be due to a combination of the factors discussed. The slow ascent rate might assist in minimising bubble formation; the depth of decompression in combination with oxygen breathing assist in off-gassing and the elimination of bubbles that are formed.

The surface interval which seems inadequate for repetitive diving, appears to have a depth limit in usage and the pearl divers appeared to have explored that use to the limit.

"It is not what we don't know that delays progress, but what we think we know that is not actually so!"

It has to be stressed that this report is confined to the mode of diving in Western Australia in the 1990s. Not all pearl diving in Australia is done in the manner described.

There is diving in the Northern Territory and in Queensland, but the mode of diving is not the same as described here, which is peculiar to Western Australia.

It is also known that prior to the 1990s, there were a number of cases of DCI with neurological symptoms. However, most of these were from pearl farm diving and not from drift diving. A lot of the minor cases, the niggles, were treated with in-water recompression, on air or oxygen or both, and only those cases which required recompression, as judged by the Head Divers, were transferred to either to the Royal Darwin Hospital or to Perth, to HMAS LEEUWIN until 1984 and then to HMAS STIRLING. The RAN treated all diving accidents in Western Australia until late 1989 when Fremantle Hospital opened its Hyperbaric Medicine Unit. The recompression chamber in Broome District Hospital became operational in 1991. It is worth noting that prior to 1987 there was no medical practitioner in Broome with any knowledge of Underwater Medicine. Since 1989 it is one of the pre-requisites for appointment to the Broome District Hospital. Currently, there are 3 Medical Practitioners with Underwater Medicine training in Broome District Hospital, one in private practice and one with the Broome Aboriginal Medical Services.

Acknowledgments

I would like to thank all those who have provided information used in this paper, especially members of the pearling industry, the Pearl Producers Association Inc. WA, pearl divers past and present and the R&D Corporation, Fisheries Department, Western Australia.

Key Words

Occuptional diving, osteonecrosis, oxygen, safety, tables.

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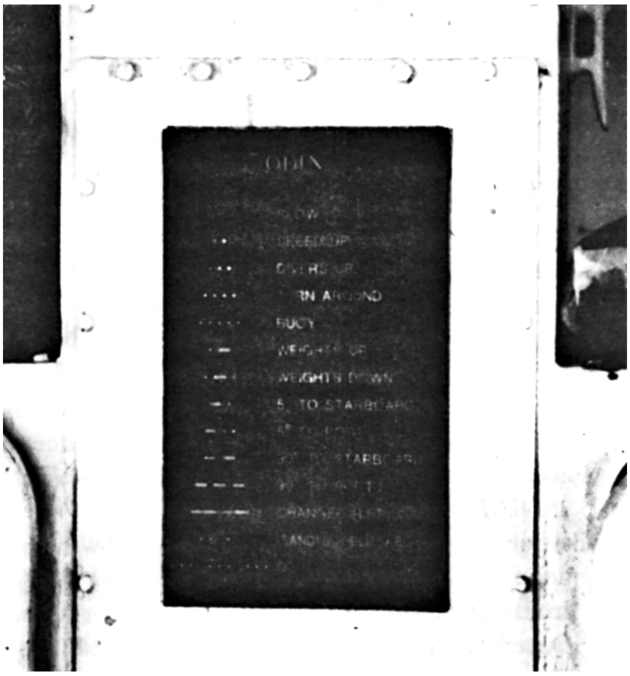
DIVER COMMUNICATION SYSTEM

Robert M Wong

The Head Diver can signal to the skipper to tell him to change speed of the vessel, change course etc. by the number of beeps he sends. "Buoy means that there a lot of oysters around and is a request to mark the spot with a buoy, but nowadays withe accuracy of GPS, it is just marked on the chart. To increase speed generally means that the divers are going over a pretty bare patch; whereas, to slow means either the vessel is going too fast or that they are onto good grounds as well. The speed is adjusted by pulling in or letting out the drogue. Adjust weights means that the weights have to be lifted off the sea bed. The divers like to have the weights about a metre off the ground. Each lead weight is 50 kg. Diver up means it is the end of the drift. The bottom time is kept by the Head Diver, when he sends the signal those on board usually just bang on the side of the vessel three times on each side, the sound can be heard by all the divers. The head diver is usually on the inside of the starboard side of the drift line.

The illustration shows the signals used on board the ODIN II.



Key Words

Communication, occupational diving.