Bühlmann Symposium 29./30. März 2019
Universitätsspital Zürich

The
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Consulting
Group
Tel Aviv – San Francisco – Stuttgart
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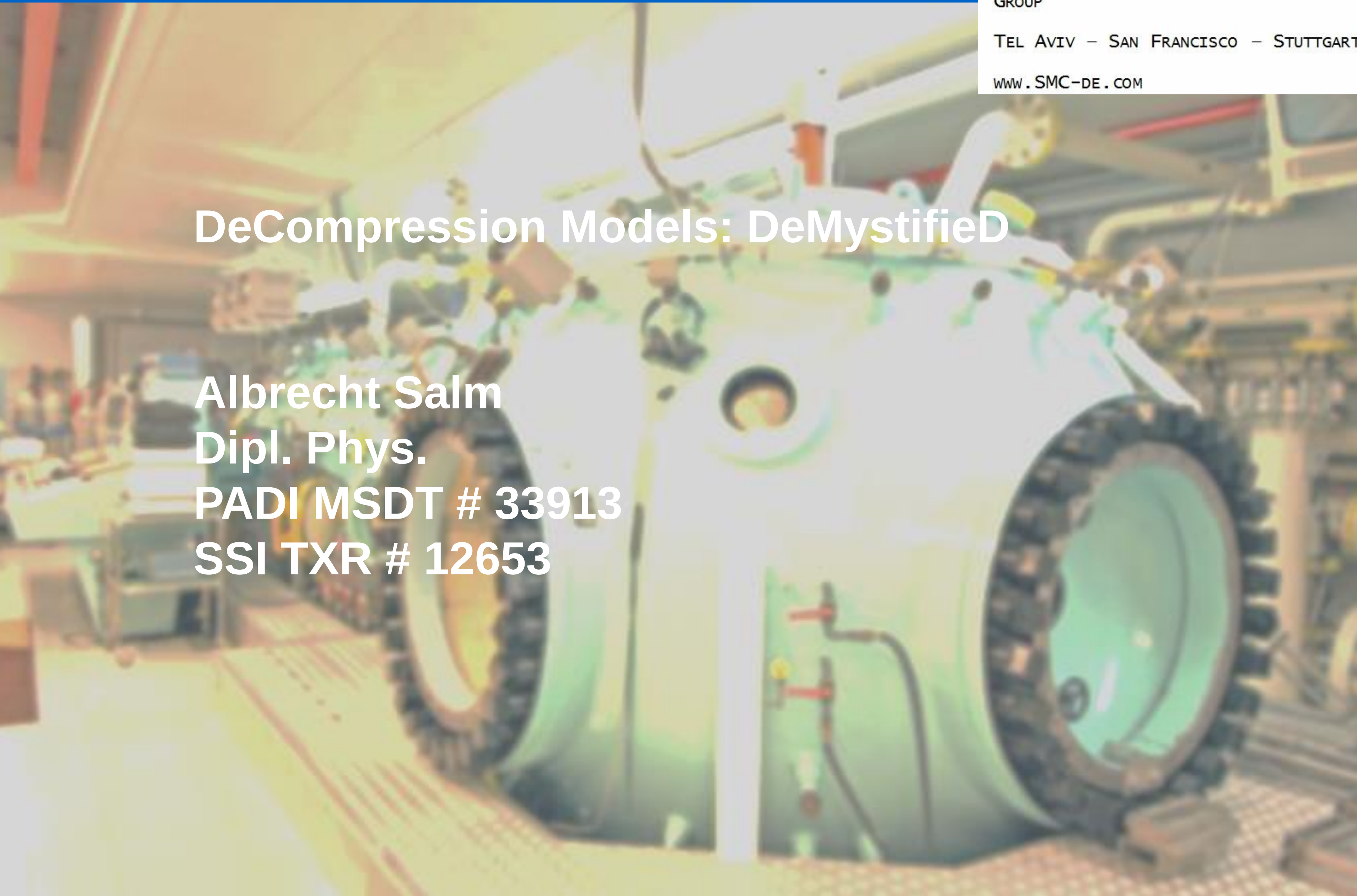

DeCompression Models: DeMystifieD

Albrecht Salm
Dipl. Phys.
PADI MSDT # 33913
SSI TXR # 12653

DeMYSTiFieD

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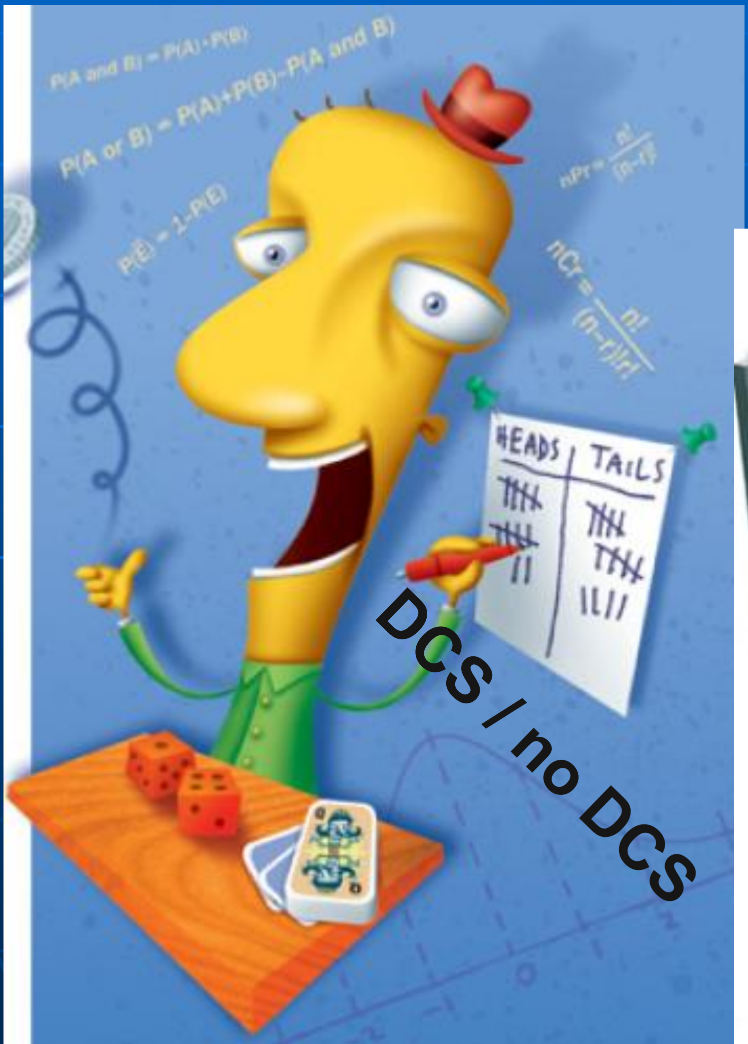
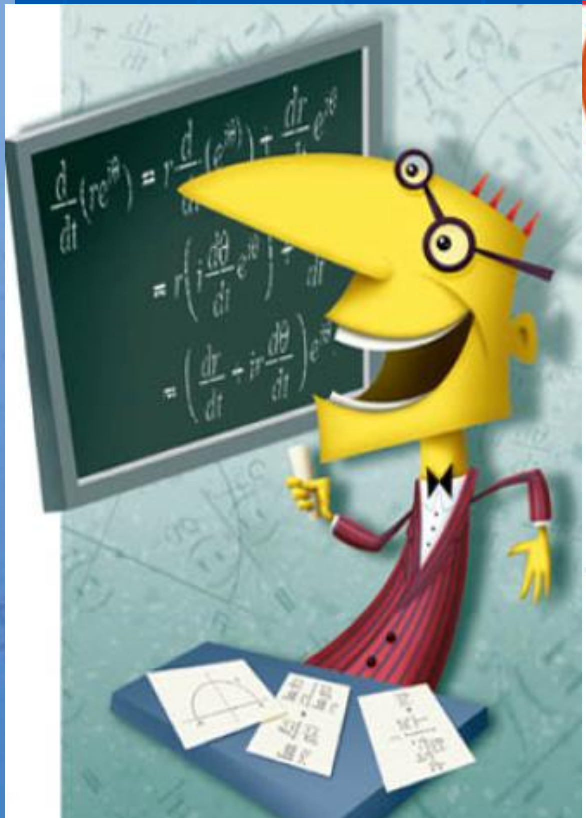
Hard stuff made easy™

DeCompression Models: DeMystifieD!





DeCompression Models: DeMystifieD!

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Agenda:

→ **From the Model to the Algorithm and Implementation**
- ***Tema con Variazioni:* TTS**

→ **Basic Limits of Perfusion Models: *Concerto Grosso***
- **„Die Grenzen meiner Daten sind die Grenzen meines Modells!“**
- **Extrapolations … & why linear extrapolations won‘t work**
- **Yo-Yo, Repetitive Dives, the „Helium Penalty“, … (NPA)**

→ **empirical Adaptions: how do they work? *Fuga***
- **How was the RDP® created?**
- **temperature, workload, oxygen corrections**
- ***Cosi fai tutti:* deep stops**

→ ***Coda:* „executive editing, typoos & undocumented features“**

→ **Bonus Material: VPM seems to simulate strange bubbles …**

DeCompression Models: DeMystifieD!

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**"The sciences do not try to explain,
they hardly even try to interpret, they mainly make models.
By a model is meant a mathematical construct which,
with the addition of certain verbal interpretations,
describes observed phenomena.
The justification of such a mathematical model
is solely and precisely that it is expected to work."**

John von Neumann

From the Model to the Algorithm and Implementation (1)

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Observation / experiment formulates a *problem or idea*

→

Physical / physiological theory gives *model* (simplified description, limited data, limited under-standing)

↓

mathematical method gives the: *Algorithm* *(how to compute,* limited time & mathematical tractability)

↓

Implementation in software gives: *program or „table“*

From the Model to the Algorithm and Implementation (2)

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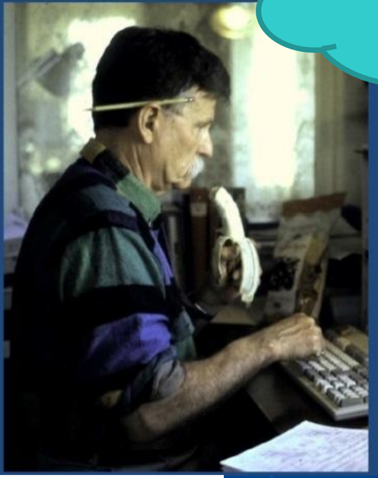
Idea !!! → Model



↓

↓

Algorithm

محمد بن موسى الخوارزمي; c. 780 – c. 850

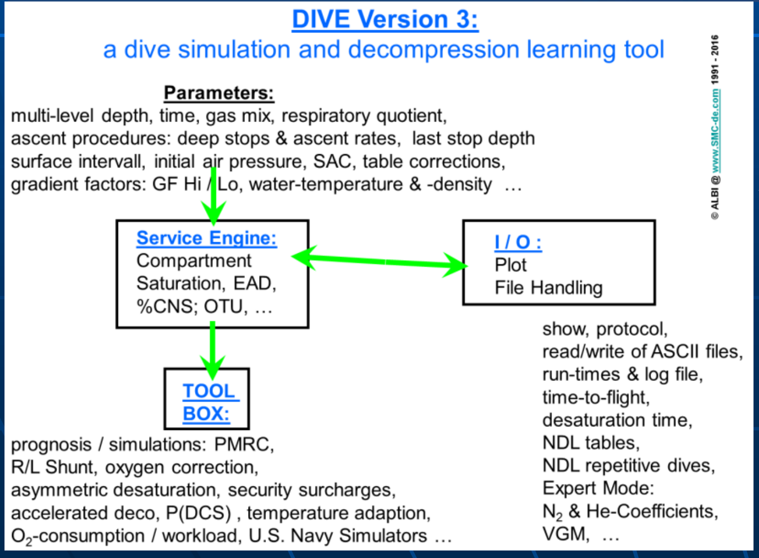
↓

↓

← ← ←

Implementation

→ → →



tema con variazioni: TTS …

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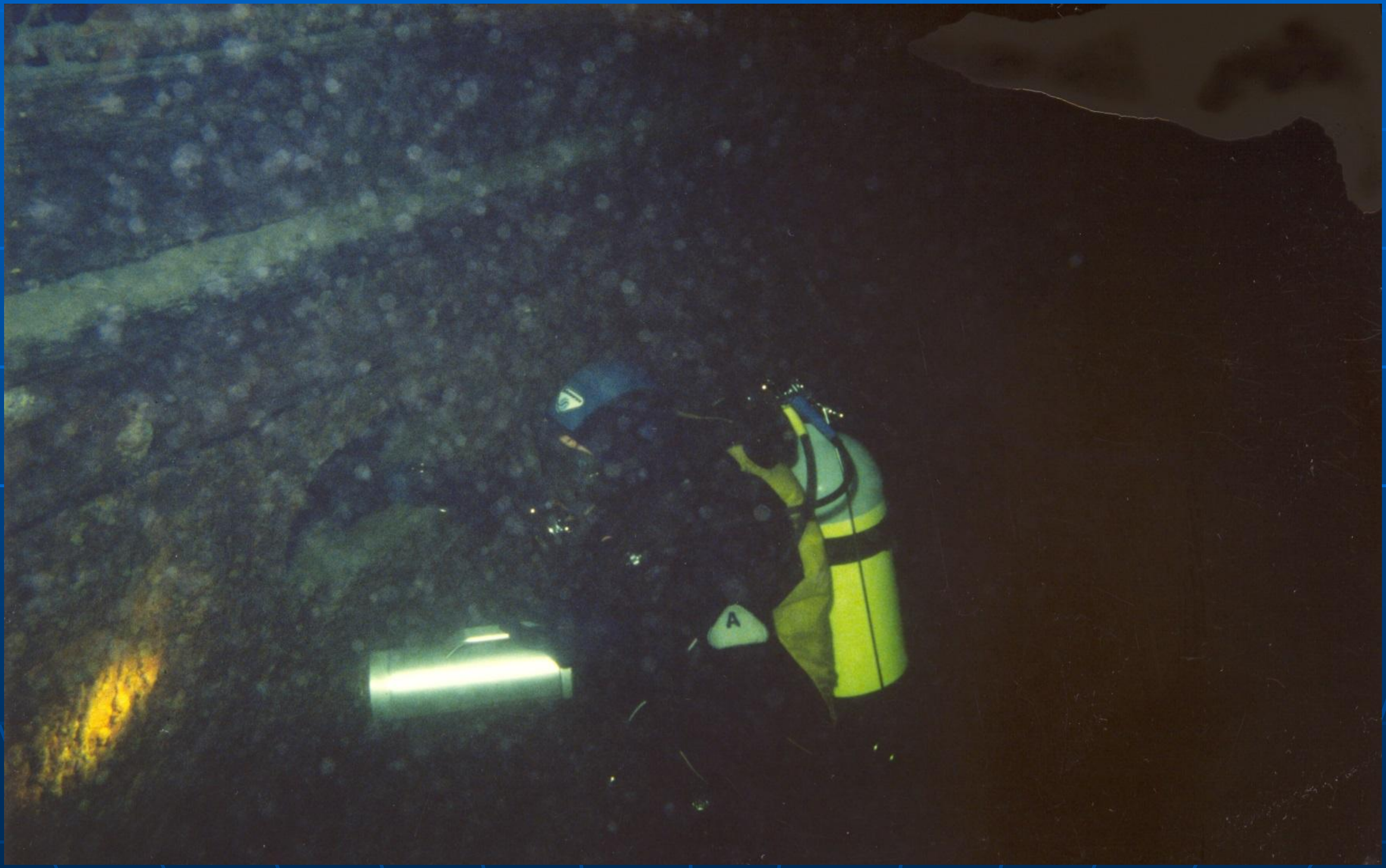
Test Dive: air @ 42 m, 25 min. bottom time

for e.g. the wreck of the „JURA“ / lake of constance



tema con variazioni: TTS …

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Test Dive: air @ 42 m, 25 min. bottom time

TDT = Total Dive Time
TTS = time-to-surface (sum of all stop times + bottom depth / ascent rate)
TEC = Uwatec / Scubapro Aladin TEC 2G, ZH-L 8
ALADIN [2] = Uwatec / Scubapro Aladin Square
DECO 2000: Max Hahn
FwDV 8 = Feuerwehr-Dienstvorschrift 8 Tauchen, per 03/2014 (up to 36 m)
Galileo G2 = Uwatec / Scubapro, HW 1.0, SW 1.2 per 08/2017
MATRIX = Uwatec / Scubapro Aladin Sport, Matrix-Display; ZH-L 16 (09/2016)
Ratio iX3M = Mix gas computer from DiveSystem (IT), Version APOS 3.1.6 from 07/2016
RGBM = printed table from rgbmdiving.com
SAA DeeP = British Subaqua Association, SAA Bühlmann DeeP-Stop System Handbook [187]
Subsurface = Subsurface 4.5.6 2016 / 4.7.4 2017; (subssurface-divelog.org/de/)
USN 2016 = Rev. 7 of the USN Diving Manuals, 01.12.2016
MDv = Marine Dienstvorschrift 450/1 Anlage 6 (equivalent to DRÄGER Table 210, from 1984)
OSTC 3: Testequipment, Softwareversion V 0.9 from 05/2013
ZH-83 & ZH-86: Bühlmann; [4] 1983, p. 66; [65] 2002, p. 225

a-/b-coefficients? HT? air pressure? water density? water temperature?
R_q? Albert Alois correction factor: + 1 m, + 3 %?
Floating Point Precision? Truncations? Math. Libraries?
… ? … ?? … ???

tema con variazioni: TTS …

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Stop depth / method:	24 m	21 m	18 m	15 m	12 m	9 m	6 m	3 m	TTS	Rem.:
FwDV 8									***0***	***Not allowed!***
BSAC 88						1	6	---	10	**26`, ascent 3`**
OSTC 3 v 2.13							1	6	**12**	**ZH-L 16 C, GF 99 / 99**
RGBM				1	2	3	3	7	16	**table**
MDv 450/1							*5*	*15*	*20*	***+ ca. 4,2 !***
IANTD Air					1	4	3	18	**26**	**Table**
ZH-83						3	5	14	**26**	
DIVE 3_3						2	6	16	**28**	**TDT = 52**
Ratio iX3M **APOS 3.1.6**					1	4	5	14	**28**	**TDT = 53,ZH-L16C** **with: GF 93/93**
U.S.N. 2008							26		31	**140 feet**
USN 2016						3	24		33	**140 feet**
ZH-86						4	7	19	**33**	**42 m / 27 min**
DECO 2000					1	4	8	16	33	
DIVE 3_3						4	7	19	**34**	**Bühlmann correction factor, density adapted**
SAA DeeP	27/1`		1		1	1	25	---	34	**ZH-L 16 C**
DCIEM						7	8	17	36	
TEC						3	k.A.	k.A.	36	**L0 (Level Stop)**
ALADIN [2]						2	k.A.	k.A	40	**L0**
Galileo G2						3	7	23	40	**L0**
Hahn DC-12					5	5	9	25	47	**24 min bottom time**
MATRIX						4	16	26	49	**L0**
Subsurface			***2***	***3***	***5***	***6***	***10***	***15***	***52***	***VPM 0***

Basic Limits of Perfusion-Models

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Extrapolations …
… & why linear extrapolations
won‘t work

Yo-Yo dives, Repetitive Dives,
apnea, the „Helium Penalty“ , …
(NPA)

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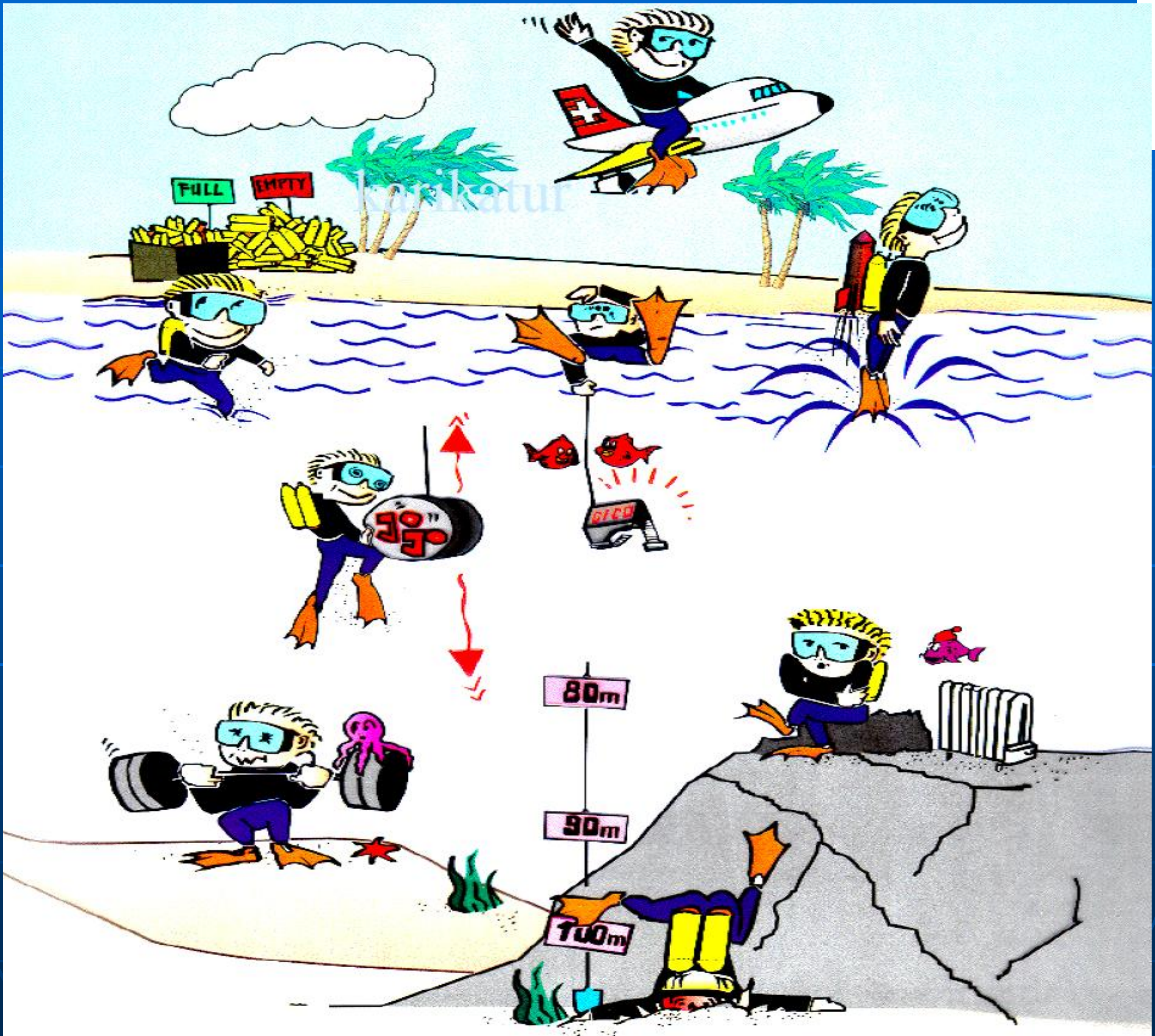

Source: UWATEC

Limits …

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depend if you take a:

→ holistic

or

→ reductionistic

look at DCS

Limits …

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simply „Inertgas-Bookkeeping“, **<u>mono</u>-exponential** per compartment

Inertgas saturation & de-saturation is **symmetrical,** i.e. the time-constants (HT) for both processes are **<u>identical</u>**

All compartments are in a **<u>parallel</u>** circuit, **serial** circuits like spleen → liver or bowel → liver are not considered

<u>Biometrics</u> (age, $VO_{2,\ max}$ (fitness), BMI, …,) and **Adaption** are not considered

high **workload, temperature** and **high pO_2 (i.e.: vasoconstriction & bradycardia)** are only partially considered

<u>High p_{amb}</u> (high gas density) changes: the Ventilation/Perfusion ratio, the dead space, the diffusion path, the difference $p_{alv} – p_{art}$ and a phase transition from **<u>laminar to turbulent</u>** situation, the non-linear **increase of CO_2** production by the respiratory muscles

dynamical change in the capillary bed: the ratio of **<u>„dormant“ vs. „working“</u>** capillaries / alveoli, **shunting** (cardiac / pulmonary), …

the 2nd. **(the n. th) <u>repetitive dive</u>** and thus: **de-hydration, haematocrit, Endothelial Dysfunction, MP, ROS, ci-miRNAs, … , … , … ,**

WARNING: this is not a concluding list!

DON / DCS

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webe mit N_2-Halbwertszeiten von mehr als 4 h ungenügend berücksichtigen.

Mauermayer et al. [50] haben die Verhältnisse beim U-Bahnbau in München 1983–1984 untersuchen können. Dort absolvierten 51 Männer in 131 Arbeitsschichten 2227 Einsätze. Die Dekompressionen erfolgten entsprechend den Vorschriften der Deutschen Druckluftverordnung (DLVO) von 1972. Von den 51 Arbeitern hatten 14 einmal, 12 mehrmals nach dem Ausschleusen Schmerzen. Übergewichtigte Männer zeigten sich besonders empfindlich. Jeweils am Mittwoch ergab sich eine Häufung der Beschwerden, ein Hinweis auf die Kumulation von N_2.

Die Schmerzereignisse traten insbesondere nach Arbeiten mit einem Überdruck von 0,9 bis 1,2 bar und nie nach Expositionen mit

Source: [65], S. 154

„Wenn es zum Fußballspiel geht oder zum Wochenend-Besäufnis wirkt DCS sehr schnell ansteckend!“ (© ALBI)

Quelle: Brit. J. industr. Med., 1957, 14,5: Lewis, H. E. & Paton, W. D. M.: Decompression Sickness during the sinking of a caisson, p. 10

(Original: “It is not infrequent, for instance, that eagerness to go to a football match, or to collect and spend the week’s pay, lead to a severe outbreak of bends“)

DON / DCS

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“ … my contention,
that each cause of bends is simply an act of God –
if one is to believe the victim!“

George F. Bond, in: [130] (TOC)
Siiteri, Helen A. (1993) Papa Topside,
The Sealab Chronicles of Capt. George F. Bond, USN;
download @ Manuals_4_free:
https://www.divetable.eu/130_complete.pdf
or:
Naval Institute Press, Annapolis, Maryland,
ISBN 1-55750-795-3 , p. 252

DON / DCS Type I @ 8.5 m

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„Die Grenzen meiner Daten sind die Grenzen meines Modells! (*)

(*) Ludwig Josef Johann Wittgenstein
(* 26. April 1889 in Wien; † 29. April 1951 in Cambridge):

“Die Grenzen meiner Sprache bedeuten die Grenzen meiner Welt!”

From his famous book: Tractatus logico-philosophicus, Satz 5.6

„Die Grenzen meiner Daten sind die Grenzen meines Modells! (*)

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animals, and human experience, render it possible to calculate. In the case of men of exceptionally heavy build, and inclined to obesity, the time allowed after very prolonged exposures ought to be increased by about a third, although such men, particularly if over about 45 years of age, ought not to expose themselves to the risk of a prolonged stay in very deep water.

p. 368:

[1] Whether the law holds good for pressures much exceeding six atmospheres is still doubtful, as no experimental data exist.

p. 357, footnote:

Source: Boycott AE, Damant GCC, Haldane JS.
The prevention of compressed air illness. J Hyg. 1908; 8: 342–443

„Die Grenzen meiner Daten sind die Grenzen meines Modells! (*)

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HALDANE'S DECOMPRESSION TABLES (AIR ONLY)—*continued*

(See explanation on page 94)

Duration of dive: In ordinary circumstances, the diver should not be allowed to remain on the bottom longer than the time shown immediately above the thick black line drawn from the fourth column to the thirteenth column at each depth.

Depth. Feet.	Depth. Fathoms.	Pressure Pounds per Square Inch	Time under Water, *i.e.*, from Surface to beginning of Ascent.	Stoppages at different Depths in Minutes. 80 ft.	70 ft.	60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	Total Time for Ascent in Minutes.	Number of Cylinders needed.†	Revolutions of Pump per Minute.‡	Number of Men per Shift on Pumps.
			20 to 30 mins.	—	—	—	—	—	—	5	11	18			
			30 to 35 mins.	—	—	—	—	—	—	5	15	22			
			35 to 45 mins.	—	—	—	—	—	2	8	15	27			
			45 to 55 mins.	—	—	—	—	—	5	10	15	32			
90–96 *Contd.*	15–16	40–42½	55 mins. to 1 hr. 12 mins. ..	—	—	—	—	—	5	10	25	42	2	30*	6
			1 hr. 12 mins. to 1½ hrs.	—	—	—	—	—	5	15	30	52			
			1½ hrs. to 1 hr. 54 mins.	—	—	—	—	—	5	25	30	62			
			1 hr. 54 mins to 2 hrs. 18 mins. ..	—	—	—	—	—	10	30	30	72			
			2 hrs. 18 mins. to 2½ hrs. ..	—	—	—	—	—	10	30	35	77			
			2½ hrs. to 2 hrs. 54 mins. ..	—	—	—	—	—	20	30	35	87			
			Over 2 hrs. 54 mins.	—	—	—	—	—	30	35	35	102			
			Up to 5 mins.	—	—	—	—	—	—	—	3	6			
			5 to 10 mins.	—	—	—	—	—	—	—	5	8			
			10 to 15 mins.	—	—	—	—	—	—	3	5	11			
			15 to 20 mins.	—	—	—	—	—	—	4	8	15			
			20 to 25 mins.	—	—	—	—	—	1	5	10	19			
			25 to 30 mins.	—	—	—	—	—	3	7	10	23			
			30 to 35 mins.	—	—	—	—	—	4	8	13	28			
			35 to 40 mins.	—	—	—	—	—	5	10	15	33			
96–108	16–18	42½–48	40 to 50 mins.	—	—	—	—	—	8	10	20	41	4	20	12
			50 mins. to 1 hr.	—	—	—	—	—	10	15	20	48			
			1 hr. to 1 hr. 18 mins.	—	—	—	—	—	10	20	25	58			
			1 hr. 18 mins. to 1 hr. 44 mins. ..	—	—	—	—	—	15	20	35	73			(*see page* 50)
			1 hr. 44 mins. to 2 hrs.	—	—	—	—	5	15	25	35	83			
			2 hrs. to 2 hrs. 18 mins.	—	—	—	—	5	20	30	35	92			
			2 hrs. 18 mins. to 2 hrs. 34 mins.	—	—	—	—	10	25	30	35	102			
			2 hrs. 34 mins. to 2 hrs. 50 mins.	—	—	—	—	15	25	30	40	112			
			Over 2 hrs. 50 mins.	—	—	—	—	15	30	35	40	122			

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* If found difficult to maintain 30 revolutions, another cylinder may be used instead.
† These figures are calculated on the supposition that the pump does not leak more than 20 per cent. at pressures up to 60 lbs. For actual quantities of air required at different depths, see page 38.
‡ *i.e.*, using a Siebe, Gorman two-cylinder double-acting pump.

Quelle: [89] Robert Henry Davis: Deep Diving and Submarine Operations: A Manual for Deep Sea Divers and compressed Air workers, S. 103

Perfusion & Altitude: LEM (linear extrapolation of M-Values)

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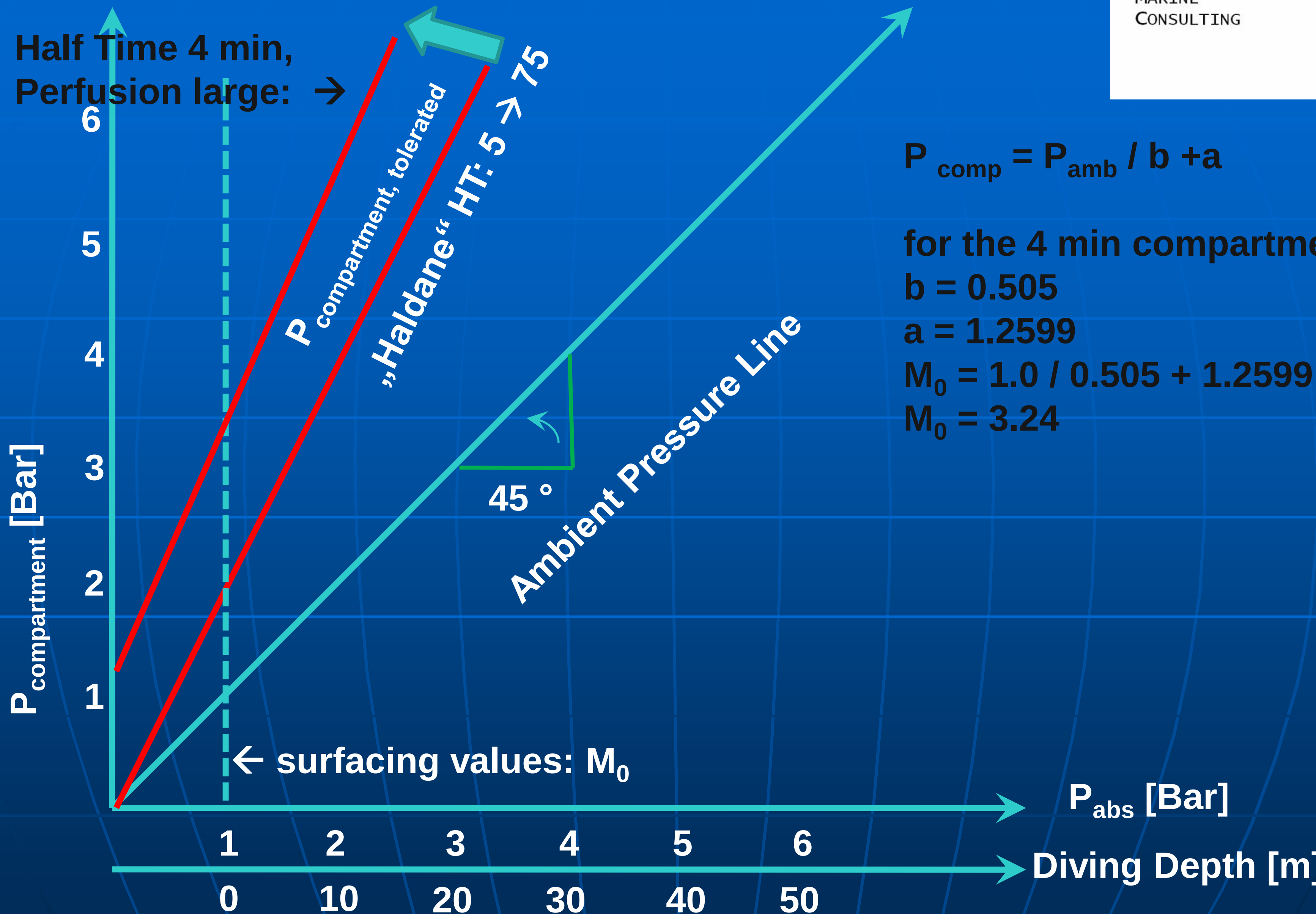

$P_{comp} = P_{amb} / b + a$

for the 4 min compartment:

b = 0.505

a = 1.2599

$M_0 = 1.0 / 0.505 + 1.2599$ =>

$M_0 = 3.24$

„Die Grenzen meiner Daten sind die Grenzen meines Modells! (*)

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Altitude Diving:

→ **LEM**: Linear Extrapolation of M-Values (Bühlmann, Hahn, …)
→ **CRT**: Constant Ratio Translation („Cross“ correction, …)
→ **CRE**: Constant Ratio Extrapolation (Boni, Wienke, …)
→ **NLHE**: Non-Linear Hypobaric Extrapolation (Egi, Gürmen, …)
→ .
→ ..
→ …

and, opinion:

„There is no documentation of the efficacy of this method”
Medical Aspects of Harsh Environments; Vann D., Vorosmarti J., Vol. 2, Chapter 30 , p. 946

WARNING: this is not a concluding list!

Helium Penalty

Grahams Law:
Diffusion rate is proportional to the square root of the molecular weight

the molecular weight of Nitrogen (N_2) is ca. 28,
the molecular weight of Helium (He) ca. 4;
this ratio is 28 / 4 = 7
the square root of 7 is ca. 2,65.

Ergo: HT N_2 / HT He = 2,65 is used for mix gas (Trimix)
BUT: …

Sources:

→ D'Aoust, B.G., K. H. Smith, H.T. Swanson, R. White, L. Stayton, and J. Moore. 1979, Prolonged bubble production by transient isobaric counter-equilibration of helium against nitrogen. Undersea Biomed Res. 6(2): 109 -125

→ Doolette DJ, Upton RN and Grant C. (2005). Perfusion-diffusion compartmental models describe cerebral helium kinetics at high and low cerebral blood flows in sheep. J Physiol. 563: 529–539

→ David J. Doolette , Richard N. Upton , Cliff Grant Journal of Applied Physiology Published 1 March 2015 Vol. 118 no. 5, 586-594. Altering blood flow does not reveal differences between nitrogen and helium kinetics in brain or in skeletal miracle in sheep

Yo-Yo, repetitive dives, apnea, ..

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UHMS 81(DC)6-1-94

THE EFFECTIVENESS OF DIVE COMPUTERS IN REPETITIVE DIVING

Edited by

R.W. Hamilton

Table VIII. 60/No-D: 55 min SI x 4. (J > H). Times allowed for 4 repetitive No-D dives with a 55 min surface interval, during which a diver in repetitive Group J decays to Group H.

No-D Times (min)
[TDT min]

Repet # -->	1	2	3	4	5	P(DCS)
NMRI Prob.	64	13	12	12	11	6.1%
USN Std Air	60	8	8	8	8	5.1%
PADI No-D	55	28	28	28	28	10.2%
PADI No-D, with stop 3 min @ 15 fsw.						9.3%

p. 64, Thalmann

p. 19, Hahn →
„Yo-Yo";
Fish Farming profiles;
...;

The first stems from properties of the underlying differential equation: Monoexponential compartments, describing in- and outflow of dissolved gas only, behave like an electrical low pass filter (resistor + capacitor). That is, yo-yo diving—the equivalent of a high frequency—does not provoke a proper reaction of the slow compartments, whose low tolerances might otherwise stop too many repetitions.

Yo-Yo, rep. Dives, apnea: NPA (Never Properly Adressed …)

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→ Multi-Level (versus box-profiles)
→ Trimix (versus „binary“ mixtures like Air / EAN or Heliox)
→ „endless loop“ in the tables with repetitive dives:
DCIEM: corrective procedure via increase of RF (repetitive factor)!

And, and, and, …

WARNING: this is not a concluding list!

Yo-Yo, rept. dives, apnea, …

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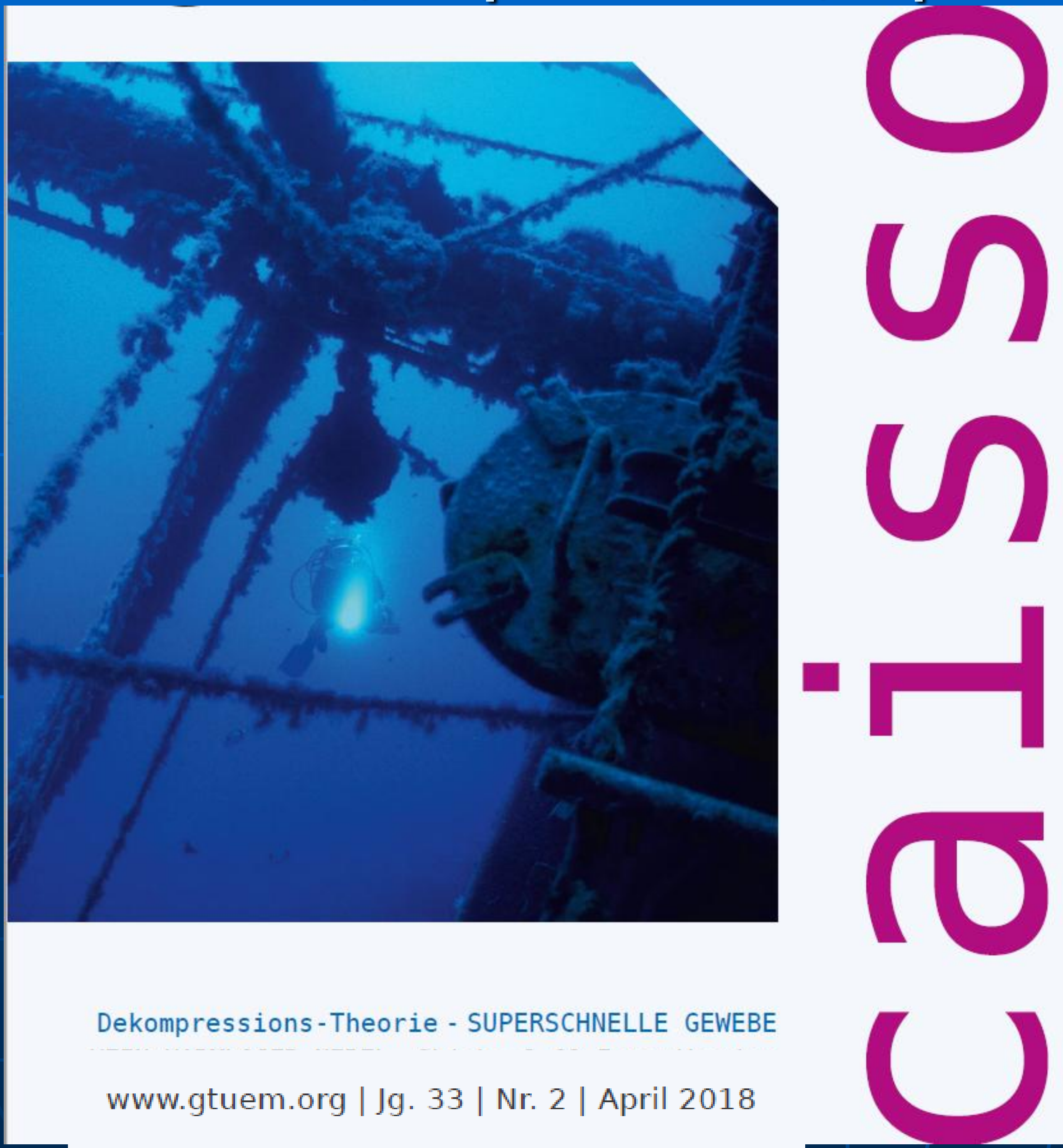

GESELLSCHAFT FÜR TAUCH- UND ÜBERDRUCKMEDIZIN e.V.
G T Ü M

Basis of the empirical adaptions

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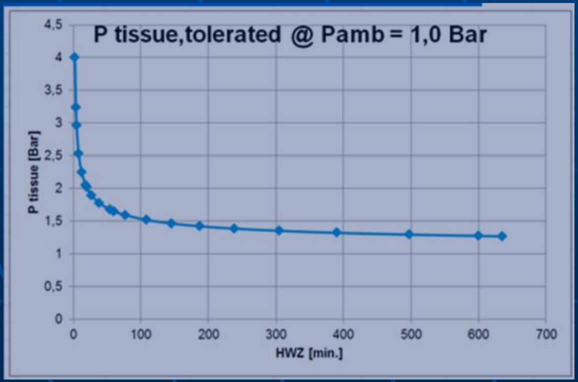
$$P_{t.tol.}ig = P_{amb} / b + a$$

$$a = 2\ \text{Bar} * \tau^{-1/3}$$

$$b = 1.005 - \tau^{-1/2}$$

Source:
[65], p. 117 & 129

$$P_{tissue,tolerated} = (1\ \text{Bar} / (1{,}005 - \tau^{-1/2})) + (2\ \text{Bar} * \tau^{-1/3})$$



Basis of the empirical adaptions

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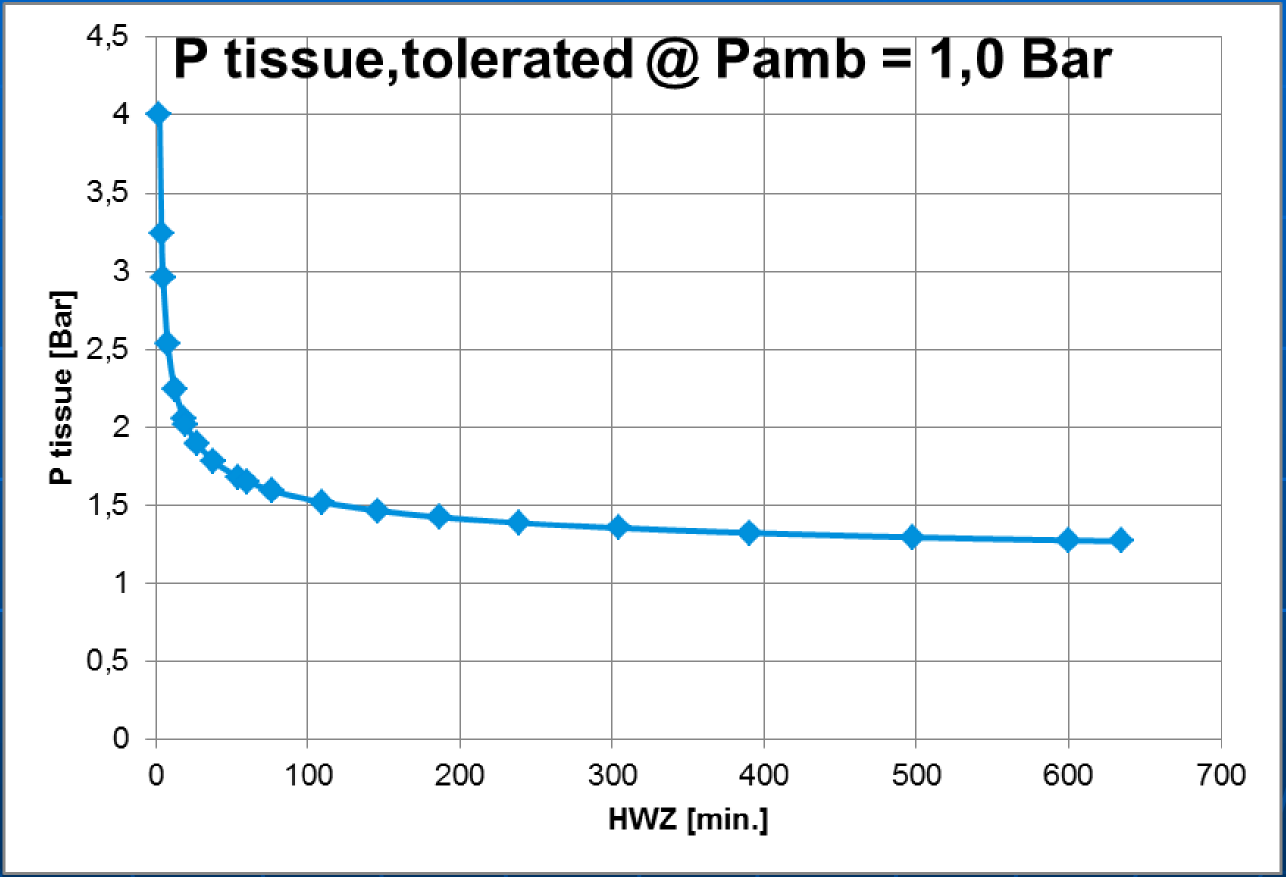
Quellen: ALBI, Manual zum „deco workshop“ 2019, S. 209



$$P_{tissue,tolerated} = (1\ Bar\ /\ (1{,}005 - \tau^{-1/2})) + (2\ Bar * \tau^{-1/3})$$

Basis of the empirical adaptions

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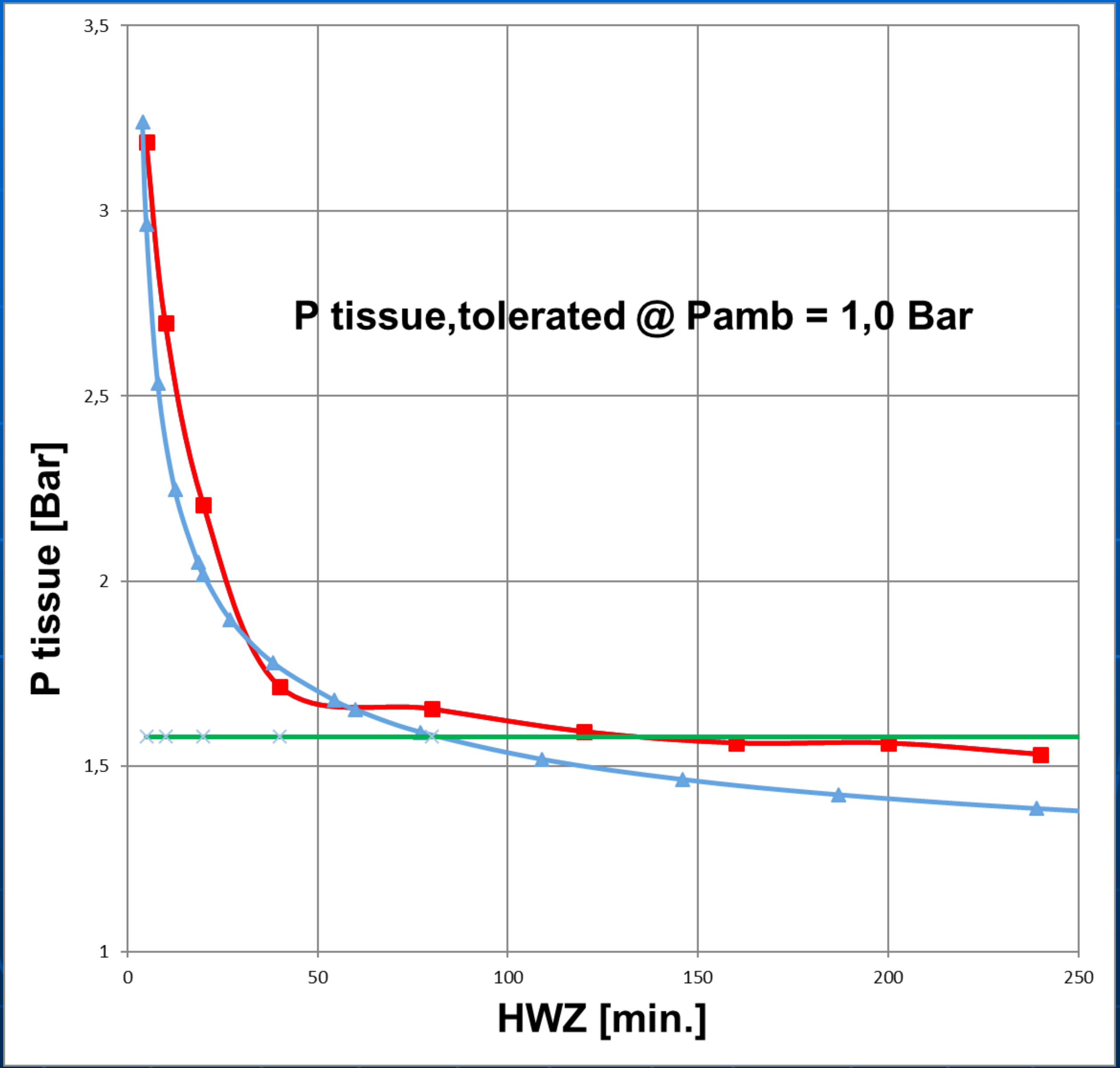
Quellen: ALBI, Manual zum „deco workshop“ 2019, S. 211



Haldane
Workman
Bühlmann

empirical adaptions: temperature, workload, oxygen corrections, deep stops, … *Fuga*

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Temperature:

Halftime (normal) [min]	**40**	**80**	**160**
Perfusion (normal) [l/min]	0,41	0,96	2,47
Halftime (cold) [min]	**59,6**	**97,6**	**166,4**
Perfusion (cold) [l/min]	0,21	0,29	0,17

Quelle:„Accounting for Cold Water Effects in a Decompression Algorithm“, Sergio Angelini in: Lang, M.A. and M.D.J. Sayer (eds.) 2007. Proceedings of the International Polar Diving Workshop. Svalbard, March 15-21, 2007. Smithsonian Institution, Washington, DC. 213 pp. S. 55 – 62

empirical adaptions …

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workload:

HT_work = HT_rest / (1+WF(VO2_work − VO2_rest))

Source: Doolette DJ, Gerth WA, Gault KA. Probabilistic Decompression Models With Work-Induced Changes In Compartment Gas Kinetic Time Constants. Navy Experimental Diving Unit, Panama City, FL, USA; in: UHMS Annual Scientific Meeting, St. Pete Beach, Florida, June 3-5, 2010, Session A6

oxygen corrections:

Reduction in blood flow due to hyper-oxygen vasoconstriction

Inspired oxygen partial pressure (bar)	Blood flow as % of normal
1	94
1.3	93
1.6	91.5
1.9	90
2	89.5
2.2	89
2.5	86.8
3.0	86

Source: Flook, V: Predictions from a mathematical model of decompression compared to Doppler scores. UHM 2011, Vol. 38, No. 3, p. 189

empirical adaptions …

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Cosi fai tutti; deep stops:

→ Method USN for Heliox tables:
fast, sensitive compartment, i.e.: short halftime, low inertgas-tolerance

→ Method Haldane, „Papa Topside“ (George F. Bond), Bühlmann, …
All ☺ :
percentwise decrease of the allowed / tolerated inertgas saturation

… aka: „Gradient Factors“

→ equivalent to method COCHRAN, MARES, SUUNTO, etc.:
Safety Factors = percentwise increase of the calculated inertgas saturation

empirical adaptions …

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Cosi fai tutti: deep stops & USN

Results from the USN / NEDU „deep stop“ study:

- → **NEDU Report**
- → **Source: NEDU TR 11-06 July 2011**
- → **REDISTRIBUTION OF DECOMPRESSION STOP TIME FROM SHALLOW TO DEEP STOPS INCREASES INCIDENCE OF DECOMPRESSION SICKNESS IN AIR DECOMPRESSION DIVES. Navy Experimental Diving Unit, Authors: DAVID J. DOOLETTE, WAYNE A. GERTH, KEITH A. GAULT.**

empirical adaptions …

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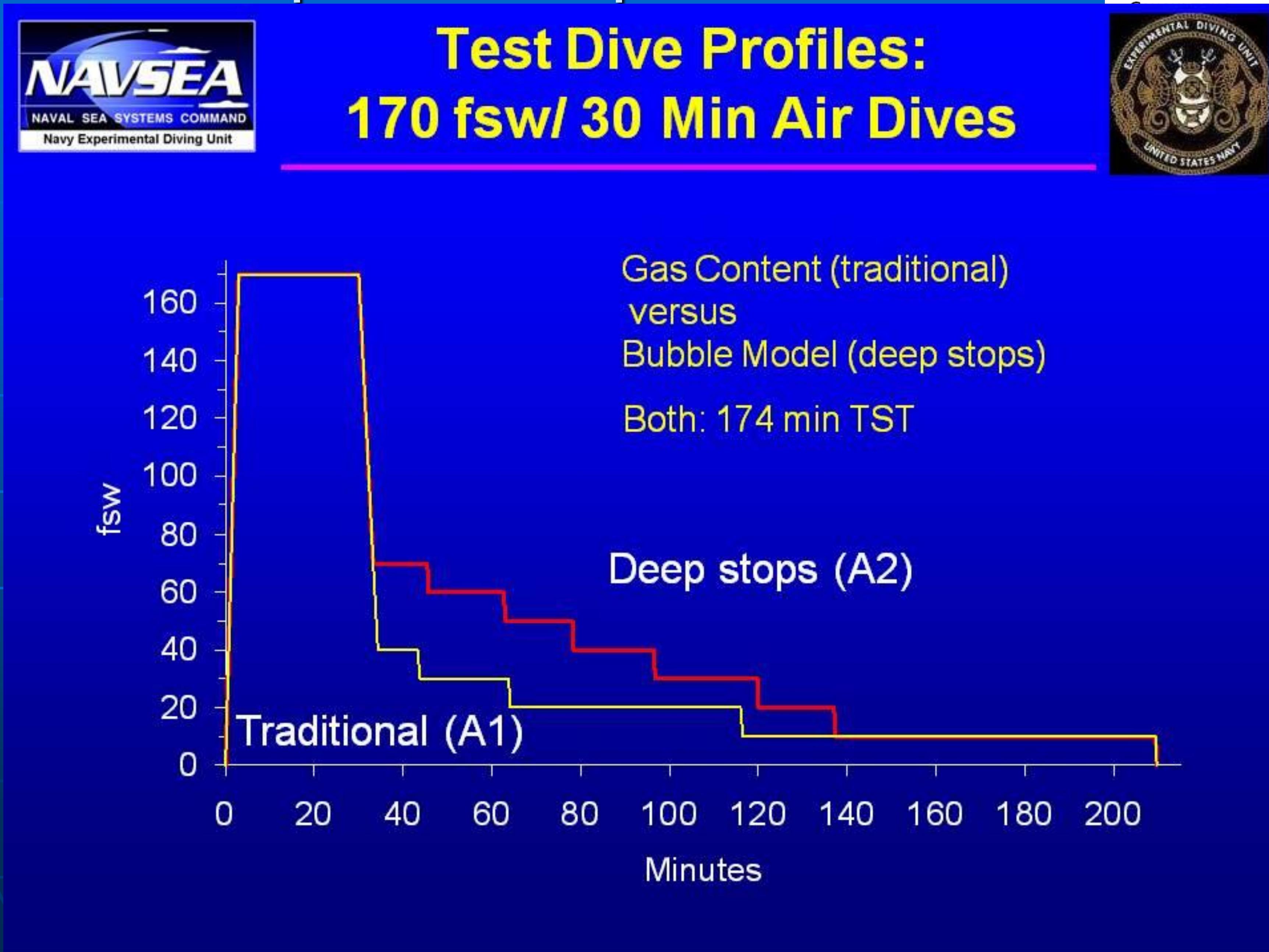

170 feet: ca. 51,8 m

empirical adaptions …

Cosi fai tutti: deep stops & USN

empirical adaptions …

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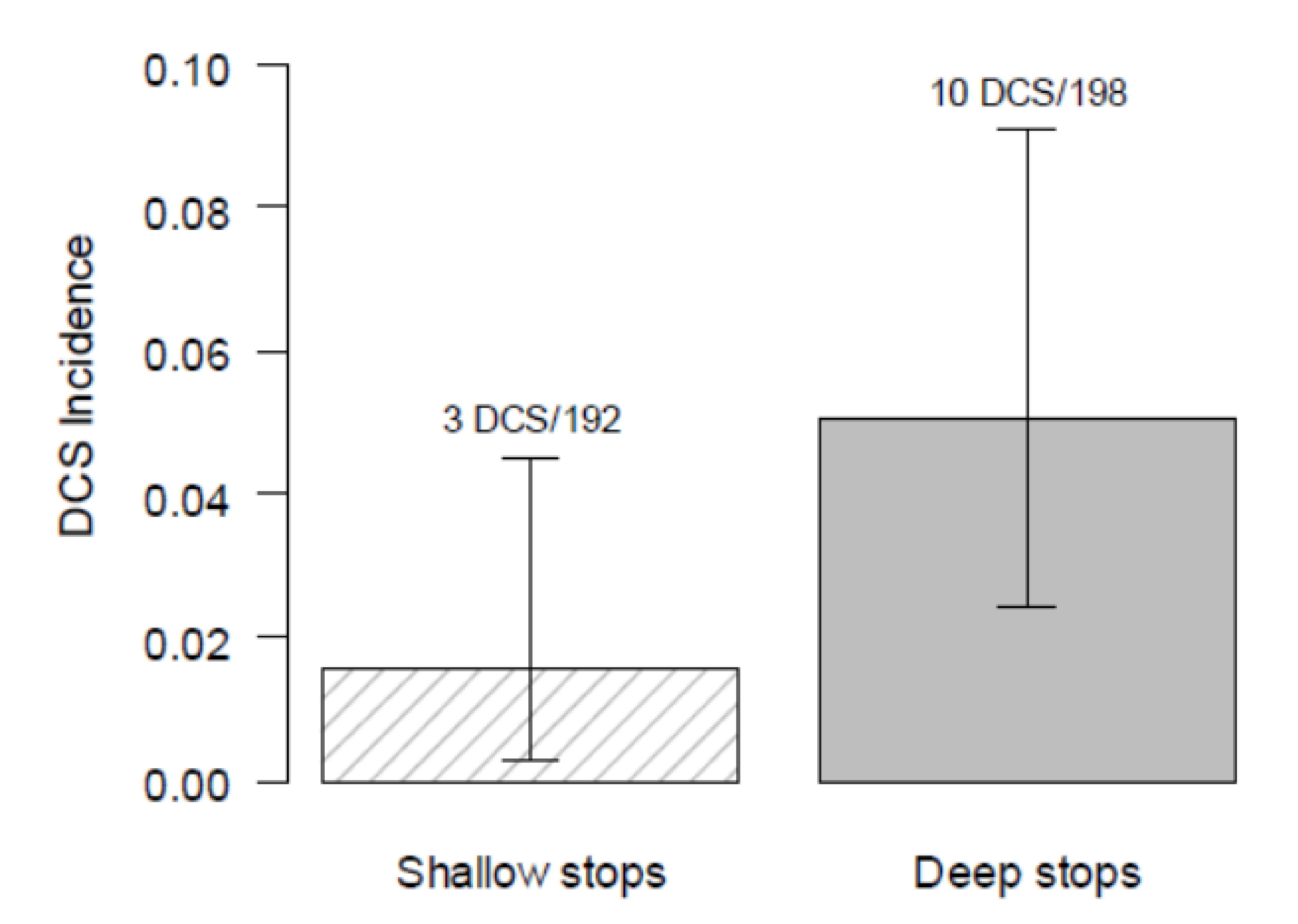
Cosi fai tutti: deep stops & USN



empirical adaptions …

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Cosi fai tutti: deep stops & USN

CONCLUSIONS

The practical conclusion of this study is that controlling bubble formation in fast compartments with deep stops is unwarranted for air decompression dives.

empirical adaptions …

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Cosi fai tutti: deep stops & USN

empirical adaptions …

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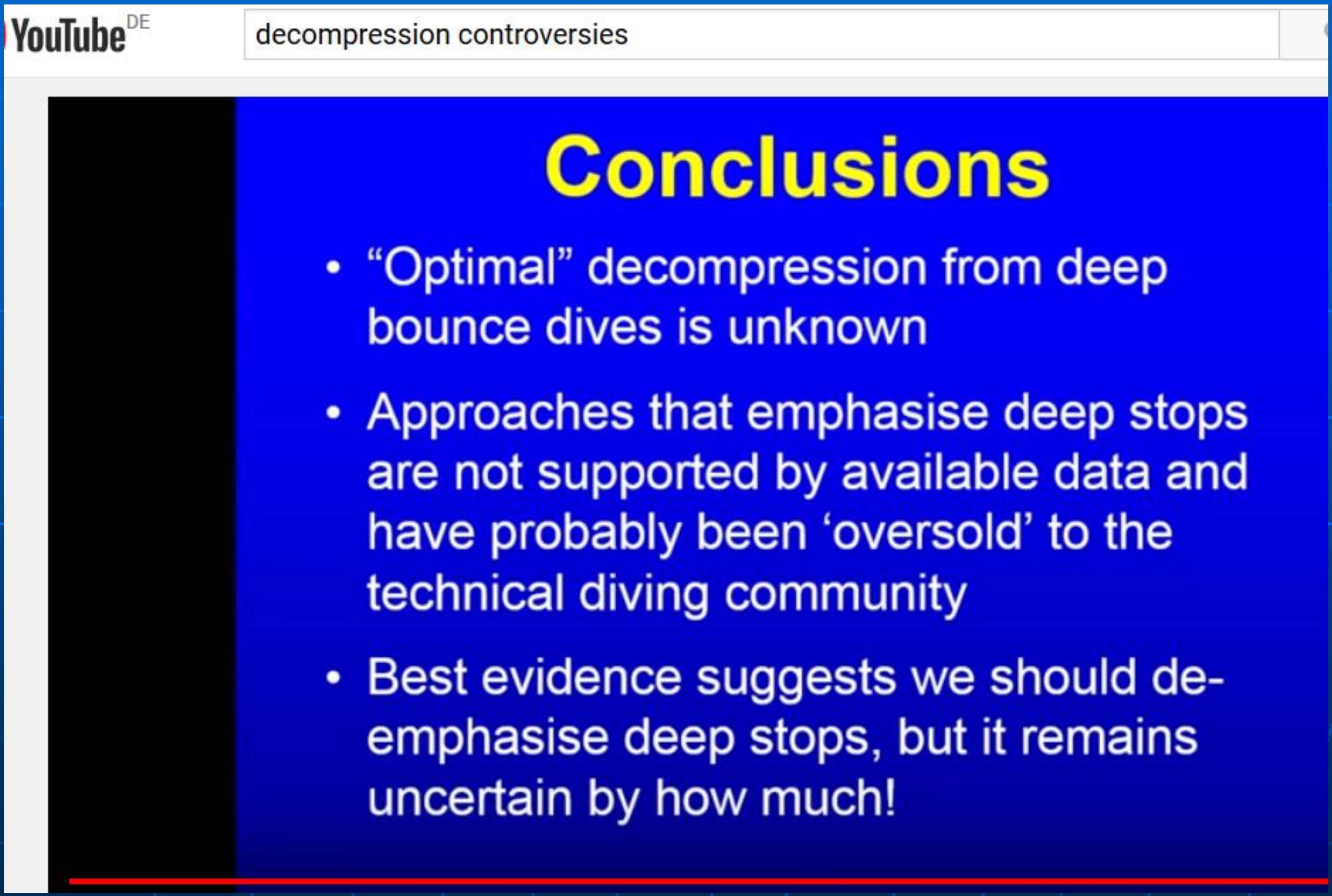
Cosi fai tutti: deep stops & USN



How was the RDP® created?

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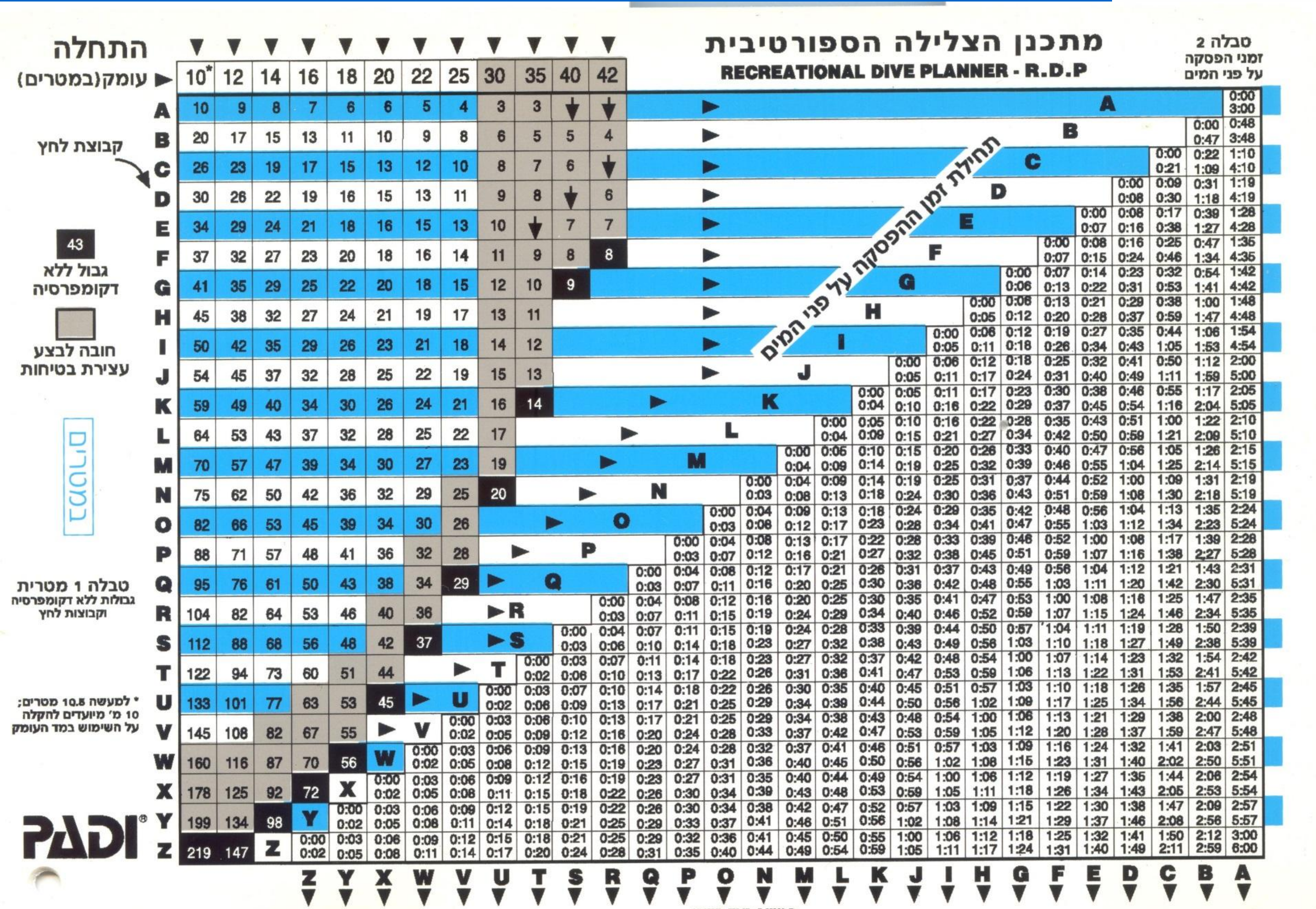

מתכנן הצלילה הספורטיבית

RECREATIONAL DIVE PLANNER - R.D.P

טבלה 1 מטרית
גבולות ללא דקומפרסיה
וקבוצות לחץ

התחלה

קבוצת לחץ / עומק(במטרים) ►	10*	12	14	16	18	20	22	25	30	35	40	42
A	10	9	8	7	6	6	5	4	3	3	↓	↓
B	20	17	15	13	11	10	9	8	6	5	5	4
C	26	23	19	17	15	13	12	10	8	7	6	↓
D	30	26	22	19	16	15	13	11	9	8	↓	6
E	34	29	24	21	18	16	15	13	10	↓	7	7
F	37	32	27	23	20	18	16	14	11	9	8	8
G	41	35	29	25	22	20	18	15	12	10	9	
H	45	38	32	27	24	21	19	17	13	11		
I	50	42	35	29	26	23	21	18	14	12		
J	54	45	37	32	28	25	22	19	15	13		
K	59	49	40	34	30	26	24	21	16	14		
L	64	53	43	37	32	28	25	22	17			
M	70	57	47	39	34	30	27	23	19			
N	75	62	50	42	36	32	29	25	20			
O	82	66	53	45	39	34	30	26				
P	88	71	57	48	41	36	32	28				
Q	95	76	61	50	43	38	34	29				
R	104	82	64	53	46	40	36					
S	112	88	68	56	48	42	37					
T	122	94	73	60	51	44						
U	133	101	77	63	53	45						
V	145	108	82	67	55							
W	160	116	87	70	56							
X	178	125	92	72								
Y	199	134	98									
Z	219	147										

43 גבול ללא דקומפרסיה

חובה לבצע עצירת בטיחות

* למעשה 10.8 מטרים; 10 מ' מיועדים להקלה על השימוש במד העומק

טבלה 2
זמני הפסקה
על פני המים

תחילת זמן ההפסקה על פני המים

	Z	Y	X	W	V	U	T	S	R	Q	P	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
A																										0:00 3:00
B																									0:00 0:47	0:48 3:48
C																								0:00 0:21	0:22 1:09	1:10 4:10
D																							0:00 0:08	0:09 0:30	0:31 1:18	1:19 4:19
E																						0:00 0:07	0:08 0:16	0:17 0:38	0:39 1:27	1:28 4:28
F																					0:00 0:07	0:08 0:15	0:16 0:24	0:25 0:46	0:47 1:34	1:35 4:35
G																				0:00 0:06	0:07 0:13	0:14 0:22	0:23 0:31	0:32 0:53	0:54 1:41	1:42 4:42
H																			0:00 0:05	0:06 0:12	0:13 0:20	0:21 0:28	0:29 0:37	0:38 0:59	1:00 1:47	1:48 4:48
I																		0:00 0:05	0:06 0:11	0:12 0:18	0:19 0:26	0:27 0:34	0:35 0:43	0:44 1:05	1:06 1:53	1:54 4:54
J																	0:00 0:05	0:06 0:11	0:12 0:17	0:18 0:24	0:25 0:31	0:32 0:40	0:41 0:49	0:50 1:11	1:12 1:59	2:00 5:00
K																0:00 0:04	0:05 0:10	0:11 0:16	0:17 0:22	0:23 0:29	0:30 0:37	0:38 0:45	0:46 0:54	0:55 1:16	1:17 2:04	2:05 5:05
L															0:00 0:04	0:05 0:09	0:10 0:15	0:16 0:21	0:22 0:27	0:28 0:34	0:35 0:42	0:43 0:50	0:51 0:59	1:00 1:21	1:22 2:09	2:10 5:10
M														0:00 0:04	0:05 0:09	0:10 0:14	0:15 0:19	0:20 0:25	0:26 0:32	0:33 0:39	0:40 0:46	0:47 0:55	0:56 1:04	1:05 1:25	1:26 2:14	2:15 5:15
N													0:00 0:03	0:04 0:08	0:09 0:13	0:14 0:18	0:19 0:24	0:25 0:30	0:31 0:36	0:37 0:43	0:44 0:51	0:52 0:59	1:00 1:08	1:09 1:30	1:31 2:18	2:19 5:19
O												0:00 0:03	0:04 0:08	0:09 0:12	0:13 0:17	0:18 0:23	0:24 0:28	0:29 0:34	0:35 0:41	0:42 0:47	0:48 0:55	0:56 1:03	1:04 1:12	1:13 1:34	1:35 2:23	2:24 5:24
P											0:00 0:03	0:04 0:07	0:08 0:12	0:13 0:16	0:17 0:21	0:22 0:27	0:28 0:32	0:33 0:38	0:39 0:45	0:46 0:51	0:52 0:59	1:00 1:07	1:08 1:16	1:17 1:38	1:39 2:27	2:28 5:28
Q										0:00 0:03	0:04 0:07	0:08 0:11	0:12 0:16	0:17 0:20	0:21 0:25	0:26 0:30	0:31 0:36	0:37 0:42	0:43 0:48	0:49 0:55	0:56 1:03	1:04 1:11	1:12 1:20	1:21 1:42	1:43 2:30	2:31 5:31
R									0:00 0:03	0:04 0:07	0:08 0:11	0:12 0:15	0:16 0:19	0:20 0:24	0:25 0:29	0:30 0:34	0:35 0:40	0:41 0:46	0:47 0:52	0:53 0:59	1:00 1:07	1:08 1:15	1:16 1:24	1:25 1:46	1:47 2:34	2:35 5:35
S								0:00 0:03	0:04 0:06	0:07 0:10	0:11 0:14	0:15 0:18	0:19 0:23	0:24 0:27	0:28 0:32	0:33 0:38	0:39 0:43	0:44 0:49	0:50 0:56	0:57 1:03	1:04 1:10	1:11 1:18	1:19 1:27	1:28 1:49	1:50 2:38	2:39 5:39
T							0:00 0:02	0:03 0:06	0:07 0:10	0:11 0:13	0:14 0:17	0:18 0:22	0:23 0:26	0:27 0:31	0:32 0:36	0:37 0:41	0:42 0:47	0:48 0:53	0:54 0:59	1:00 1:06	1:07 1:13	1:14 1:22	1:23 1:31	1:32 1:53	1:54 2:41	2:42 5:42
U						0:00 0:02	0:03 0:06	0:07 0:09	0:10 0:13	0:14 0:17	0:18 0:21	0:22 0:25	0:26 0:29	0:30 0:34	0:35 0:39	0:40 0:44	0:45 0:50	0:51 0:56	0:57 1:02	1:03 1:09	1:10 1:17	1:18 1:25	1:26 1:34	1:35 1:56	1:57 2:44	2:45 5:45
V					0:00 0:02	0:03 0:05	0:06 0:09	0:10 0:12	0:13 0:16	0:17 0:20	0:21 0:24	0:25 0:28	0:29 0:33	0:34 0:37	0:38 0:42	0:43 0:47	0:48 0:53	0:54 0:59	1:00 1:05	1:06 1:12	1:13 1:20	1:21 1:28	1:29 1:37	1:38 1:59	2:00 2:47	2:48 5:48
W				0:00 0:02	0:03 0:05	0:06 0:08	0:09 0:12	0:13 0:15	0:16 0:19	0:20 0:23	0:24 0:27	0:28 0:31	0:32 0:36	0:37 0:40	0:41 0:45	0:46 0:50	0:51 0:56	0:57 1:02	1:03 1:08	1:09 1:15	1:16 1:23	1:24 1:31	1:32 1:40	1:41 2:02	2:03 2:50	2:51 5:51
X			0:00 0:02	0:03 0:05	0:06 0:08	0:09 0:11	0:12 0:15	0:16 0:18	0:19 0:22	0:23 0:26	0:27 0:30	0:31 0:34	0:35 0:39	0:40 0:43	0:44 0:48	0:49 0:53	0:54 0:59	1:00 1:05	1:06 1:11	1:12 1:18	1:19 1:26	1:27 1:34	1:35 1:43	1:44 2:05	2:06 2:53	2:54 5:54
Y		0:00 0:02	0:03 0:05	0:06 0:08	0:09 0:11	0:12 0:14	0:15 0:18	0:19 0:21	0:22 0:25	0:26 0:29	0:30 0:33	0:34 0:37	0:38 0:41	0:42 0:46	0:47 0:51	0:52 0:56	0:57 1:02	1:03 1:08	1:09 1:14	1:15 1:21	1:22 1:29	1:30 1:37	1:38 1:46	1:47 2:08	2:09 2:56	2:57 5:57
Z	0:00 0:02	0:03 0:05	0:06 0:08	0:09 0:11	0:12 0:14	0:15 0:17	0:18 0:20	0:21 0:24	0:25 0:28	0:29 0:31	0:32 0:35	0:36 0:40	0:41 0:44	0:45 0:49	0:50 0:54	0:55 0:59	1:00 1:05	1:06 1:11	1:12 1:17	1:18 1:24	1:25 1:31	1:32 1:40	1:41 1:49	1:50 2:11	2:12 2:59	3:00 6:00

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RDP®: Reduction of NDL / M_0

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Table II. Comparison of no-stop times. Dive depth shown at left, with maximum allowable times by the USN, British Navy, and RDP.

Depth	US Navy	British Navy	RDP
30	None	232	---
40	200	137	140
50	100	72	80
60	60	46	55
70	50	38	40
80	40	27	30
90	30	23	25
100	25	18	20
110	20	16	17
120	15	12	14
130	10	11	12

Table III. RDP M-values. Compartment half times are at left, with the ultimate RDP values based on timed descent, the values using a square descent, and those given in Powell et al, 1988 (sometimes called the Blue Book).

Ht	RDP	Square	Blue Book
5	99.08	103.1	102.9
10	82.63	84.2	84.1
20	66.89	67.3	67.2
30	59.74	59.9	59.8
40	55.73	55.8	55.7
60	51.44	51.5	51.4
80	49.21	49.2	49.1
100	47.85	47.9	
120	46.93	46.9	46.9
160	45.78	45.8	
200	45.07	45.1	
240	44.60	44.6	
360	43.81	43.8	
480	43.40	43.4	

Source: [3], download @ Manuals_4_free:
The DSAT Recreational Dive Planner: Development and validation of no-stop decompression procedures for recreational diving, Hamilton, Rogers, Powell, Vann, 28 Februar 1994, p. 20 & 21

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Reduction of U.S.N. NoDecompressionLimits →
implies reduction of M_0

Data base:
n = 911, single square & multilevel
n = 475, repetitive square
(thereof 51 with 6 per day)

Result:

common practices of recreational divers. Even so, based on this evidence and the suggestions of other experts, we recommend limiting the number of full-time dives per day to 3 or at most 4, and suggest including a day with a reduced level of diving (or none) every 2 or 3 days.

Source: [3], abstract, p.1

Coda: "executive editing, typoos & undocumented features"

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→ „The final tables contain a variety of executive edits to algorithmically-computed entries."
(Source: NEDU TR 09-05 / TA-8-20, p. 1 & 5)

→ "Did Haldane really use his "2:1"?
(Source: Tech Diving Mag, Issue 25 / 2016, p. 13 – 20)

→ tissue tensions. Professor Bühlmann (personal communication), for example, extends the half-times of selected tissues to take into account nocturnal reduction in the rate of perfusion in decompressing subjects. Dr. Workman (personal communication) employs arbitrarily increased alveolar inert gas partial pressures in calculating decompression schedules, to cope with the problem of vasoconstriction caused by the breathing of O_2 at high partial pressures.

(Source: Proc. of the 4th Symposium on Underwater Physiology, p. 215)

VPM seems to simulate strange bubbles …

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The Bristol stool form scale

Type 1		Separate hard lumps, like nuts (hard to pass)	*Maintain MOVICOL dose*
Type 2		Sausage-shaped but lumpy	*Maintain MOVICOL dose*
Type 3		Like a sausage but with cracks on its surface	✓
Type 4		Like a sausage or snake, smooth and soft	✓
Type 5		Soft blobs with clear-cut edges (passed easily)	*Decrease MOVICOL dose*
Type 6		Fluffy pieces with ragged edges, a mushy stool	*Decrease MOVICOL dose*
Type 7		Watery, no solid pieces ENTIRELY LIQUID	*Decrease MOVICOL dose*

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Dr KW Heaton, Reader in Medicine at the University of Bristol

Idea:
Dr. Simon Mitchell
Department of Anesthesiology
Auckland City Hospital
@ 2008 DAN TEC Conference [100]
Download @ Manuakls_4_free:
https://www.divetable.eu/100.pdf

Bonus Material:
VPM seems to simulate strange bubbles

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VPM is the „Varying Permability Model“
Sources:

and
D.E. Yount,
D.C. Hoffman: On the Use of a Bubble Formation Model to Calculate Diving Tables. Aviation, Space, and Environmental Medicine, February, 1986, 57: 149 – 156

ON THE USE OF A GAS-CAVITATION MODEL TO GENERATE PROTOTYPAL
AIR AND HELIUM DECOMPRESSION SCHEDULES FOR DIVERS

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN PHYSICS

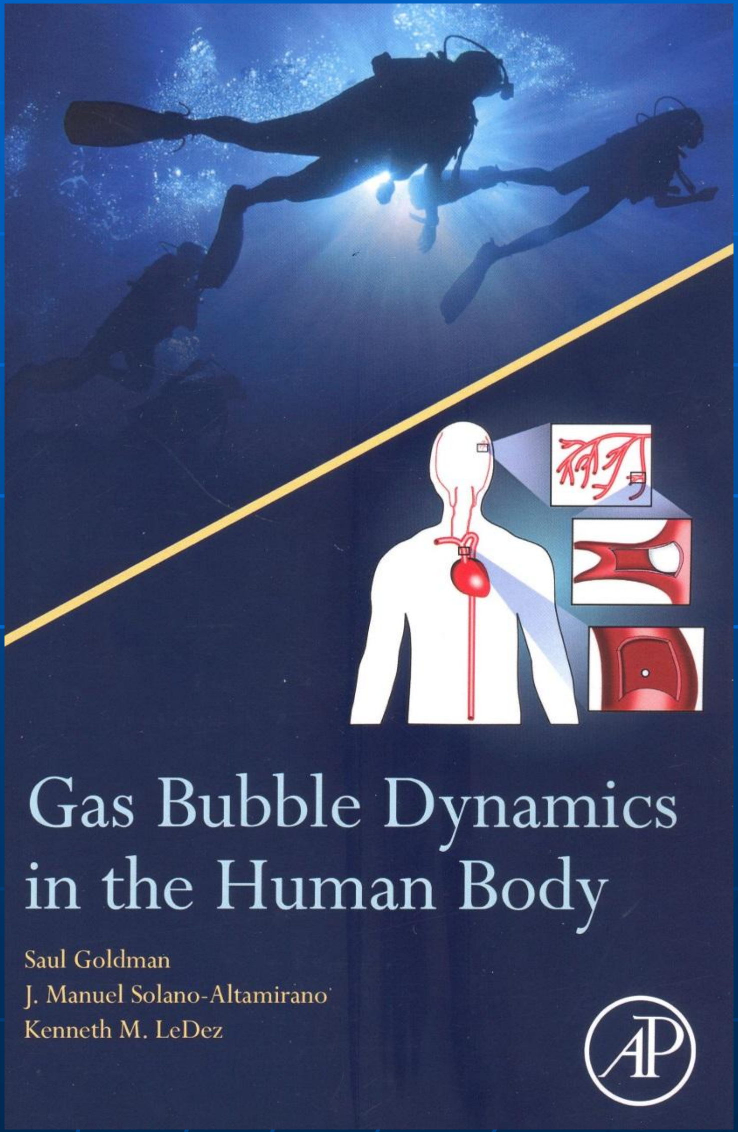
AUGUST 1985

By

Donald Clinton Hoffman

Bonus Material: VPM seems to simulate strange bubbles …

Goldman, Saul;
Solano-Altamiro, J. Manuel;
LeDez, Kenneth M (2018)
Gas Bubble Dynamics in the Human Body,
AP Elsevier, ISBN 978-0-12-810519-1
[199]



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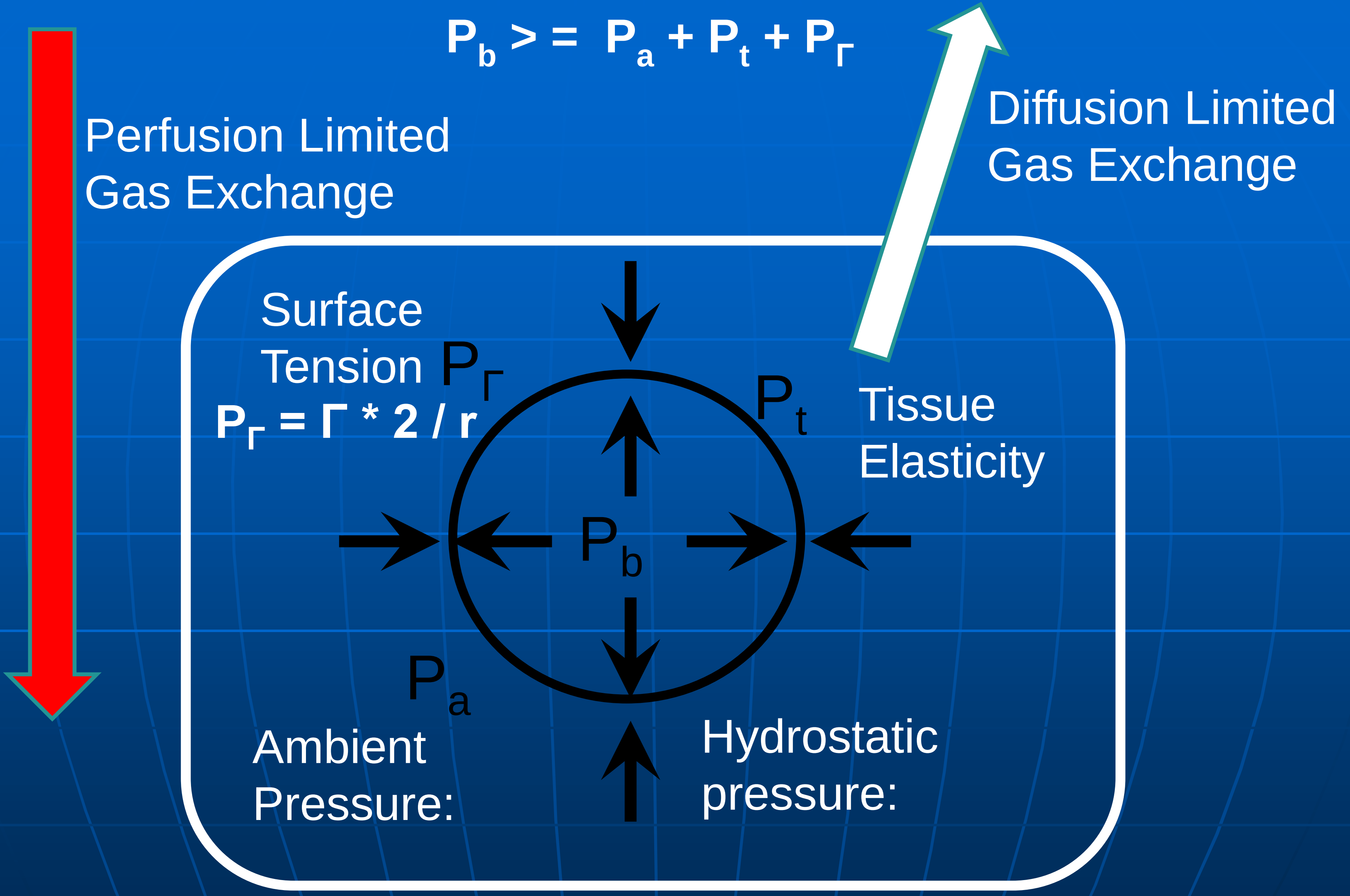
VPM in a nutshell:

- 5 Parameters, via best fit with established tables:

→ USN (United States Navy)
→ RNPL (Royal Navy Physiological Laboratory)
→ Tektite, saturation dives @ 110 feet, Carribean, 1971, with ca. 21 h decompression

- Test-Bubble, min. initial radius $r_{0\ min}$ ca. 0,8 µm
- Surface Tension: Γ = 17,9 dyn/cm
- Skin Compression: Γ_c = 257 dyn/cm
- Regeneration Time constant: 20160 min
- Composite Parameter λ = 7500 fsw x min
- (Onset of impermeability: p* = ca. 9.2 ata)

$$P_b >= P_a + P_t + P_\Gamma$$



$$P_b = P_{H2O} + P_{N2} + P_{O2} + P_{CO2} + P_{He}$$

The „real“ physics:

only the partial pressures of the gases:

$$P_b = P_{H2O} + P_{N2} + P_{O2} + P_{CO2} + P_{He}$$

only the basic pressure components:

$$P_b >= P_a + P_t + P_\Gamma$$

with:

$$P_a = P_{hydrostatic} + P_{dynamic/blood}$$
$$P_t = H * V$$
$$P_\Gamma = \Gamma * 2 / r$$

R : radius of the bubble
V : volume of bubble (= displaced tissue)
H : tensor of bulk modulus for tissue elasticity

Γ : surface tension constant

The critical radius r_c

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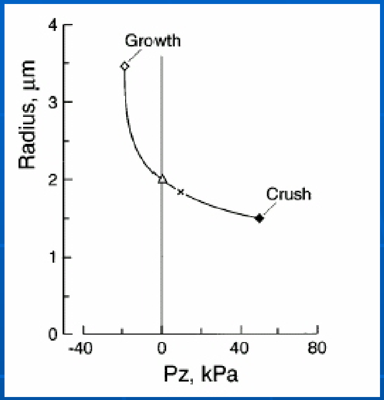

Metastable state, bubble either:
→ crushes
→ expands

$$P_b = P_a + P_t + P_\Gamma$$

$P_t = 0$, thus:

$$P_b = P_a + P_\Gamma = P_a + \Gamma * 2 / r$$

$$r_c = \Gamma * 2 / (P_b - P_a) = \Gamma * 2 / P_{SS}$$

Supersaturation $P_{SS} = P_b - P_a$

The critical radius r_c

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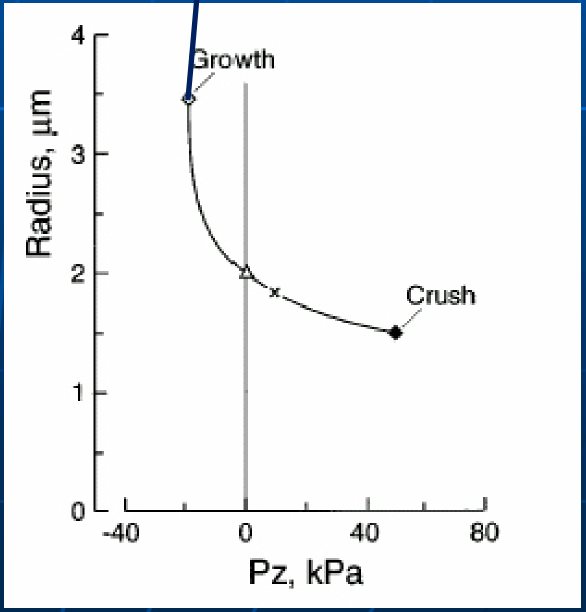
But that‘s only (linear) theory!!!

In reality:
2nd stable point („saddle“)
around 70 → 120 µm!
(due to ~ $r^4_c + r^3_c + r^2_c + \ldots.$)

[Monte Carlo Simulation
yields the same …]

[[notwithstanding that „the
real DCS-bubble“ is
not spherical in shape …]]



The critical radius r_c

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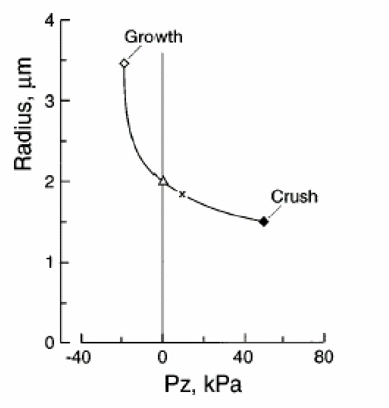

practical
Application of Murphy's Law:

Linear Models
produce simple, beautiful
and easy to understand

wrong answers ....

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Bühlmann Symposium 29./30. März 2019
Universitätsspital Zürich

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DeCompression Models: DeMystifieD

Albrecht Salm
Dipl. Phys.
PADI MSDT # 33913
SSI TXR # 12653

Q & A ?
Contact: