DIVE TABLES AND COMPUTERS; FLYING AFTER DIVING

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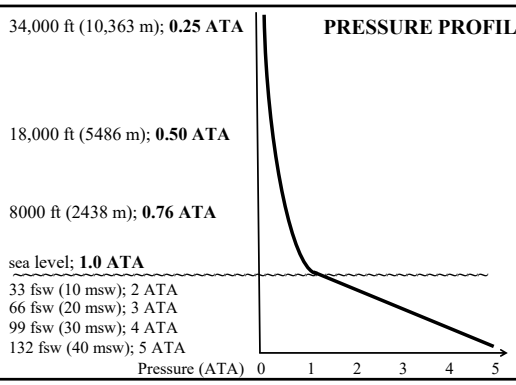
OBJECTIVES

- We will discuss foundations and applications related to decompression
  - underlying physiological/mathematical relationships
  - decompression procedures
    - air diving tables
      - US Navy
      - DCIEM*
        - *Defence and Civil Institute of Environmental Medicine
      - alternative tables
    - treatment tables
  - decompression algorithms and dive computers
  - flying after diving
  - altitude diving

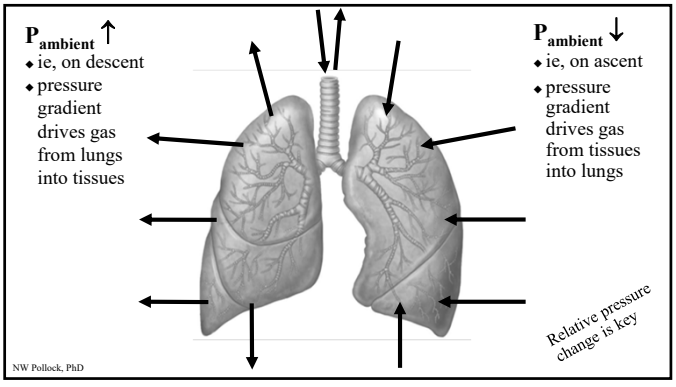
PRESSURE PROFILE



LINEAR GAS PRESSURE-VOLUME RELATIONS IN SEAWATER

Depth	Pressure				Volume	Density
(fsw / msw)	(ATA)	($lb \cdot in^{-2}$)	(bar)	(kPa)		
0 / 0	**1**	14.7	1.01	101.3	**1**	**1x**
33 / 10	**2**	29.4	2.03	202.6	**1/2**	**2x**
66 / 20	**3**	44.1	3.04	303.9	**1/3**	**3x**
99 / 30	**4**	58.8	4.05	405.2	**1/4**	**4x**
132 / 40	**5**	73.5	5.07	506.5	**1/5**	**5x**
165 / 50	**6**	88.2	6.08	607.8	**1/6**	**6x**

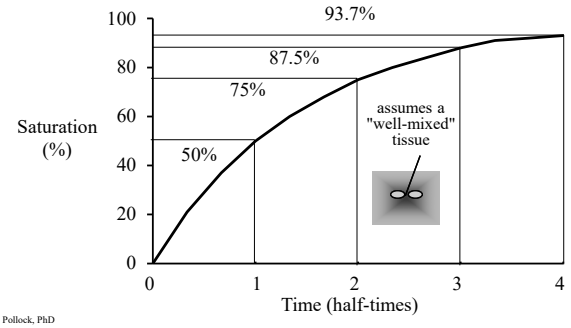
- Critical relationships to understand the physiological impact of diving
  - sea level pressure references are convenient, but not always the most relevant



CRITICAL CONCEPTS IN INERT GAS EXCHANGE

- **Gas Uptake/Elimination**
  - uptake (ongassing) and elimination (offgassing) follow pressure gradients
  - half-times can predict for a range of mathematical constructs ("compartments")
    - eg, 5, 10, 20, 40, 60, 120 min, etc.
      - equilibration is presumed to be complete in ~6 half-times in static conditions
        - Pollock and Buteau (2017)
- **Supersaturation**
  - gas $pressure_{tissue}$ > gas $pressure_{ambient}$
  - Haldane conducted saturation experiments with animals
    - reported a maximum safe 2:1 pressure reduction ratio
      - since N_2 is 78% of air mixture, 1.56:0.78 for N_2
    - now known to be more complicated
- **M-value**
  - maximum tissue tension in supersaturation that can be tolerated without problem
    - theoretical construct - both bubbles and DCS can develop within M value limits
    - note: faster tissues have higher M-values

CONCEPTUAL HALF-TIME UPTAKE



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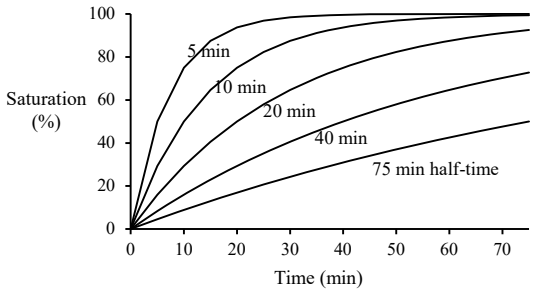
MATHEMATICAL COMPARTMENT GAS UPTAKE



Equilibration is achieved in approximately 6 half-times for any compartment

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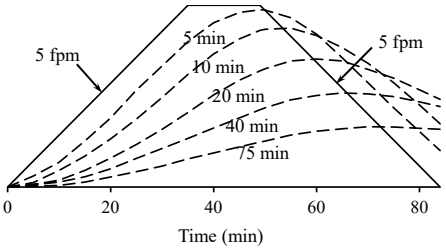
NITROGEN EXCHANGE DURING DIVING

52 msw (168 fsw; 28 fathoms) for 19 min



Inert gas elimination described with half-time curves

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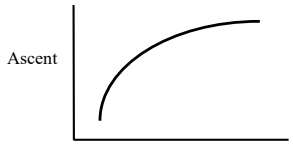
RELATIVE PRESSURE CHANGES WITH DEPTH

- Rate of relative pressure change increases progressively through ascent
  - from **90 msw** to **80 msw** (300 fsw to 267 fsw) **10%** reduction
  - from **50 msw** to **40 msw** (165 fsw to 132 fsw) **17%** reduction
  - from **20 msw** to **10 msw** (66 fsw to 33 fsw) **33%** reduction
  - from **10 msw** to **surface** (33 fsw to surface) **50%** reduction
- Physiological impact of depth change is increasingly important through ascent



Ascent speed should be progressively slower through ascent

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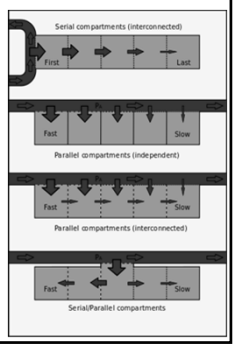
MODELING PHYSIOLOGY

- Models provide manageable representations of complex events
  - sophistication increases as a function of understanding and technical capabilities (eg, measurement and computational power)
- Models will almost inevitably be incomplete and probably at least partially wrong
  - but they can still be useful



Examples of conceptual physiological models

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DECOMPRESSION STRESS CONTINUUM

← **? True Safety Threshold ?** →

- Reality - DCS is a probabilistic event
- Risk tolerance is personal, but should be informed

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US NAVY DIVE TABLES

- Developed by US Navy for military use but escaped into the civilian world
  - – developed mathematically with limited human testing
  - – liberation fueled rapid growth of recreational diving in 1950s
  - – latest version in Revision 7 of US Navy dive manual
    - – USN (2016) - available for free download
- Structure
  - – single or repetitive exposures
  - – not intended for multi-level computation

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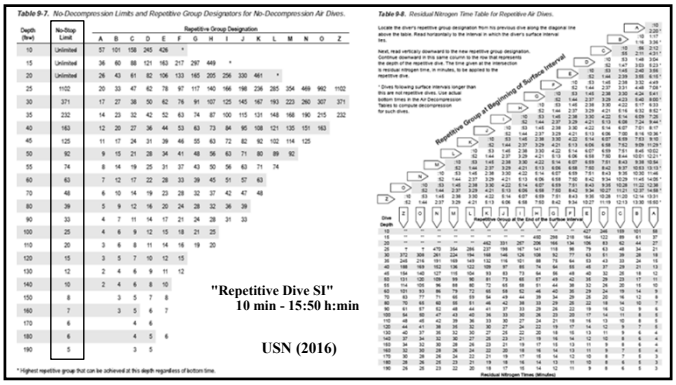
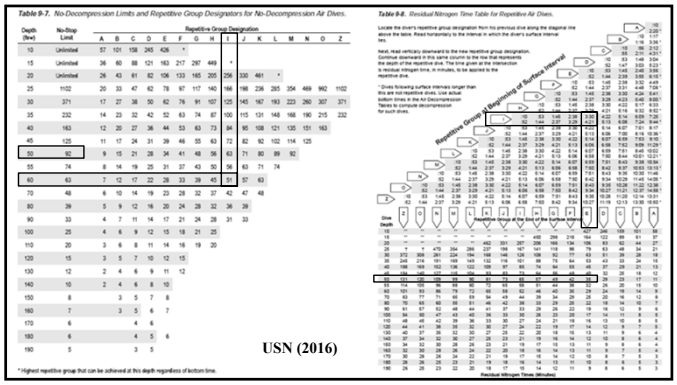
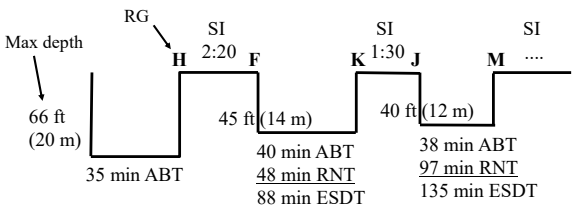




US NAVY DIVE TABLES 9-7/9-8 - AIR NO DECOMPRESSION (2016)



US Navy tables compute decompression status based on maximum dive depth and actual bottom time (**ABT**) to compute a repetitive group (**RG**). The RG falls as the post-dive surface interval (**SI**) increases. The impact of previous dives on the next dive is computer with residual nitrogen time (**RNT**). (ABT + RNT = **ESDT** [equivalent single dive time]). ESDT is entered to compute the RG for repetitive dives.

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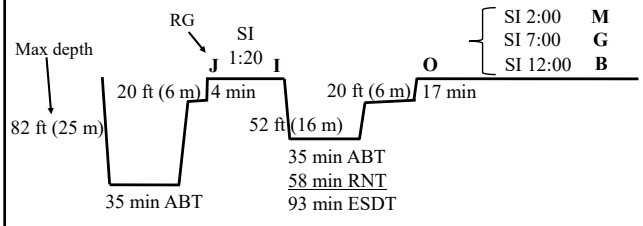
US NAVY DIVE TABLE 9-9 - AIR DECOMPRESSION (2016)



Dive tables require interim stops during ascent when the exposure exceeds no-decompression limits. These allow additional time for off-gassing before the remaining step(s) in the depressurization occurs. The repetitive group (**RG**) at the end of a dive decreases alphabetically as the post-dive surface interval (**SI**) lengthens and excess inert gas is eliminated until the diver is "off the tables" (or does another dive to accumulate more inert gas).

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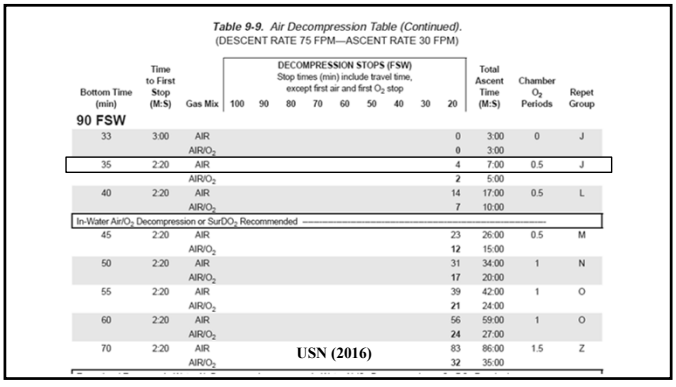


Table 9-9. Air Decompression Table (Continued).
(DESCENT RATE 75 FPM—ASCENT RATE 30 FPM)

Bottom Time (min)	Time to First Stop (M:S)	Gas Mix	DECOMPRESSION STOPS (FSW) Stop times (min) include travel time, except first air and first O_2 stop 100	90	80	70	60	50	40	30	20	Total Ascent Time (M:S)	Chamber O_2 Periods	Repet Group
90 FSW														
33	3:00	AIR										0 3:00	0	J
		AIR/O_2										0 3:00		
35	2:20	AIR										4 7:00	0.5	J
		AIR/O_2										2 5:00		
40	2:20	AIR										14 17:00	0.5	L
		AIR/O_2										7 10:00		
In-Water Air/O_2 Decompression or $SurDO_2$ Recommended														
45	2:20	AIR										23 26:00	0.5	M
		AIR/O_2										12 15:00		
50	2:20	AIR										31 34:00	1	N
		AIR/O_2										17 20:00		
55	2:20	AIR										39 42:00	1	O
		AIR/O_2										21 24:00		
60	2:20	AIR										56 59:00	1	O
		AIR/O_2										24 27:00		
70	2:20	AIR										83 86:00	1.5	Z
		AIR/O_2										32 35:00		

USN (2016)

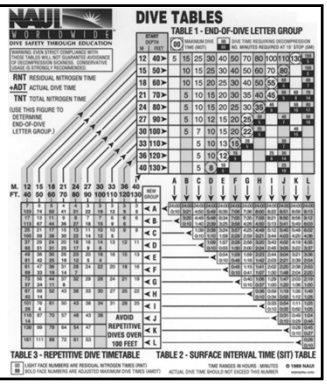
Table 9-9. Air Decompression Table (Continued).
(DESCENT RATE 75 FPM—ASCENT RATE 30 FPM)

Bottom Time (min)	Time to First Stop (M:S)	Gas Mix	DECOMPRESSION STOPS (FSW) Stop times (min) include travel time, except first air and first O_2 stop 100	90	80	70	60	50	40	30	20	Total Ascent Time (M:S)	Chamber O_2 Periods	Repet Group
55 FSW														
74	1:50	AIR									0	1:50	0	L
		AIR/O_2									**0**	1:50		
75	1:10	AIR									1	2:50	0.5	L
		AIR/O_2									**1**	2:50		
80	1:10	AIR									4	5:50	0.5	M
		AIR/O_2									**2**	3:50		
90	1:10	AIR									10	11:50	0.5	N
		AIR/O_2									**5**	6:50		
In-Water Air/O_2 Decompression or SurfDO_2 Recommended														
100	1:10	AIR									17	18:50	0.5	O
		AIR/O_2									**8**	9:50		
110	1:10	AIR									34	35:50	0.5	O
		AIR/O_2									**12**	13:50		
120	1:10	AIR									48	49:50	1	Z
		AIR/O_2									**17**	18:50		
130	1:10	AIR									59	60:50	1	Z
		AIR/O_2									**22**	23:50		
140	1:10	AIR									84	85:50	1	Z
		AIR/O_2									**26**	27:50		

USN (2016)

RECREATIONAL VARIANTS

- Many recreational variants based on the US Navy dive tables exist
  - more conservative no-decompression limits
    - eg, NAUI, SSI
  - more liberal no-decompression limits
    - eg, PADI recreational dive planner
  - note: typically include some steps beyond no-decompression limits



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DCIEM DIVE TABLES

- Developed by Canadian military
  - based on 1962 Kidd-Stubbs four compartment serial model
    - the goal was to develop tables more conservative than those of the US Navy
  - largest manned dive verification testing effort
    - 1800 person-dives in initial series
      - endpoints of DCS and aurally monitored vascular bubbles
  - conservative limits set based on Doppler ultrasound
    - very limited bubble grades III-IV bubbles allowed (0-IV scale)
  - current air diving tables approved in 1992
    - DCIEM (1992)
- Structure
  - single or repetitive exposures
  - allow multi-level profile computation
  - provide some altitude correction
- Algorithm developed for dive computer implementation by Shearwater in 2020

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NO-DECOMPRESSION LIMITS (in min)

Depth (m/ft)	**USN** (2016)	**DCIEM**	**% Δ**
9 / 30	371	300	-19
12 / 40	163	150	-8
15 / 50	92	75	-18
18 / 60	63	50	-21
21 / 70	48	35	-27
24 / 80	39	25	-36
27 / 90	33	20	-39
30 / 100	25	15	-40
33 / 110	20	12	-40
36 / 120	15	10	-33
39 / 130	12	8	-33
42 / 140	10	7	-30
45 / 150	8	6	-25

- DCIEM no-decompression limits were adjusted based on symptoms and high grade bubbles observed in testing, contributing to the inconsistent differences from the USN table limits

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DIVE TABLE COMPARISON

- No decompression limits for first dive

There is a pretty good chance that there is no simple truth with this degree of variability

- No decompression limits for second dive
  - first dive: 60 fsw (18 msw) for 50 min followed by a 60 min surface interval

Depth (ft/m)	USN 2016	DCIEM	RDP	HUGI	Doppler	Max Δ (%)
40 / 12	163	150	140	135	130	**+25**
50 / 15	92	75	80	75	70	**+31**
60 / 18	63	50	55	50	50	**+26**
70 / 21	48	36	40	40	40	**+33**
80 / 24	39	25	30	30	30	**+56**
90 / 27	33	20	25	25	25	**+65**
100 / 30	25	15	20	20	20	**+67**

Depth (ft/m)	USN 2016	DCIEM	RDP	HUGI	Doppler	Max Δ (%)
40 / 12	89	93	103	43	57	**+140**
50 / 15	35	38	52	18	14	**+271**
60 / 18	17	26	32	7	6	**+433**
70 / 21	9	17	21	7	3	**+600**
80 / 24	6	13	13	4	-	
90 / 27	4	10	10	4	-	
100 / 30	-	8	7	4	-	

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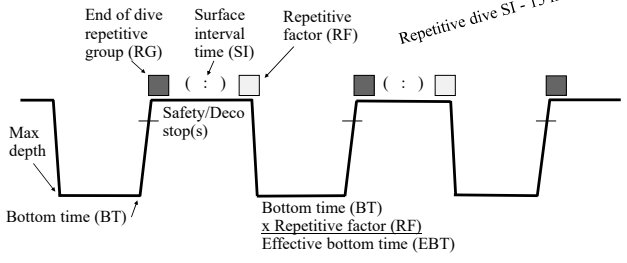
DCIEM DIVE TABLES



Effective bottom time (EBT) = Bottom time (BT) * Repetitive factor (RF)

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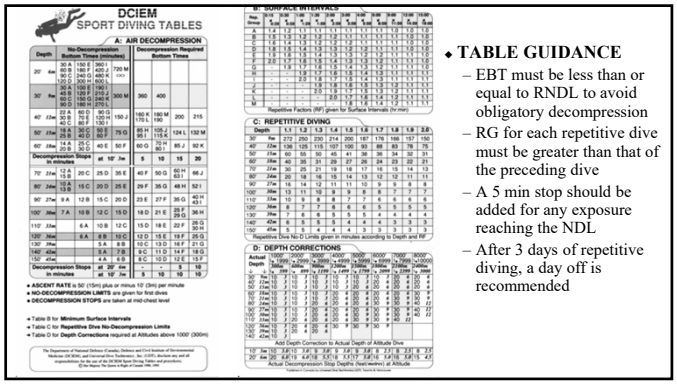
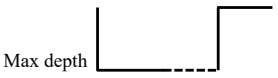


- **TABLE GUIDANCE**
  - EBT must be less than or equal to RNDL to avoid obligatory decompression
  - RG for each repetitive dive must be greater than that of the preceding dive
  - A 5 min stop should be added for any exposure reaching the NDL
  - After 3 days of repetitive diving, a day off is recommended

NO DECOMPRESSION LIMIT (NDL)



- **BT** - time from start of descent to start of direct ascent to the surface or a decompression stop
- **NDL** - maximum time for a given depth interval beyond which obligatory decompression stops are required

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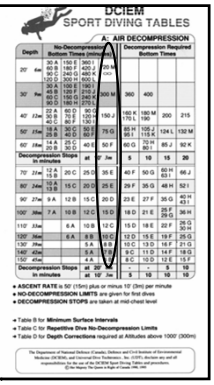
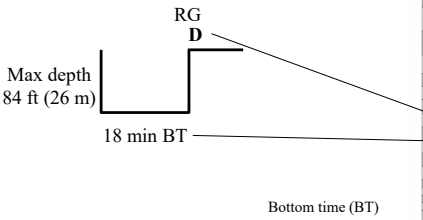


REPETITIVE GROUP (RG)



- Round to next greater depth and time if exact values not found
- Computation of status is finished with the RG if no more diving will be done in the next 18 h

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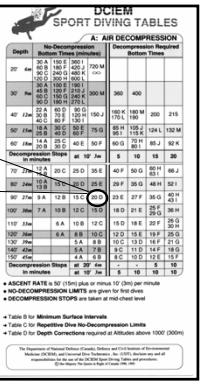
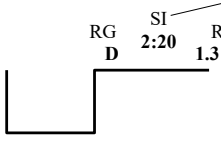


SURFACE INTERVAL (SI) AND REPETITIVE FACTOR (RF)



- For surface intervals <15 min, the bottom times are added
- If the surface interval is between 15 min and 18 h the impact of the previous dive(s) must be considered in planning the next

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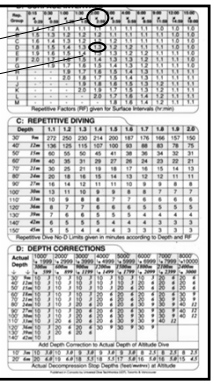
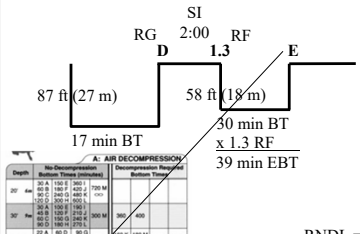
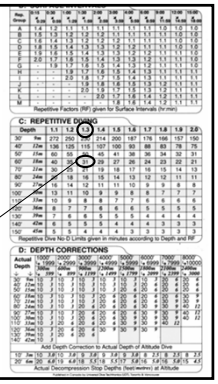


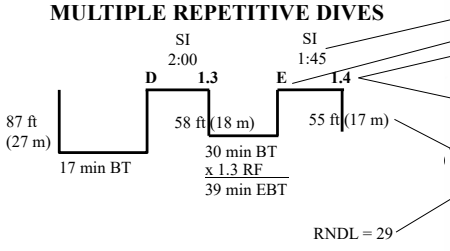
REPETITIVE DIVES



Repetitive no-decompression limit (RNDL)



MULTIPLE REPETITIVE DIVES



- EBT is not real time, but it estimates the physiological impact of the cumulative diving activity on decompression status
- Subsequent repetitive dives are computed exactly as the first repetitive dive

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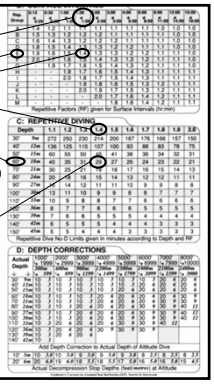
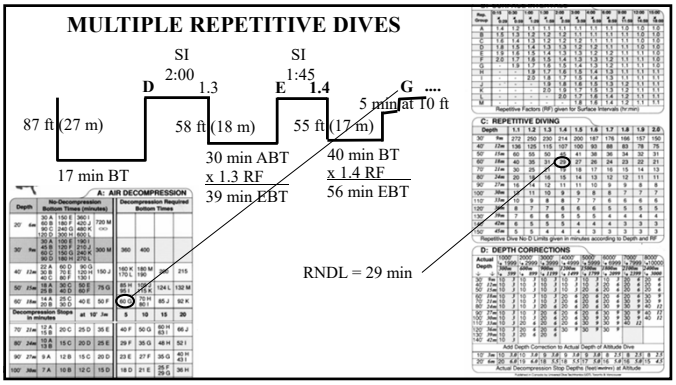
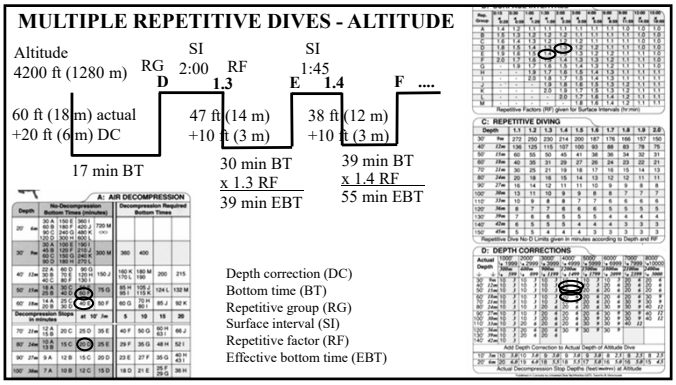


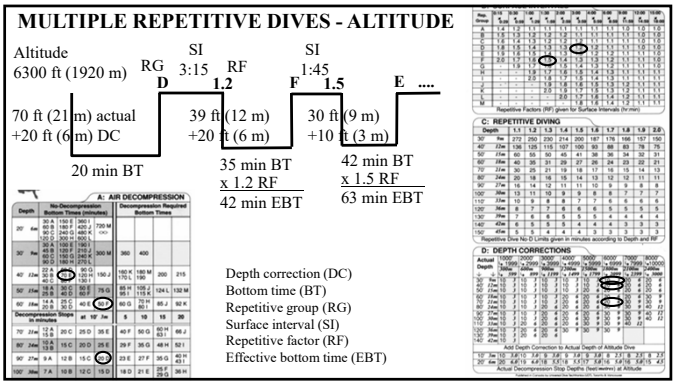
MULTIPLE REPETITIVE DIVES



MULTIPLE REPETITIVE DIVES - ALTITUDE



MULTIPLE REPETITIVE DIVES - ALTITUDE



USE OF DCIEM DIVE TABLES

- Required for some diving in several countries
  - eg, Canada, Australia, New Zealand
    - commercial and scientific
- Good option for persons sensitive to or concerned with decompression stress
  - now available in Shearwater dive computers
    - implementation complete; manned trials began in 2019 at DRDC in Toronto

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ADDITIONAL DIVE TABLES

- Enriched air nitrox (EAN)
  - increased oxygen / decreased nitrogen
  - mathematically corrected for nitrogen fraction
    - thus iso-risk diving nitrox to limit of nitrox tables or air to limit of air tables
  - risk of oxygen toxicity is increased
    - PO_2 is generally limited to 1.4 atm during working phase of dives
- Surface decompression (surD)
  - divers brought to surface after 40 fsw (12 msw) stop to finish deco in chamber
- Mixed gas
  - eg, trimix - oxygen, helium, nitrogen
- Treatment tables
  - US Navy 6, 5, 6A, 9
  - Catalina
  - COMEX

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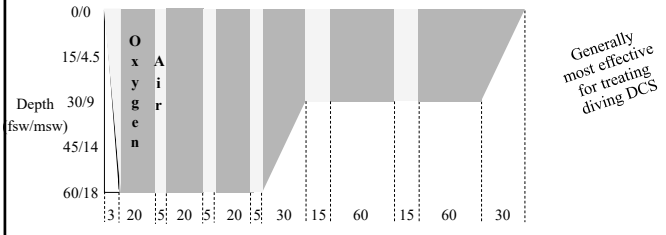
US NAVY TREATMENT TABLE 6 (USN 2016)



- Total elapsed time **4:45 h:min** (excluding descent time)
  - descent rate: 20 ft·min^{-1} (6 m·min^{-1}); ascent rate not to exceed 1 ft·min^{-1} (0.3 m·min^{-1})
  - most popular table to treat DCI

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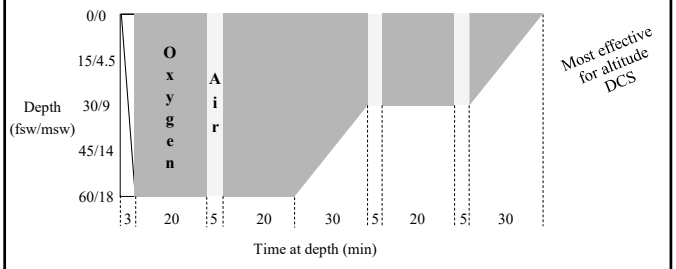
US NAVY TREATMENT TABLE 5 (USN 2016)



- Total elapsed time **2:15 h:min** (excluding descent time)
  - descent rate: 20 ft·min^{-1} (6 m·min^{-1}); ascent rate not to exceed 1 ft·min^{-1} (0.3 m·min^{-1})

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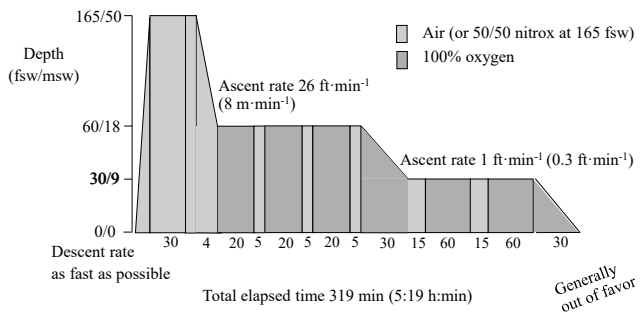
USN TREATMENT TABLE 6A (USN 2016)



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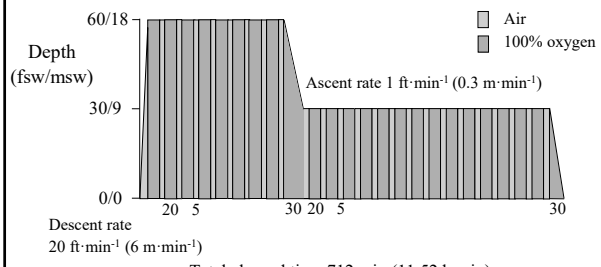
CATALINA TREATMENT TABLE

Extended treatment for severe DCS



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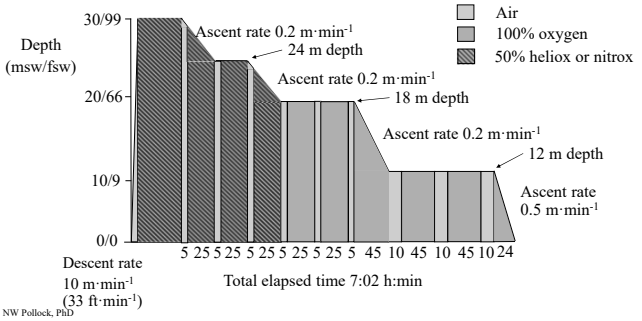
COMEX 30 TREATMENT TABLE



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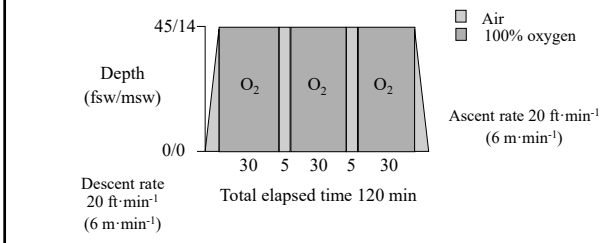
US NAVY TREATMENT TABLE 9 (USN 2016)



Used for residual symptoms following treatment for DCS/AGE
- similar to most 'wound healing' treatment protocols

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DIVE COMPUTERS

- Have allowed a seismic shift in dive planning
  - enabling complex dive profiles with minimal effort
- Many decompression algorithms (mathematical models) and versions used
  - substantial variability in both limits and testing
- Provide only first order approximation of risk
  - they should be used thoughtfully, with caution

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POPULAR DECOMPRESSION ALGORITHMS

- **Multi-Tissue Model** (Haldane)
  - original gas content model; uptake/elimination half-time basis
- **Buhlmann**
  - empirically-derived; code openly released
- **DCIEM** (Defence and Civil Institute of Environmental Medicine)
  - empirically-derived; 1800 Doppler-monitored person-dives
- **VPM** (Varying Permeability Model) (Yount)
  - mathematically-derived bubble model; code openly released
- **RGBM** (Reduced Gradient Bubble Model) (Wienke)
  - mathematically-derived bubble model; follows VPM; proprietary
- **VVAL-79**
  - used in US Navy revision 7 (2016) air diving tables
- **DSAT** (Diving Safety and Technology / Recreational Dive Planner)
  - repetitive dive limits based on 60 min instead of 120 min half-time

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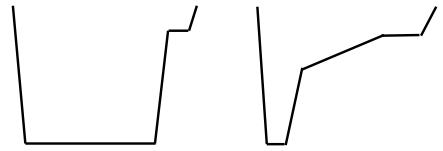

Square profile Multi-level profile

Inert gas uptake and decompression risk are much greater with square profiles than with multi-level profiles.

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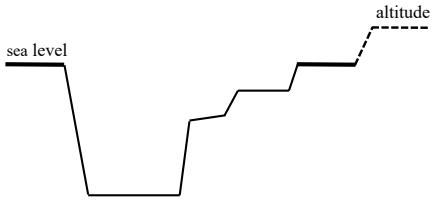
DECOMPRESSION - FOUNDATIONS

- Decompression stress is a function of relative pressure change
  - ascent during diving
  - ascent from surface to altitude
    - eg, flying or driving



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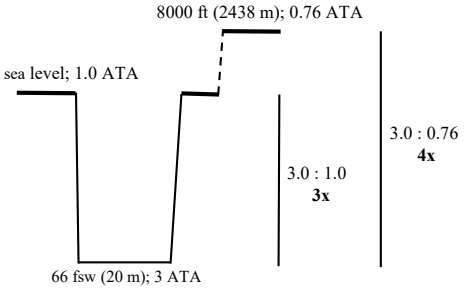
DECOMPRESSION STRESS - SURFACE OR FLY



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DECOMPRESSION SAFETY FOR FLYING

- DCS risk low for most flying
  - most unpressurized aircraft fly at altitudes less than 12,000 ft (3658 m; ~0.65 atm abs)
- FAR* require pressurized craft to be able to maintain a cabin altitude of ≤8000 ft (2438 m; ~0.76 atm abs) at maximum cruise altitude
  - *Federal Aviation Regulations

Dive hole at Gneiss Pt, Antarctica

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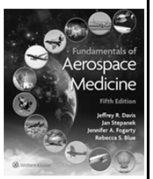
CABIN PRESSURE DIFFERENTIAL

Altitude (ft [m])	P_{out} (atm abs)	ΔP (psi)	P_{in} (atm abs)	Cabin Altitude (ft [m])
sea level	1.00			
24,000 [7315]	0.39	4.0	0.66	11,000 [3353]
		8.0	0.93	2000 [610]
		10.0	1.07	---
36,000 [10,973]	0.22	4.0	0.50	18,000 [5,486]
		8.0	0.77	7000 [2134]
		10.0	0.90	2750 [838]
48,000 [14,630]	0.12	4.0	0.40	23,500 [7163]
		8.0	0.67	11,200 [3414]
		10.0	0.80	6000 [1829]



Stepanek et al. (2021)

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ALTITUDE DECOMPRESSION SICKNESS

- Threshold altitude for DCS?
  - 16,000-19,000 ft (4900-6400 m; 0.54-0.48 atm abs)
    - Houston (1947); Davis et al. (1971); Haske and Pilmanis (2002)
  - <14,000 ft (4267 m)
    - Files et al. (2005)
  - 11,000 ft (3350 m; 0.66 atm abs) - direct ascent from near sea level and physical exercise (combined events atypical)
    - Kumar et al. (1990)
- Threshold duration at altitude for DCS?
  - insufficient data
  - activity level, pressure profile and decompression rate will all influence threshold altitude
- Flying after diving can increase decompression stress

CURRENT FLYING AFTER DIVING GUIDANCE

- **US Federal Aviation Regulations** - have **Guidelines Only**
  - 12 h surface interval (SI) after no-decompression dives (max 8000 ft cabin altitude)
  - 24 h SI after decompression dives (max 8000 ft cabin altitude)
  - 24 h SI after any dive if cabin altitudes >8000 ft (2438 m; 75.3 kPa)
    - Aeronautical Information Manual (2023)

- **Divers Alert Network (DAN) Consensus Guidelines**
  - 12 h SI after single no-decompression dives (2000-8000 ft [610-2438 m] cabin altitude)
  - 18 h SI after multiple dives per day or multiple diving days
  - 'substantially longer than 18 h SI' after decompression dives
    - Sheffield and Vann (2004)

- **Health Canada Regulations**
  - 12 h following a no-decompression dive
  - 24 h following a decompression dive
  - such time as specified by a physician who treated the diver for a pressure-related injury
    - Canada OHS Regulations (SOR/86-304) (2023)
- Common guidance calls for 24-h pre-flight surface interval

ALTITUDE EXPOSURE AFTER DIVING TABLES

- **US Navy**
  - based on available data with much interpolation/extrapolation
  - 2016 - Table 9-6
    - USN Dive Manual (2016)
  - less conservative but more flexible option
    - similar to computations used in some dive computers

EXCERPT: USN TABLE 9-6 - REQUIRED SURFACE INTERVAL BEFORE ASCENT TO ALTITUDE AFTER DIVING (2008; 2016)

		Increase in Altitude (ft)				
		2000	**4000**	**6000**	**8000**	**10,000**
	F	0:00	0:00	1:32	**7:06**	15:20
	G	0:00	0:00	3:38	**9:13**	17:27
	H	0:00	1:06	5:29	**11:04**	19:18
Repetitive Group Designator	**I**	0:00	2:45	7:09	**12:44**	20:58
	J	0:41	4:15	8:39	**14:13**	22:27
	K	2:03	5:37	10:00	**15:35**	23:49
	L	3:18	6:52	11:15	**16:50**	25:04
	M	4:28	8:01	12:25	**18:00**	26:14
still based on much interpolation / extrapolation	**N**	5:32	9:06	13:29	**19:04**	27:18
	O	6:33	10:06	14:30	**20:05**	28:19
	Z	7:29	11:03	15:26	**21:01**	29:15

USN TABLE 9-5 - REPETITIVE GROUPS ASSOCIATED WITH INITIAL ASCENT TO ALTITUDE (2008; 2016)

Altitude (ft)	Repetitive Group	Altitude (m)
1000	**A**	305
2000	**A**	610
3000	**B**	914
4000	**C**	1219
5000	**D**	1524
6000	**E**	1829
7000	**F**	2134
8000	**G**	2438
9000	**H**	2743
10,000	**I**	3048

ALTITUDE DEPTH CORRECTION

- Effectively, any depth at altitude has the impact of a deeper depth at sea level
- Altitude correction allows adjusted depth to be used with normal dive tables
  - 'Equivalent Depth' = Altitude Depth * $\frac{\text{Sea Level Pressure}}{\text{Altitude Pressure}}$
    - US Navy Dive Manual (2016)
  - eg, equivalent depth = 18 m (60 ft) * $\frac{1013 \text{ mb}}{843 \text{ mb}}$ = 22 m (72 ft)

Lake Minnewanka, Alberta
(1372 m; 4500 ft altitude)

DECOMPRESSION AND ALTITUDE DIVING

- 'Equivalent depth' may be most reasonable to use for conservative no-decompression diving only
- Tolerable tissue gas tension to ambient pressure ratios may vary as a function of altitude
  - DCS models differ substantially between ocean diving exposures and altitude exposures
  - potential confounders with much of the available data include immersion, exercise and thermal stress
- A limited number of decompression models incorporate altitude computations
  - eg, DCIEM, Buhlmann
    - Boni et al. (1976); Egi and Brubakk (1995); Egi and Gurmen (2000)

TAKE HOME MESSAGES

- Decompression status is predicted by mathematical models
  - imperfectly, but reliably; based on tissue compartments models
- Dive tables represent a single compartment model
  - key: US Navy, DCIEM, and treatment (USN TT6 and TT5, Catalina, Comex 30)
  - largely supplanted by multi-compartment dive computer algorithms
- Key concepts in decompression modeling/execution
  - gas uptake and elimination (and half-times)
  - supersaturation and undersaturation states
  - M-value as mathematical estimator of safe supersaturation limit for given tissue
  - relative pressure change is inversely proportional to depth
- Diver behavior can play a critical role in moderating exposure stress
- Altitude exposure increases decompression stress
  - diving at altitude
  - travel to altitude (flying or driving) after diving

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