DIVING AND DECO HISTORY

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Early Diving

Man has probably practised breathold diving in some form across all stages of development, first becoming adept at swimming and then recovering food from lakes and oceans. Now, breathold diving and snorkeling are popular sports. Breathold and inverted bell diving reach back over many centuries, like fifty or so. Written records of Cretan sponge divers (3000 BC) and Chinese pearl divers (2000 BC) exist today. Detailed military accounts link to Xerxes who employed combat divers to recover treasure from sunken ships (519 BC), as chronicled by the Greek historian, Herodotus. Alexander the Great (356 BC) also deployed breathold divers in the siege for Tyre. Depths rarely exceeded 60 fsw in these exploits. According to Pliny (77 AD), reed breathing tubes were employed by Roman Legions, hiding or waiting in ambush. Aristotle (384 BC), pupil of Plato, and tutor of Alexander, writes of diving bells used to recover treasure. These inverted receptacles, utilizing trapped compressed air as breathing mixture, gained renown in Europe in the 1600s. Ancient Assyrians and Persians also carried air in goatskins underwater. Some Korean and Japanese breathold divers (armaghs) still gather pearls and sponges with lung power, but most of the fishing, pearling, and sponging divers of the world today have gone over to SCUBA. Terroists in Southeast Asia avoided capture by lying beneath swamp surfaces and breathing through hollow reeds. SEALs adopted similar assault tactics in the Mekong Delta in Vietnam.

Halley patented a large diving bell in 1690, refurbished with surface air for periods beyond an hour. In 1770, Le Havre developed a manual air compressor. Surface supplied air and demand regulators were employed in hard hat diving by the 1800s, with the first demand regulator, patented by Rouquayrol in 1866, supplied by hand bellows. The first case of nitrogen narcosis was reported by Junod in 1835. Full diving suits, in which air escapes through a one way exhaust valve, were invented by Siebe in 1840, and a few are still around. Quietly, the revolutionary *aqua lung* of Cousteau, a refinement of the Rouquayrol surface supplied demand regulator, ushered the modern era of SCUBA in wartime Europe in 1943. Diving would never be the same afterward. In the US Navy, elite SRs, NCDUs, and UDTs (SEALs now) honed their skills above and below the surface, extending the meaning of combat utility. Freed from surface umbilical, open and closed circuit units enhanced the mobility and range of tactical operations for sure, but the impact on nonmilitary diving was orders of magnitude greater. Coupled to high pressure compressed air in tanks, SCUBA offered the means to explore the underwater world for fun and profit.

Commercial availability of the demand regulator in 1947 initiated sport diving and a fledgling equipment industry. Serious diver training and certifying agencies, such as the National Association of Underwater Instructors, YMCA, and Professional Association of Diving Instructors, strong and vital today, organized in the late 1950s and 1960s. In the mid 1950s, the Royal Navy released their bulk diffusion decompression tables, while a little later, in 1958, the US Navy compiled their modified Haldane tables with six perfusion limited compartments. Both would acquire biblical status over the next 25 years, or so. In the mid to late 1950s, Fredrickson in the USA and Alinari in Italy designed and released the first analog decompression meters, or decometers, emulating tissue gas uptake and elimination with pressure gauges, porous plugs, and distensible gas bags. The first digital computers, designed by DCIEM in Canada, appeared in the mid 1950s. Employed by the Canadian Navy, they were based on a four compartment analog model of Kidd and Stubbs. Following introduction of a twelve compartment Haldanian device, linked to Doppler technolgy, by Barshinger and Huggins in 1983, decompression computers reached a point in addressing repetitive exposures and staging regimens for the first of maturation and acceptance. Flexible, more reliable to use, and able to emulate almost any mathematical model, digital computers rapidly replaced pneumatic devices in the 1980s. Their timely functionality and widespread use heralded the present era of high tech diving, with requirments for comprehensive decompression models across a full spectrum of activity. Computer usage statistics, gathered in the 1990s, suggest an enviable track record of diver safety, with an underlying decompression sickness (DCS) incidence below 0.05% roughly.

Diver mobility concerns ultimately fostered development of the modern SCUBA unit, and the quest to go deeper led to exotic gas breathing mixtures. High pressure cylinders and compressors similarly expedited deeper diving and prolonged exposure time. The world record dives of Keller to 1,000 fsw in 1960 not only popularized multiple gas mixtures, but also witnessed the first real use of computers to generate decompression schedules. Saturation diving and underwater habitats followed soon after, spurred by a world thirst for oil. Both multiple gas mixtures and saturation diving became a way of life for some commercial divers by the 1970s, particularly after the oil embargo. Oil concerns still drive the commercial diving industry today.

Cochrane in England invented the high pressure caisson in 1830. Shortly afterward, the first use of a caisson in 1841 in France by Triger also precipitated the first case of decompression sickness, aptly termed the bends because of the position assumed by victims to alleviate the pain. Some fifty years later, in 1889, the first medical lock was employed by Moir to treat bends during construction of the Hudson River Tunnel. Since that time many divers and caisson workers have been treated in hyperbaric chambers. Indeed, the operational requirements of diving over the years have provided the incentives to study hyperbaric physiology and its relationship to decompression sickness, and impetus for describing fundamental biophysics. Similarly, limitations of nitrogen mixtures at depth, because of narcotic reactivity, prompted recent study and application of helium, nitrogen, hydrogen, and oxygen breathing mixtures at depth, especially in the commercial sector.

Increases in pressure with increasing depth underwater impose many of the limitations in diving, applying equally well to the design of equipment used in this environment. Early divers relied on their breathholding ability, while later divers used diving bells. Surface supplied air and SCUBA are rather recent innovations. With increasing depth and exposure time, divers encountered a number of physiological and medical problems constraining activity, with decompression sickness perhaps the most restrictive. By the 1800s, bubbles were noted in animals subject to pressure reduction. In the 1900s, they were postulated as the cause of decompression sickness in caisson workers and divers. Within that postulate, and driven by a need to both optimize diver safety and time underwater, decompression modeling has consolidated early rudimentary schedules into present more sophisticated tables and meters. As knowledge and understanding of decompression sickness increase, so should the validity, reliability, and range of applicability of models.

Modern Diving

A concensus of opinions, and for a variety of reasons, suggests that modern diving began in the early 1960s. Technological achievements, laboratory programs, military priorities, safety concerns, commercial diving requirements, and international business spurred diving activity and scope of operation. Diving bells, hot water heating, mixed gases, saturation, deep diving, expanded wet testing, computers, and efficient decompression algorithms signaled the modern diving era. Equipment advances in open and closed circuit breathing devices, wet and dry suits, gear weight, mask and fin design, high pressure compressors, flotation and buoyancy control vests, communications links, gauges and meters, lights, underwater tools (cutting, welding, drilling, explosives), surface supplied air, and photographic systems paced technological advances. Training and certification requirements for divers, in military, commercial, sport, and scientific sectors, took definition with growing concern for underwater safety and well being.

In the conquest and exploration of the oceans, saturation diving gained prominence in the 1960s, thereby permitting exploitation of the continental shelf impossible within exposure times permitted by conventional regimens. Spurred by both industrial and military interests in the ability of men to work underwater for long periods of time, notable *habitat* experiments, such as Sealab, Conshelf, Man In Sea, Gulf Task, and Tektite established the feasibility of living and working underwater for extended periods. These efforts followed proof of principle validation, by Bond and coworkers (USN) in 1958, of saturation diving. Saturation exposure programs and tests have been conducted from 35 fsw down to 2,000 fsw.

The development and use of underwater support platforms, such as habitats, bell diving systems, lockout and free flooded submersibles, and diver propulsion units also accelerated in the 1960s and 1970s, for reasons of science and economics. Support platforms extended both diver usefulness and bottom time, by permitting him to live underwater, reducing descent and ascent time, expanding mobility, and lessing physical activity. Today, operating from underwater platforms themselves, remotely operated vehicles (ROVs) scan the ocean depths at 6,000 fsw for minerals and oil.

Around 1972, strategies for diving in excess of 1,000 fsw received serious scrutiny, driven by a commercial quest for oil and petroleum products, and the needs of the commercial diving industry to service that quest. Questions concerning pharmacological additives, absolute pressure limits, thermal exchange, therapy, compression-decompression procedures, effective combinations of mixed breathing gases, and equipment functionality addressed many fundamental issues, unknown or only partially understood. By the early 1980s, it became clear that open sea water work in the 1,000 to 2,000 fsw range was entirely practical, and many of the problems, at least from an operational point of view, could be solved. Today, the need for continued deep diving remains, with demands that cannot be answered with remote, or 1 atm, diver systems. Heliox and trimix have become standards for deep excursion breathing gases, with heliox the choice for shallower exposures, and trimix a choice for deeper exposures in the field.

Yet, despite tremendous advances in deep diving technology, most of the ocean floor is outside human reach. Breathing mixtures that are compressible are limiting. Breathing mixtures that are not compressible offer interesting alternatives. In the 1960s, serious attention was given to liquid breathing mixtures, physiological saline solutions. Acting as inert respiratory gas diluents, oxygenated fluids have been used as breathing mixtures, thereby eliminating decompression requirements. Some synthetic fluids, such as fluorocarbon (FX_{80}), exhibit enormous oxygen dissolution properties.

Decompression Theory

Pearling fleets, operating in the deep tidal waters off northern Australia, employed Okinawan divers who regularly journeyed to depths of 300 fsw for as long as one hour, two times a day, six days per week, and ten months out of the year. Driven by economics, and not science, these divers developed optimized decompression schedules empirically. As reported by Le Messurier and Hills, deeper decompression stops, but shorter decompression times than required by Haldane theory, were characteristics of their profiles. Such protocols are entirely consistent with minimizing bubble growth and the excitation of nuclei through the application of increased pressure, as are safety stops and slow ascent rates. With higher incidence of surface decompression sickness, as might be expected, the Australians devised a simple, but very effective, in-water recompression procedure. The stricken diver is taken back down to 30 fsw on oxygen for roughly 30 minutes in mild cases, or 60 minutes in severe cases. Increased pressures help to constrict bubbles, while breathing pure oxygen maximizes inert gas washout (elimination). Recompression time scales are consistent with bubble dissolution experiments.

Similar schedules and procedures have evolved in Hawaii, among diving fishermen, according to Farm and Hayashi. Harvesting the oceans for food and profit, Hawaiian divers make beween 8 and 12 dives a day to depths beyond 350 fsw. Profit incentives induce divers to take risks relative to bottom time in conventional tables. Three repetitive dives are usually necessary to net a school of fish. Consistent with bubble and nucleation theory, these divers make their deep dive first, followed by shallower excursions. A typical series might start with a dive to 220 fsw, followed by 2 dives to 120 fsw, and culminate in 3 or 4 more excursions to less than 60 fsw. Often, little or no surface intervals are clocked between dives. Such types of profiles literally clobber conventional tables, but, with proper reckoning of bubble and phase mechanics, acquire some credibility. With ascending profiles and suitable application of pressure, gas seed excitation and any bubble growth are constrained within the body's capacity to eliminate free and dissolved gas phases. In a broad sense, the final shallow dives have been tagged as prolonged safety stops, and the effectiveness of these procedures has been substantiated *in vivo* (dogs) by Kunkle and Beckman. In-water recompression procedures, similar to the Australian regimens, complement Hawaiian diving practices for all the same reasons.

The past ten years, or so, have witnessed a number of changes and additions to diving protocols and table procedures, such as shorter nonstop time limits, slower ascent rates, discretionary safety stops, ascending repetitive profiles, deep decompression stops, helium based breathing mixtures, permissible, reverse profiles, multilevel techniques, both faster and slower controlling repetitive tissue halftimes, lower critical tensions (M-values), longer flying-after-diving surface intervals, and others. Stimulated by Doppler technology, decompression meter development, theory, statistics, or safer diving concensus, these modifications affect a gamut of activity, spanning bounce to decompression, single to multiday, and air to mixed gas diving. As it turns out, there is good support for these protocols on operational, experimental, and theoretical grounds, and bubble models addressing these concerns on firmer basis than earlier models exist now, having been proposed and tested by numbers of investigators.

Spencer pioneered the use of Doppler bubble counting to suggest reductions in the nonstop time limits of the standard US Navy Tables, on the order of a repetitive group or two at each depth in the Tables (1-4 fsw in critical tensions), basing recommendations on lowering bubble counts at shorter nonstop time limits. Others have also made similar recommendations over the past 15 years.

Neuman, Hall, and Linaweaver found that slower ascent rates with nominal shallow stops reduced Doppler scores by an order of magnitude on air dives.

Smith and Stayton noted marked reductions in precordial bubbles when ascent rates were cut from 60 fsw/min to 30 fsw/min. In similar studies, Pilmanis witnessed an order of magnitude drop in venous gas emboli (VGE) counts in divers making short, shallow, safety stops following nominal bounce exposures at the 100 fsw level, while Neumann, Hall, and Linaweaver recorded comparable reductions in divers making short, but deeper, stops after excursions to 200 fsw for longer periods of time.

An American Academy Of Underwater Sciences (AAUS) workshop on repetitive diving, recorded by Lang and Vann, and Divers Alert Network (DAN) statistics suggest that present diving practices appear riskier under increasing exposure time and pressure loading, spawning development of ancillary safety measures for multidiving. Dunford, Wachholz, and Bennett noted persistent Doppler scores in divers performing repetitive, multiday diving, suggesting the presence of VGE in divers, all the time, under such loadings.

Ascent rates, safety stops, decompression computers, altitude diving reverse profiles, nitrox, deep, mixed gas, and technical diving have been the subject of extensive discussion at workshops and technical forums sponsored by the American Academy of Underwater Sciences, Smithsonian Institute, and the Undersea And Hyperbaric Medical Society (UHMS), as summarized by Lang and Hamilton, Lang and Egstrom, Lang and Vann, Sheffield, Wienke and O'Leary, Schreiner and Hamilton, and Smith. Some results of discussions culminated in sets of recommendations, folded within standard Haldane table and meter procedures, even for exposures exceeding neither time limits nor critical tissue tensions. Other sets, framed against modern decompression theory, underscored the significance of deep decompression stops, the coupled use of helium rich breathing mixtures, decompression software, technical diving training, and modern dive testing and validation.

In the past 5 years or so, the introduction of deep stops into diving and decompression regimens has also gained prominence and widespread acceptance, particularly in the mixed gas and technical sectors.

Neuman, Hall, and Linaweaver also found that Doppler scores of divers making deep stops on air dives to 230 fsw for 50 minutes, and 170 fsw for 30 minutes, were significantly lower (and statistically significant) than those of divers making conventional shallow stops for longer times than nominally required by convnetional schedules.

Bennett suggested that decompression injuries are likely due to ascending too quickly. He found that the introduction of deep stops, without changing the ascent rate, reduced bubble grades to near zero, from 30.5% without deep stops.

Marroni suggested the same, but found ascent speed itself did not reduce bubble formation. He suggested that a slowing down in the deeper phases of the dive (deep stops) should reduce bubble formation.

Brubakk and Wienke saw more bubbling in chamber tests when pigs were exposed to longer but shallower decompression profiles, where staged shallow decompression stops produced more bubbles than slower (deeper) linear ascents.

The upshot of these studies, workshops, discussions, and tests are a set of discretionary protocols, not necessarily endorsed in all diving sectors, but which might be summarized as follows:

- reduce nonstop time limits a repetitive group, or two, below the standard US Navy limits;
- maintain ascent rates below 33 fsw/min, preferably slower, and requisitely slower at altitude;
- limit repetitive dives to a maximum of three per day, not exceeding the 100 fsw level;
- avoid multiday, multilevel, or repetitive dives to increasing depths;
- wait 12 hr before flying after nominal diving, 18 hr after heavy diving (taxing, decompression, or prolonged repetitive) activity, and 24 hr after repetitive decompression diving;
- avoid multiple surface ascents and short repetitive dives (spikes) within surface intervals of 1 hr;
- surface intervals of more than an hour are recommended for repetitive diving;
- a deep stop for a minute or two in the range of 1/2 the bottom depth is a prudent exercise for recreational divers, while systematic deep stops at 1/2 the distance to the first required stops (ala Haldane staging) are similarly expedient for decompression and mixed gas divers;
- safety stops for 2-4 min in the 10-20 fsw zone are advisable for all diving, but particularly for deep (near 100 fsw), repetitive, and multiday exposures;
- do not dive at altitudes above 10,000 ft using modified conventional tables, or linear extrapolations of sea level critical tensions;
- ride helium rich diving mixtures as close to the surface as possible (decompression diving) before switching to oxygen rich nitrox, and switch to pure oxygen in the shallow zone (20 fsw);
- dual phase staging algorithms for mixed gas, decompression, extended range, and deep diving have been largely validated by the worldwide technical diving community (especially the dual phase RGBM protocols);
- use dual phase diving tables, software, and decompression meters on the market today;
- in short, dive conservatively, remembering that tables and meters are not bends proof, and also remembering that Haldane protocols (if they must be used) are only half correct (address dissolved gas only).

Procedures such as those above are prudent, theoretically sound, and safe diving protocols. Ultimately, they link to free phase and bubble mechanisms.