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# DEVELOPMENT OF ADVANCED DECOMPRESSION TABLES FOR JAPANESE DIVING SCIENTISTS

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A number of marine scientists in Japan use diving techniques in their work. In recent years a number of advanced diving methods have become available that offer greater efficiency to divers. The Japan Marine Science and Technology Center, JAMSTEC, has launched a project to provide improved capability to study marine life and global environmental changes, among other things. The project includes developing decompression procedures for breathing gas mixtures other than air, breathing oxygen during decompression, and improved decompression tables for air diving. For preparing special decompression tables, JAMSTEC has acquired the computer program DCAP for calculating and analyzing decompression profiles, and the collaboration of DCAP's developers, Hamilton Research, Ltd. This report reviews this project, including the generation and preliminary validation of a set of new tables. The tables are called the "JAMSTEC Special Air Decompression Tables" They include new tables for standard air dives with air decompression, tables for air dives with decompression using oxygen breathing while divers are in the water, and tables for breathing mixtures of oxygen enriched air ("nitrox"), using this gas mixture or oxygen during decompression. In order to make the tables practical the decompression times are limited to about one hour. Depths of the new tables range from 12 to 72 msw, with bottom times appropriate to the depth, and ranging from 5 to 300 min. The tables are being made available through a Research Diving Network organized by JAMSTEC, and the network scientists are participating in making the table design as useful as possible. JAMSTEC intends to maintain close contact with initial users, and to seek feedback on their experience with the new tables. Initial verification testing at JAMSTEC included 8 air dives with air decompression, 24 air dives with oxygen decompression to 45 msw for 30 min, and 32 dives to 30 msw for 60 min using 36% oxygen enriched air. One subject in the latter series developed pain-only decompression sickness that was promptly resolved with USN Treatment Table 6. Additional operational evaluation will continue.

## Background

Japan has always relied upon and exploited the treasures of the sea. As part of current development in this area is a need for research, both to optimize the use of marine resources, but also to assist in an overall program dedicated to global environmental changes. For a long time Japan has been a leader in research and advanced technology in diving. However, strong traditions and lack of adequate information exchange has limited the use of the latest diving techniques by Japanese diving scientists, and there is room for development of still better techniques. In an attempt to improve this situation JAMSTEC has launched a program to develop advanced techniques and to provide a two-way information exchange with diving scientists in support of coastal zone research (Hamilton et al, 1998).

The information exchange aspect of this program has been described by Ueda and colleagues (Ueda et al. 1998).

The new program involves evaluating new scuba-oriented decompression techniques that are established yet advanced beyond traditional air diving, and configuring them to the needs of the Japanese diving scientist. The program includes the use of optimized validation methods (Schreiner and Hamilton, 1989) . with laboratory validation testing of these procedures where required, and implementation of the new tables in the field as soon as possible. A feedback system is being im-

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plemented to monitor the application of the new techniques as they are put to use in the coastal zone.

### Technical development objectives

The overall objective is to improve scientific diving, with the ultimate objective to improve access to data about the coastal zone as it relates to the global environment. Specifically this element of the project is to develop and implement procedures for improved self-contained diving with air and air-based breathing mixtures. The first step has been the generation of new decompression tables. These include first improvements in air diving, and then diving with special air-based mixtures. The following new decompression tables have been prepared.

- Air with normal air decompression ; more conservative tables.
- Air with oxygen decompression.
- Oxygen-enriched air ("nitrox") dives with a single breathing mixture.
- Enriched air dives with oxygen breathing during decompression.

### Method used for generating new tables

In order to have the capability to prepare special decompression tables, JAMSTEC acquired the computer program DCAP for calculating and analyzing decompression profiles from Hamilton Research, Ltd. "DCAP" (Decompression Computation and Analysis Program) was developed over many years to make decompression computation available without the need for a specialized programmer, and it has been refined to allow a wide variety of computations (Hamilton and Kenyon 1990).

In order to generate the new tables with DCAP we used the Tonawanda II a neo-Haldanian model, a modern version of the classical Haldane method. We used as ascent constraints a well established "matrix" of limits designated MM11F6. These limits were developed for extreme air training dives (Hamilton, Muren, et al 1988). and they have worked well for a large number of technical trimix dives (Irvine and Hamilton 1995) and other air-based dives. The new tables have a sound empirical basis.

### Description of the tables

The tables generated for this phase are designated "JAMSTEC Special Air Decompression Tables." They cover the depth range from 12 to 72 msw, for times appropriate to the depth that range from 5 to 300 min. The times and depths represented by the tables are chosen so as to limit decompression times to no more than about one hour. This is at the outer limits of most scientific diving, so the range of the tables should cover most needs for scuba-based diving.

For the tables using oxygen breathing in the water the divers switch the breathing mixture to oxygen at 6 msw, and since the exposures are relatively short the tables do not call for on-off "cycles" during oxygen breathing. We encourage divers to take the last stop at 3 msw rather than taking it at 6 msw.

The enriched air tables use oxygen levels of 32% and 36%, calculated with an oxygen range of ±1%. The "range" of oxygen allows a lower value to be used for decompression calculations, and an upper value for oxygen tolerance calculations.

Oxygen exposure is checked on all table calculations. It is compared against exposure limits derived conservatively from the 1991 NOAA Diving Manual, which is a widely used guide for scientific diving. Should a limit for oxygen exposure be exceeded the DCAP program prints a warning on the table. Tables that exceed the limits for practical bottom times will not be used. For example, using a mixture with 36% oxygen at 36 msw produces a $PO_2$ of 1.64 atm, and this is too high. Using 36% oxygen at 33 msw, however, involves a $PO_2$ of 1.53 atm and this allows 40 min bottom time without exceeding the limits ; for longer times at that depth with that mix the limits would be exceeded and the table would show a warning.

The tables at this time are available in two formats. The first is a detailed presentation for each depth and bottom time combination. This display includes a title giving the specific identification of the table and the para-meters used for the calculations ; this provides an "audit trail" giving the computational basis for each table. Columns of data include the depth, stop time, decompression time, running time, name of the gas mix in use, the oxygen partial pressure, and instructions for conducting the dives. Summary data at the end includes information about the oxygen exposure. Samples of this format are shown in Figure 1.

```
Air w/inwater O2; nf                                DEPTH          27 MSW
RWH (11f6)            97Feb24                       BOTTOM TIME    50 MIN
DF2KA3.HO2            MM11f6.dcp                    BOTTOM MIX   Air
                                                    BOTTOM PO2   0.78 BAR
DEPTH STOP DEC  RUN       HIPO2                     Time in minutes
 MSW  TIME TIME TIM  MIX    BAR            COMMENTS
-------------------------------------------------------------------------
  00   00   00   00 Air    0.21 Descent optional, included in bottom t
  27   50   00   50 Air    0.78 Ascend to first stop at 20 msw/min
                                 After first stop rate=10 msw/min
  06   02   03   53 Oxygen 1.60 Begin oxygen breathing at 06 msw
  03   13   16   66 Oxygen 1.30
  00   00   17   67 Air    0.21 Surface.  Oxygen Limit Fraction=0.11
=========================================================================

Air w/inwater O2; nf                                DEPTH          27 MSW
RWH (11f6)            97Feb24                       BOTTOM TIME    60 MIN
DF2KA3.HO2            MM11f6.dcp                    BOTTOM MIX   Air
                                                    BOTTOM PO2   0.78 BAR
DEPTH STOP DEC  RUN       HIPO2                     Time in minutes
 MSW  TIME TIME TIM  MIX    BAR            COMMENTS
-------------------------------------------------------------------------
  00   00   00   00 Air    0.21 Descent optional, included in bottom t
  27   60   00   60 Air    0.78 Ascend to first stop at 20 msw/min
                                 After first stop rate=10 msw/min
  06   05   06   66 Oxygen 1.60 Begin oxygen breathing at 06 msw
  03   16   22   82 Oxygen 1.30
  00   00   23   83 Air    0.21 Surface.  Oxygen Limit Fraction=0.16
=========================================================================

Air w/inwater O2; nf                                DEPTH          27 MSW
RWH (11f6)            97Feb24                       BOTTOM TIME    80 MIN
DF2KA3.HO2            MM11f6.dcp                    BOTTOM MIX   Air
                                                    BOTTOM PO2   0.78 BAR
DEPTH STOP DEC  RUN       HIPO2                     Time in minutes
 MSW  TIME TIME TIM  MIX    BAR            COMMENTS
-------------------------------------------------------------------------
  00   00   00   00 Air    0.21 Descent optional, included in bottom t
  27   80   00   80 Air    0.78 Ascend to first stop at 20 msw/min
                                 After first stop rate=10 msw/min
  09   03   04   84 Air    0.40
  06   13   17   97 Oxygen 1.60 Begin oxygen breathing at 06 msw
  03   17   35  115 Oxygen 1.30
  00   00   35  115 Air    0.21 Surface.  Oxygen Limit Fraction=0.28
=========================================================================
```

**Figure 1.** Sample of the detailed format, showing three inwater oxygen tables, for 27 msw for times 50, 60, and 80 min.

A second "condensed" format gives the same title information and includes up to 10 dives on a page, including a range of bottom times for a given depth. At each stop both stop time and decompression time are displayed. Decompression time begins when the diver leaves the bottom. To run the table the diver only needs to start the decompression clock on beginning ascent and then leave each stop at the time indicated ; it is not necessary to time the individual stops. This simplifies timing for working dives, and in fact incorporates techniques from commercial diving experience. A sample of the condensed format in shown in Figure 2.

Plans are in progress to prepare different presentations or formats of the tables. One of these will be a horizontal plan similar to the familiar U. S. Navy tables.

**Tables prepared**

The following tables were prepared for this phase of the project. As mentioned, each category includes coverage of times and depths consistent with no more than one hour of decompression time and not exceeding suitable oxygen limits.

- Air dives with air decompression
- Air dives with air decompression, condensed format
- Air dives with inwater oxygen decompression
- Air dives with inwater oxygen decompression, condensed format
- Oxygen enriched air, 32% and 36% oxygen
- Oxygen enriched air, condensed format
- Oxygen enriched air with inwater oxygen decompression, 32%, 36%, and 100% oxygen
- Oxygen enriched air with inwater oxygen decompression, condensed format

**Validation and implementation**

The validation program began in 1998 and has continued into 1999. The principles of the UHMS Validation Workshop ( Schriener and Hamilton, 1989) are being followed, to minimize unnecessary efforts and reduce costs. This means that dive patterns considered to be " interpolative" or falling within existing experience can be tested under specially controlled field conditions as " provisional" operational tables. However, for protocol purposes the overall table set has been subjected to some selected chamber validation in the diving simulator at JAMSTEC.

The following table categories were included in this phase of the validation process.

- Air dives with air decompression
- Air dives with inwater oxygen decompression
- Oxygen enriched air

The air dive simulation used for validation was 45 msw for 30 min, which has a total decompression time of 59 min. Eight man-exposures to this profile were performed. The same bottom time and depth, 45 msw/30 min was used to simulate dives with oxygen decompression for a total of 24 man-exposures ; the decompression took 30 min for this profile. For the oxygen enriched air profiles a mixture of 36% oxygen, balance nitrogen, was used ; the simulated depth was 30 msw for a bottom time of 60 min, requiring 28 min for decompression.

In overall numbers this is a modest series of decompression validation dives, but the dives were stressful. There was one case of decompression sickness in the exposures to 30 msw for 60 min using

```
Air with inwater 02                                DEPTH        27 MSW
RWH                97Feb25                         MIX          Air
DF2KA4.H22         MM11f6.dcp                      P02          0.78 BAR
==========Condensed table, stop and decompression times, min==========
 Bottom time   30   35   40   45   50   60   80  100  120  150
 time to 1st  1.2  1.2  1.2  1.1  1.1  1.1  0.9  0.9  0.9  0.8
  Depth MSW                                                      Depth

             Descent optional, included in bottom t
             Ascend to first stop at 20 msw/min
             After 1st stop ascend at 10 msw/min
             Begin breathing oxygen at 6 msw

    12                                                      13   12
                                                            14

    09                                              03  18  30   32   09
                                                    04  19  31   46
                Breathe oxygen 6 msw to surface
    06                          01  02  05  13  14  16   24   06
                                02  03  06  17  33  47   70

    03          01  04  07  10  13  16  17  25  30   37   03
                02  05  08  12  16  22  35  58  78  108
                Surface
    00          00  00  00  00  00  00  00  00  00   00   00
                02  06  09  13  17  23  35  59  78  108
```

**Figure 2.** Sample of the condensed format, showing inwater oxygen decompression for 27 msw and times 30 to 150 min.

36% oxygen enriched air. One diver developed pain-only decompression sickness after the simulated dive that was promptly resolved with USN Treatment Table 6. This case was examined, but there is nothing unusual that might explain it. This dive involved a 25 min stop at 3 msw breathing the 36% mix, for a total decompression time of 28 min.

The results of the Doppler bubble detection showed minimal bubbles. In addition, several divers noticed skin itching during the decompressions. This is not uncommon in dry chamber dives.

The research team is reserving judgement on the case of DCS that occurred, and does not plan to change the tables at this time.

## Future plans

Provisional tables are being made available to a selected set of diving scientists who also act as advisors to JAMSTEC for this project. Tables used at sea by specially trained scientist-divers are carefully coordinated and monitored by the JAMSTEC team, to include medical backup, dive logging, and development of a data base for acquiring the outcome information and storing and evaluating the results of the project.

Next, once provisional and chamber validation allows the tables to be considered acceptable they will be distributed to divers in a Japanese" Research Diving Network," comprising at present some 440 scientist-divers (Ueda et al. 1998). This may involve additional indoctrination and training.

It is important to make the point that these tables will be offered to the divers in the Research Diving Network, but their use will not in any way be compulsory. Other scientific divers who might benefit from use of the advanced techniques will be offered an opportunity to become trained in their use and will be able to use the tables.

During the duration of the project additional tables will be generated and entered into the development project. At first this will include new presentation formats, and then when needed any new procedures determined to be beneficial and effective as a result of implementation of the first tables will be prepared. And, later, divers will live full time in the subsea environment being studied in seafloor habitats, with creative excursions, up and down.

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