IMPROVING DECOMPRESSION WITH CUSTOM TABLE DESIGN

R.W. Bill Hamilton
Hamilton Research, Ltd.
Tarrytown, NY 10591

Introduction

This paper attempts to show how a diversity of decompression tables, including some that are not "in the book," can lead to improved decompression capability. Such tables are often available from diving training organizations, they can be obtained from decompression specialists, and in some cases can be developed by the using organization. Many innovative table collections are available from specific sources.

DCAP Methods of Decompression

To introduce the concept of custom decompression tables it is pertinent to review one of the computational programs used for producing such tables. ***DCAP, Decompression Computation and Analysis Program***, has been under development and in use for well over a quarter of a century. My colleague Dave Kenyon and I worked in a laboratory dedicated to commercial diving, a company known as Ocean Systems, Inc., which was an affiliate of a major chemical company, Union Carbide Corporation. Dave as an engineer and programmer and I as a physiologist had the job of developing procedures in the lab and helping to implement them in the sea.

DCAP history

Decompression was a major concern in Ocean System's early days, the late 1960s. Commercial diving companies were beginning to learn to use heliox diving mixtures, and they quickly found that the available military decompression tables were not adequate for their operations. Our laboratory was charged with the task of developing tables for diving to the continental shelf, defined as the coastal plain extending to 200 metres depth, or msw. The decompression expert was the late Dr. Heinz Schreiner, known to a number of people at this conference. Working with programmer Pat Kelley, Heinz built on the experience of the British and U.S. navies, and collaborated with Profs. Hempleman, Bühlmann, Cabarrou, Workman, and others, especially Dr. Lambertsen (Schreiner, 1967; Schreiner and Kelley, 1971). Heinz made many trips to La Spezia during those years.

Ocean Systems' efforts were successful, and they were among a very few companies who could do short-duration or "bounce" diving in the 200 msw range (Hamilton, 1976). This exclusive capability was self defeating, however; because so few companies could do this kind of diving the customers — the oil companies — soon agreed to pay for the more expensive saturation diving.

Most of the work in the development of North Sea petroleum was done using saturation techniques.

Schreiner moved on to a management position, and Dave Kenyon and I continued with decompression development, eventually as independent consultants. Dave began to refine Heinz Schreiner's concepts into a unique computational program. We furnished tables to companies and navies, but in the days before e-mail and even faxes, we had trouble providing timely support to overseas clients.

We got the idea (from a client, by the way, Dr. Anders Muren of the Swedish Navy), to install our program in the Navy's computer to make it possible for them to generate and make changes in decompression tables.

The guiding principle behind DCAP was that it should reduce or eliminate the need for a programmer, which at the time was a unique approach. We were able to do that fairly well, such that the DCAP program has a few default values and limits built in to the FORTRAN program, but everything needed to generate a table is contained in standard ASCII text files that can be created and changed by the User (Hamilton and Kenyon, 1990).

DCAP users

To continue with this history, DCAP has been acquired by several navies. During development an interim version was used by the Canadian Forces laboratory, DCIEM, and as mentioned the Swedish Navy was the

first to acquire the full version. DCAP was later acquired by the German laboratory GKSS, and by the Finnish, Japanese, Israeli, and British Navies, plus some commercial ventures and JAMSTEC.
We are extremely pleased and indeed humbled that the Italian Navy is in the process of joining this group.
During this process we had to put DCAP on several different computers. It started on a Honeywell 316, then was migrated to several DEC PDP-11s, a Data General, and eventually to DOS and Windows.
A Macintosh version was prepared, but we found it better to use a PC emulator running on a Mac than the Mac version itself.
Although programming is not necessary, to run DCAP comfortably requires a good understanding of both computer operations and decompression physiology and operations. We do not encourage small diving contractors to acquire and operate DCAP because of its cost and the training and experience necessary, and also because of the matter of establishing confidence in new, "internally generated" or "do-it-yourself" tables. A far more practical method is to form a team that includes key people involved in the diving operation and one or more person experienced in DCAP. There is now a DCAP presence in Italy, with the operator Roberto Molteni, who lives in La Spezia and who will be working with the Italian Navy.

Custom Tables and the Italian Diving Contractor
One might wonder what this promotion of the DCAP program might mean to the Italian contractor, who might not be able to afford either the program cost or be able to divert the necessary skills of employees from other jobs to the one of producing decompression tables. Several points might be relevant. First, it is important to understand that a contractor need not be limited to the tables in the standard "book," whether that be the U.S. Navy Diving Manual or one of the others, but that there are ways around some of the traditional limitations.The popular phrase for this is to "think outside the box." Be aware of what is possible.
Many standard tables are not ideal. There may be time and depth limitations, or for any number of reasons more conservatism may be needed. In special diving situations it can be a real advantage to design the tables to fit the job rather than to have to make the job fit the available tables. Or one might want to take more advantage of the use of oxygen. Here there are a variety of opportunities, the most familiar being diving with oxygen enriched air and the use of oxygen breathing during decompression.

Optimal use of Oxygen to Improve Decompression
The optimization of oxygen is a complex thing, something that some people have dedicated almost their entire career to investigating (e.g., Donald, 1992; Lambertsen et al, 1987). This not only involves the use of oxygen in decompression, but of knowing how best to tolerate exposure to its toxicity. Many modern or custom "out of the box" tables take this into account. An optimal table should offer means of monitoring the divers' exposure to oxygen and setting adjustable limits on it. This should of course consider both of the main manifestations of toxicity, the effects on the central nervous system and the less specific effects on much of the rest of the body, the "whole body" or lung toxicity (Hamilton, 1989).

Oxygen enriched air: "Nitrox"
Although it was used as early as the 1950s, open-circuit oxygen enriched air began to catch on in the mid 1980s. Earlier uses of oxygen-rich mixtures of oxygen and nitrogen, by navies, for instance, were usually done with rebreathers. Enriched air was first introduced into NOAA by Dr. Morgan Wells, and from there became popular in recreational diving (Hamilton et al, 1989; Hamilton, 1992). Enriched air, also called OEA, enriched air nitrox (EANx) or just "nitrox," was controversial at first, due in part to misunderstanding, over-promotion, and a certain amount of risk. Mixing often involved high pressure oxygen which certainly has to be handled with care, and divers not accustomed to using non-air breathing mixtures occasionally caused mishaps by breathing the wrong mix at the wrong time. One problem with OEA mixtures is that they fall in a range between "air" and "oxygen" in occupational safety rules, and there have been no appropriate standards telling how to deal with such mixes. Requirements for oxygen cleaning vary with different organizations. Common practice in the USA dictates that mixtures with up to 40% oxygen can be used with ordinary gear appropriate for air, but I recommend that such apparatus be "informally" oxygen cleaned and that only oxygen-compatible lubricants be used.
The need for high pressure oxygen can be avoided by using a gas separation system. Two methods are in current use. One separates oxygen and nitrogen using a selectively permeable membrane (in the form of

microscopic tubes); these can generate up to 40% oxygen. Another method, pressure swing absorption, is more complex but can separate up to 95% oxygen. This method uses selective adsorption of the gases on “molecular sieve,” a synthetic zeolite with high surface area.
With regard to decompression, it is now generally accepted that the oxygen can be “ignored” in making computations, and that only the inert gas need be considered (Weathersby et al, 1987; Hamilton and Thalmann, in press 2003). This is exploited by calculating decompression on the basis of the nitrogen partial pressure, such that an oxygen-rich mixture which of course has less nitrogen, can be used with a table for a shallower depth having the same nitrogen partial pressure. This is called “equivalent air depth.” Air tables can be converted using these techniques, but they are more straightforward and more efficient if calculated explicitly for the mixture to be used.
Another factor to be considered is the toxicity of the oxygen in the breathing mix, which is a function of both the mixture and the depth. Several organizations allow oxygen to be breathed at a partial pressure up to 1.6 atm (about 162 kPa, absolute); for divers on scuba I recommend setting a limit at 1.5 atm (NOAA Diving Manual, 2001; Lang, 2001). This fixes a maximum depth for a given mixture. Common mixes range from 32% to as high as 50% oxygen, so they are effective only to depths approaching 40 msw.

Decompression with oxygen in the water
Diving with OEA is relatively simple once the mixtures are on hand, with procedures like those for air but taking oxygen toxicity into account. However, for remote operations (and for other reasons) it may be difficult to get mixes, so an effective way of using oxygen is to use oxygen decompression, since it may be easier to get oxygen to the dive site than a big supply of mixes. Surface decompression with oxygen breathed in a chamber is familiar to most commercial divers. Tables for inwater oxygen decompression are available, for example the DCIEM tables, the Dutch tables, and the French rules for work at increased pressure (see below).

Concept of Technical Trimix Diving
While considering innovative diving methods, it is pertinent to mention the relatively new concept of “technical diving.” This term had been used a half century ago to define diving with a rebreather in the British military, but recently it has been used to define untethered (i.e., no umbilical) diving with open circuit apparatus and using more than one breathing mixture. This is extended range diving, often to well beyond the air diving range (say beyond 50 msw, with the most important limiting factor being narcosis) so mixtures containing helium are routinely used. For dives in the 75 msw range these are usually trimixes of oxygen, helium, and nitrogen with the components selected to be near to optimal. Oxygen should be as high as it can conveniently be without exceeding toxicity limits in the range to be dived. The helium content is selected so as to limit the nitrogen level to a tolerable degree of narcosis. A “travel” mix for descent may be used, and an intermediate “deco” mix after leaving bottom. These are followed by a switch to air or an enriched air mix somewhere in the 30 msw range, or maybe both mixes are used. Most of these dives also call for a switch to oxygen at 6 msw.
The use of such complex mixes, especially for deeper dives, virtually demands that tables be designed for the specific dive or dive pattern. DCAP was used for many of the first such dives (Hamilton and Turner, 1988), but soon some divers with mathematical skills developed computer programs that would do a commendable job of calculating a complex table. Most of these programs were based on Prof. Bühlmann’s algorithm (1984). This was an appropriate choice, since the algorithm was published and available, and it worked quite well. Considering how complex the dives are, there have been relatively few problems with decompression. A “new” twist in these decompressions has been the empirical discovery that using a slow ascent rate or making some short stops early in the decompression seems to improve outcome and reduce decompression sickness.
It should be acknowledged that some 10 years before technical trimix diving had started in the USA that Prof. Zannini, working with colleagues Magno and Marroni, had prepared decompression tables for coral divers in the Mediterranean Sea using techniques remarkably similar to the more recently developed ones, with the single major difference that the coral divers used surface decompression (Zannini, 1987).

Sources of Innovative Decompression Tables
In this presentation our program DCAP serves as the example of a source of special decompression capability that expands beyond “standard air.” There are other sources, both as “flat” tables in books, and as computational programs.

Some tables of this sort are accessible
DCIEM (1992)
Dutch Tables (National Diving Center, 1988)
Norwegian tables (Arntzen and Eidsvik, 1980)
French Ministry of Labor tables (Direction des Journaux Officiels, 1992)

Software
Certain other computer programs do some of what DCAP does. These are harder to pin down than the specific tables in books, and both sources of programs and their characteristics seem to be evolving, so I have made the decision not to attempt to provide a representative list here.
As mentioned, using these programs requires some experience in decompression and skill in operational planning. It is fair to say that this technology is creeping into commercial diving.

The Matter of Validation of Decompression Tables
Once new tables are generated, it is necessary in some ways to validate that the new procedures do in fact provide reliable decompressions. This issue was addressed in a UHMS Workshop on Validation of Decompression Tables (Schreiner and Hamilton, 1989). One approach to table validation is to perform laboratory trials, but this is expensive and time consuming, and takes many, many trials if precise incidences are to be obtained.
There is another approach. The consensus of the UHMS Validation Workshop was that if new tables were close enough to existing tables on which there is an experience base or if they are close to a proven algorithm, then new tables can be put into the field for "*operational evaluation*" under special conditions without the need for specific laboratory trials.
The operational evaluation process is intended to be beyond the laboratory phase of development.
In laboratory operations the divers are volunteer subjects. In operational evaluation the divers are using provisional tables as part of their normal job description. Operational evaluation involves special care, with adequate medical backup and the ability to treat decompression sickness promptly and adequately, involvement of management, special training and supervision, rigorous documentation of dive and outcome, and a mechanism for feedback. There are more details in the full procedure, but the main message here is that small changes in diving operations can be made without extensive laboratory testing.

Conclusions
A wide variety of non-standard decompression tables are available, in books or by operating a computer program. Many of these can provide increased efficiency and lower risk of decompression sickness than some of the more standard military tables.

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