Bühlmann Symposium 29./30. März 2019
Universitätsspital Zürich

The
Sub
Marine
Consulting
Group

Tel Aviv – San Francisco – Stuttgart

www.SMC-de.com

History and Development of Decompression Algorithms

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

History and Development of Decompression Algorithms

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Agenda:

→ Haldane & beyond

- What did he do?
- How did he do it?
- And what the hell did his son Jack (age 13)?

→ The landscape: „ …my model is better than yours!“

- Perfusion, Diffusion, Dual Phase, Hybrid-Models, …
- Parallel versus Serial Models
- Deterministic versus Statistic Models
- Prominent representatives of the others and working examples

→ Bonus Material:

- Exotic Models & strange Implementations
- DCS as a „CUSP“ catastrophe?

History and Development of Decompression Algorithms

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Henry L. Stimson, 1948:

„History is often
not what actually happened
but what is recorded as such.“

Haldane & beyond:

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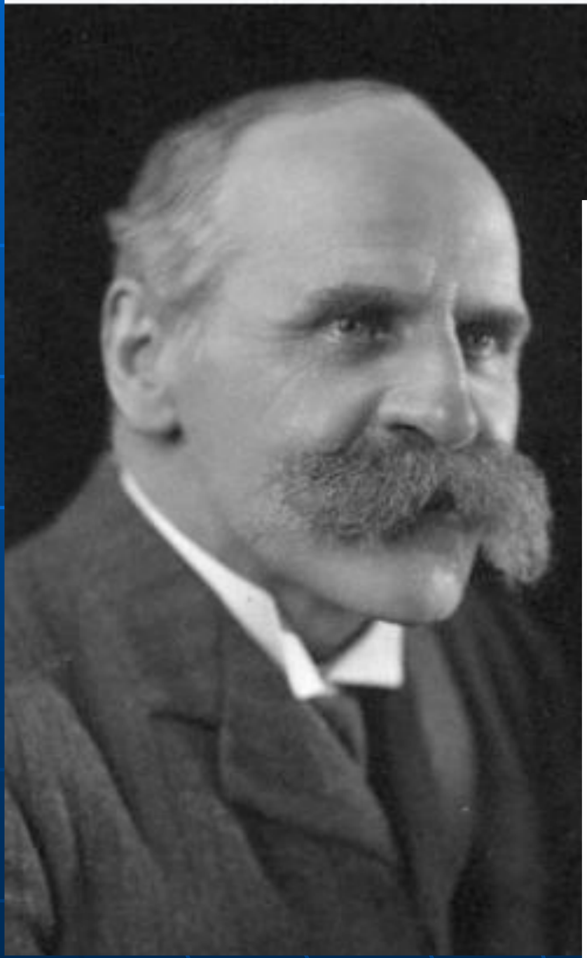
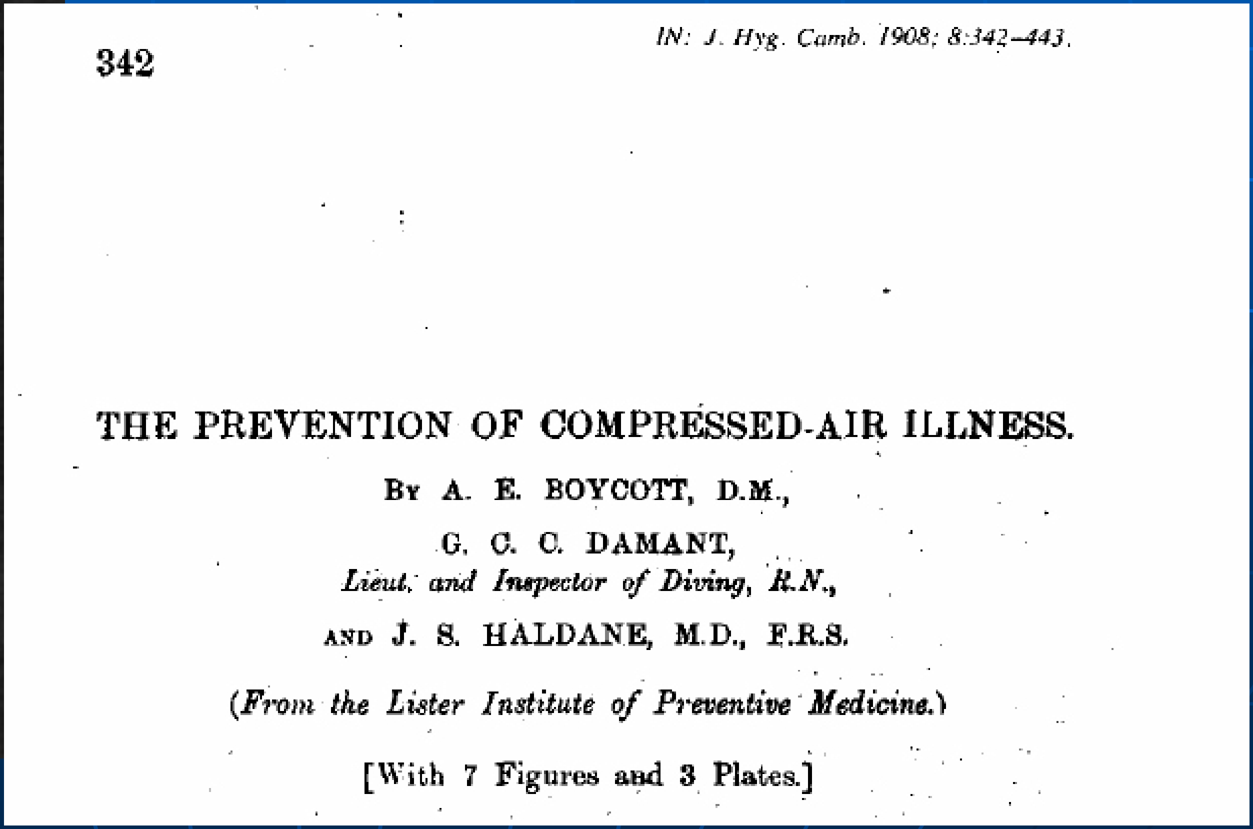
→ What did he do?
→ How did he do it?
→ And what the hell did his son Jack (age 13)?

John Scott Haldane
FRS





IN: J. Hyg. Camb. 1908; 8:342–443.

342

THE PREVENTION OF COMPRESSED-AIR ILLNESS.

BY A. E. BOYCOTT, D.M.,
G. C. C. DAMANT,
Lieut. and Inspector of Diving, R.N.,
AND J. S. HALDANE, M.D., F.R.S.

(From the Lister Institute of Preventive Medicine.)

[With 7 Figures and 3 Plates.]

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Haldanes „2:1“

<u>Fundamental Postulations:</u>

→ The human body (*) consists of 5 model-tissues, aka „<u>compartments</u>“
→ these compartments are connected in a <u>parallel</u> manner
→ the uptake & release of inert gas follows an <u>exponential</u> law
→ the characteristic exponent is a <u>half-time</u> (HT)
→ here the 5 HTs are: <u>5, 10, 20, 40, 75 min</u>
(basically, the HT is the inverse of the perfusion)
→ The uptake & release is <u>symmetrical</u> (same exponent)
→ each compartment tolerates a certain <u>super-saturation</u> with inert gas
→ this super-saturation is <u>approx. 2 * the ambient pressure:</u>
→ ergo: <u>„2:1“</u> which is valid only for:
→ „<u>uneventful“ decompression</u> (i.e. without any inert gas bubbles)

(*) we skip:
→ the allometric scaling from goat to humans …
→ $fN_2 = 1.0$;
→ TTS < 30 min, ambient pressure < 6 atm, …

Haldanes „2:1“

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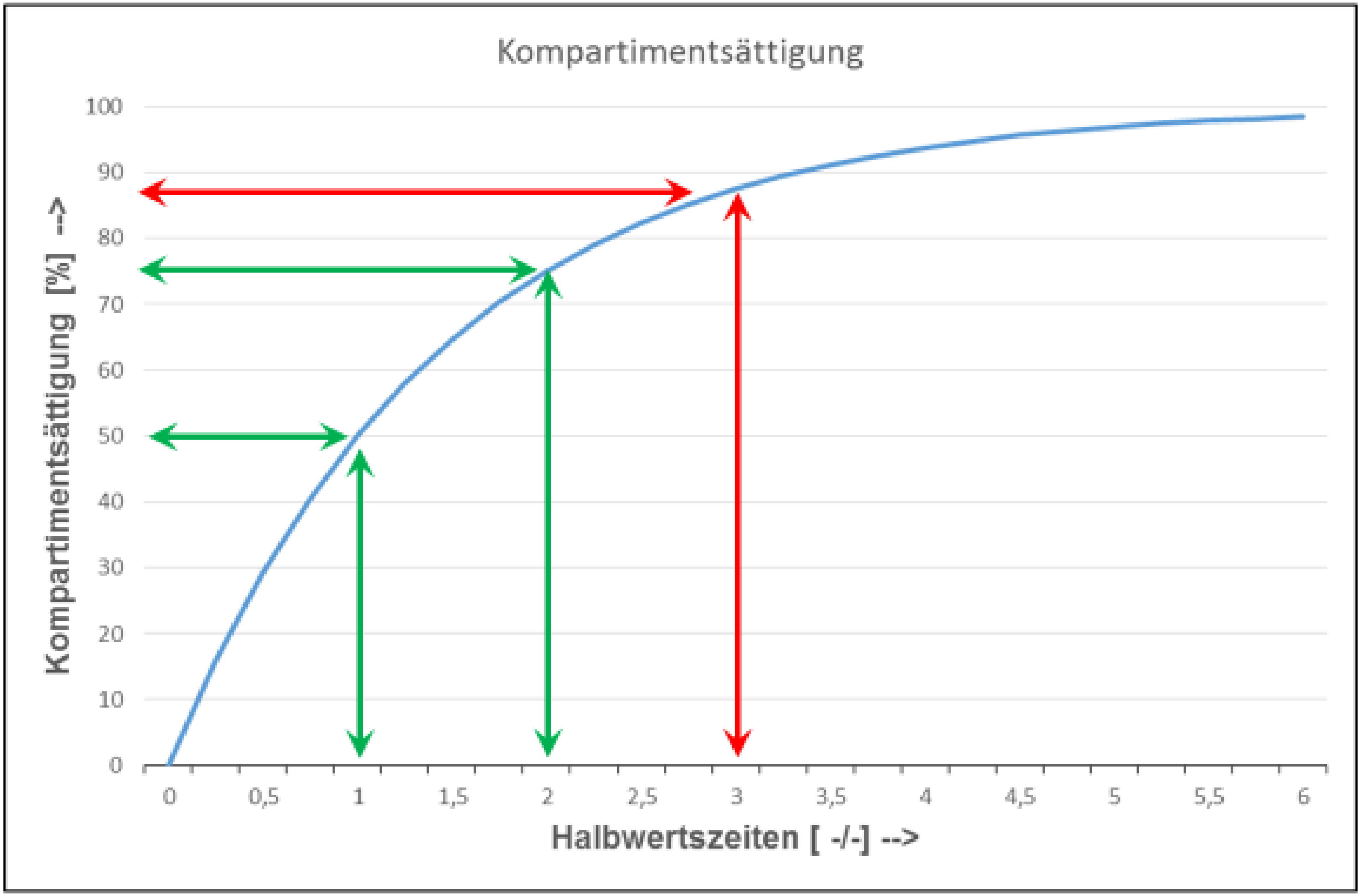

Haldanes „2:1“

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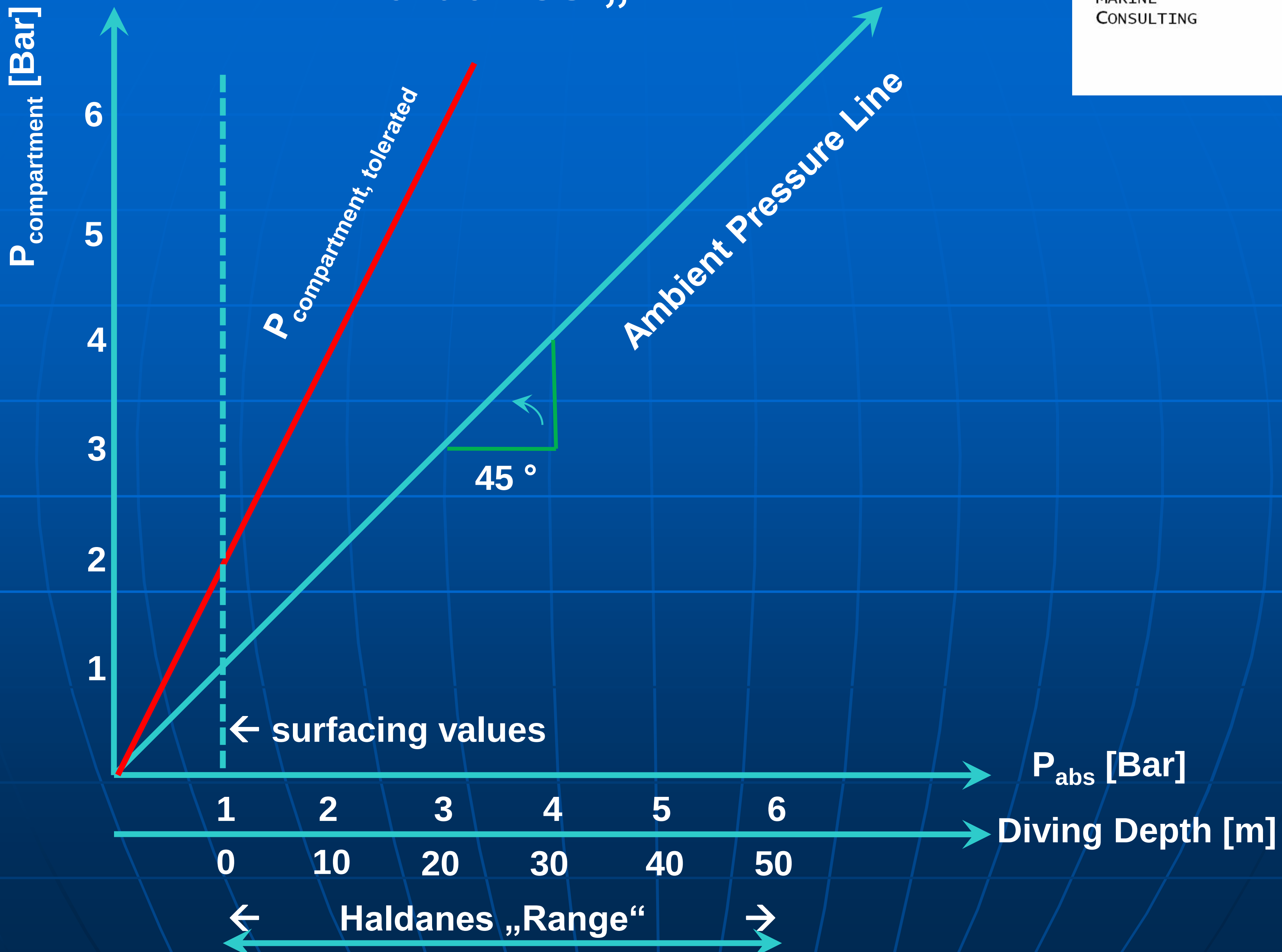

Perfusion

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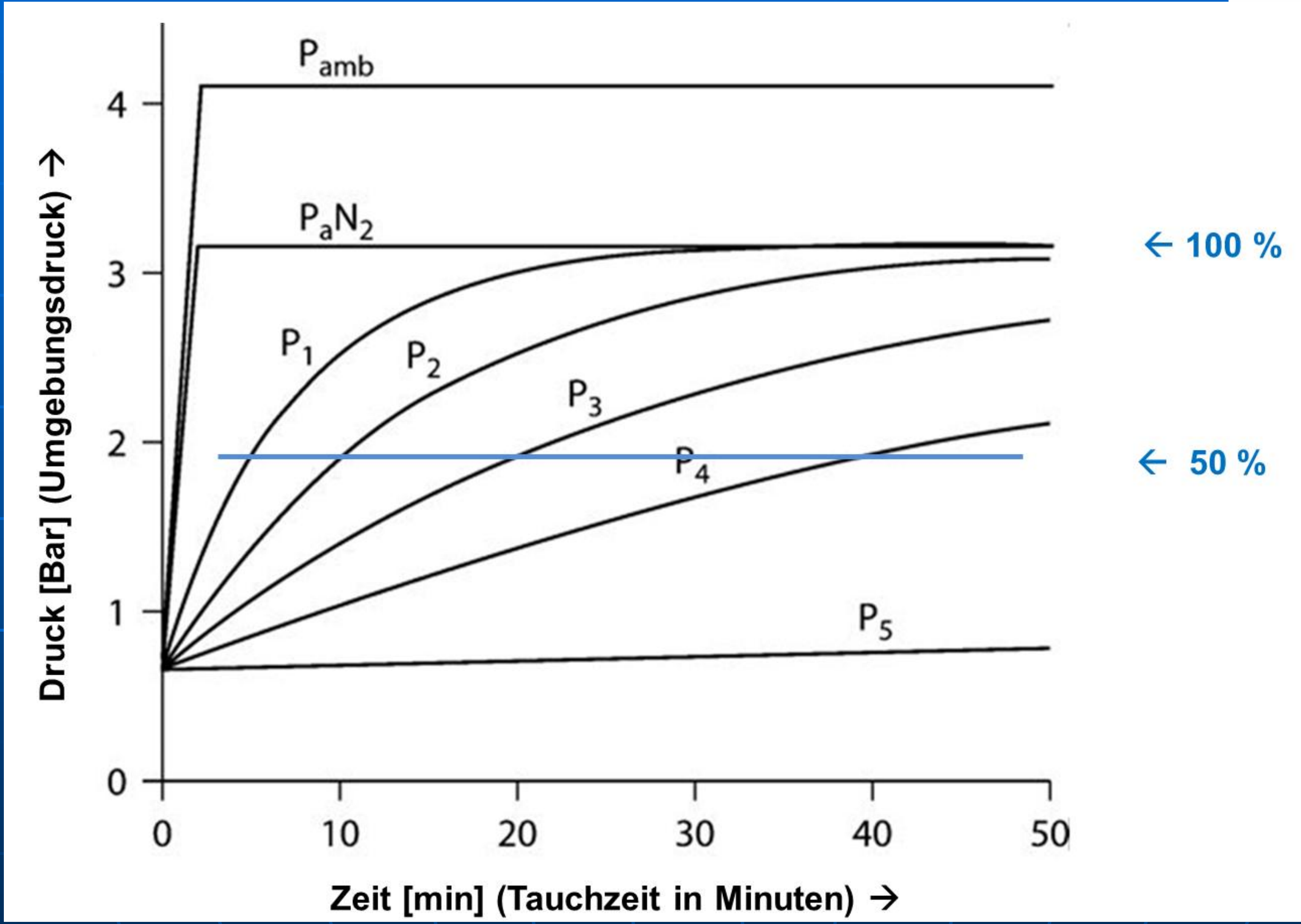

modifiziert und mit freundlicher Genehmigung von Dr. David A. Doolette, USN NEDU: Doolette, D. J. and Mitchell, S. J. 2010. Hyperbaric Conditions. Comprehensive Physiology. 1:163–201.

Perfusion

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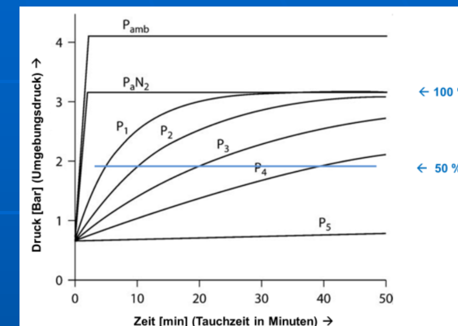
$$dP_t(t)/dt = k[P_{alv}(t) - P_t(t)]$$

LDE: linear differential equation



$$P_t(t) = P_{alv0} + [P_{t0} - P_{alv0}]\, e^{-kt}$$

Solution for ΔP = const.: Haldane equation

$$P_t(t) = P_{alv0} + R\,[t - 1/k] - [P_{alv0} - P_{t0} - R/k]\, e^{-kt}$$

Solution for ΔP / Δ t = const.: Schreiner equation

Perfusion

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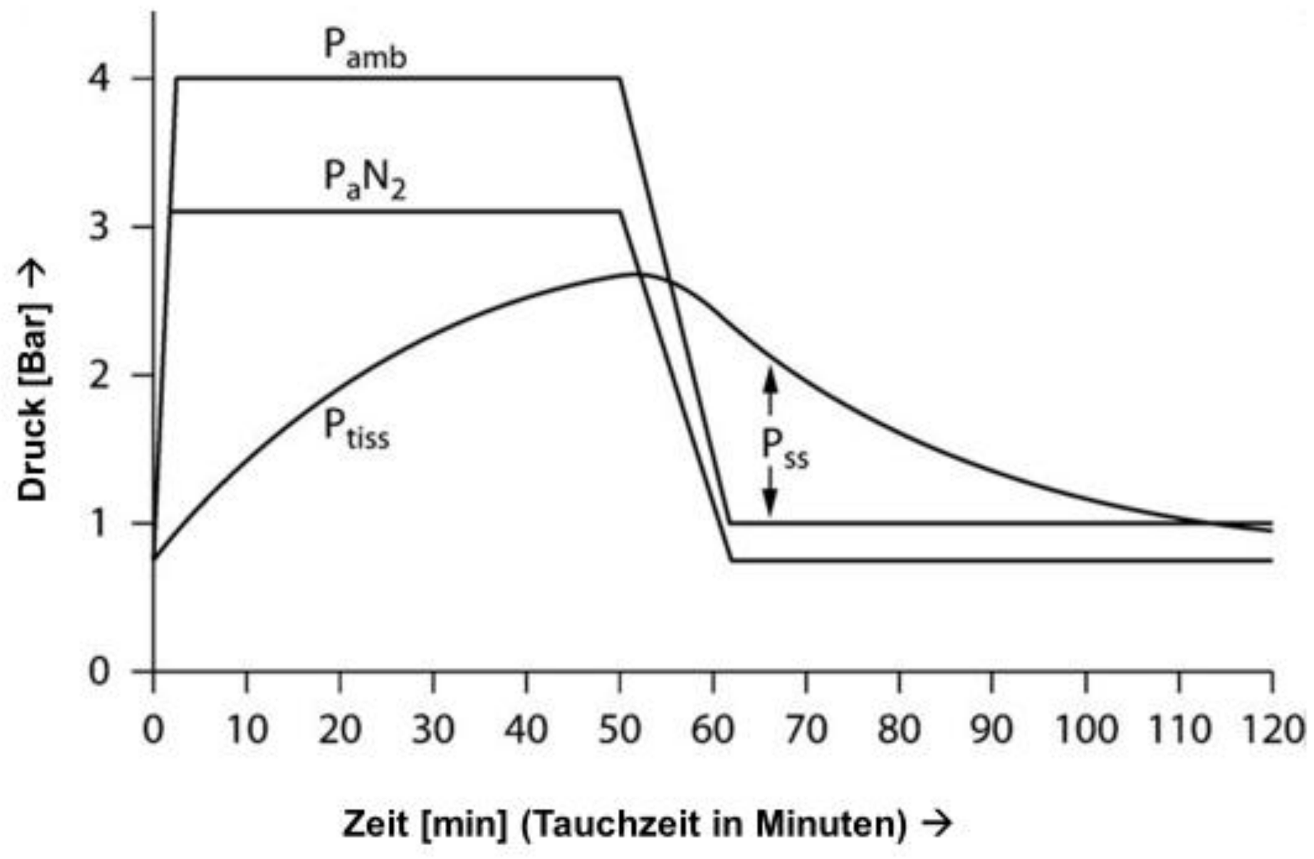

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Figure 88.
"Bends" of foreleg in a goat.

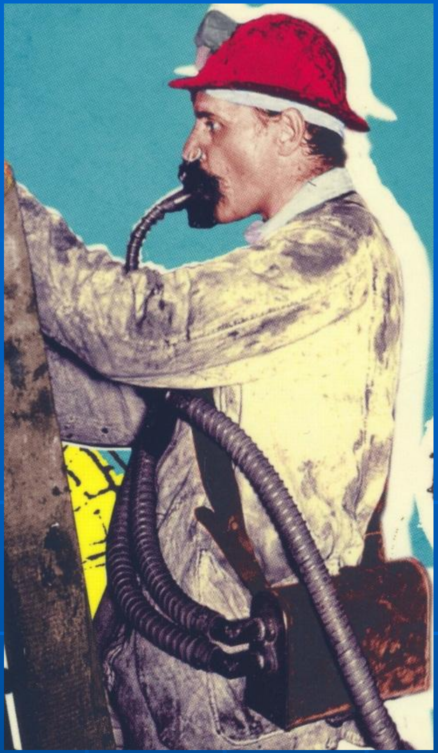
Source:
Haldane, J S.
Respiration, p. 346,
Yale University Press,
1922, 1927

ca. 1080 dives, thereof:

→ 835 dives with 85 goats

→ 316 dives with smaller critters

→ 37 dives with 4 subjects + JSH + Jack



Haldanes „ 2: 1“; picture: „Suffer & Survive“; Goodman, Martin; Pocket Books, Simon & Schuster, London, 2007.

individual susceptibility (p. 404 ff):
sex (?), size (?), activity, blood volume (?), …

(2) Twelve small rats, 13 medium rats, 8 large rats, 59 mice, 7 rabbits, 10 guinea-pigs, and 1 old hen were raised to 72 lbs. in 10 minutes, left for 1 hour and then decompressed in 50 seconds. No goats were put in since it was well established that this experience would have killed all of them. The hen and the largest rabbit (weight 2800 gms.) died in 5 minutes, and 1 guinea-pig became paraplegic in 10 minutes and died in 20 minutes. All three were extensively

436 *The Prevention of Compressed-air Illness*

Tuesday, 4th September.

The *Spanker* was anchored in six fathoms of water, and experiments were made on the bottom by Dr Haldane, Lieutenant Damant, and Mr Catto on the risks of blowing up. After being compressed in the air chamber to teach them to open their Eustachian tubes, Lieutenant and Commander E. V. F. R. Dugmore, Lieutenant G. N. Henson, Jack Haldane (age 13) all made descents in six fathoms of water. This was the first time that these had ever dived in a diving dress, which illustrates the usefulness of the re-compression chamber in the practical teaching of divers.

72 lbs = 4,97 Bar
6 fathoms =
36 feet = 11 m

The first diving table of the world with staged decompression (1907),
Table I,
p. 442

approx. 55 profiles;
JSH wanted to have
> 30 goats per profile

APPENDIX IV.

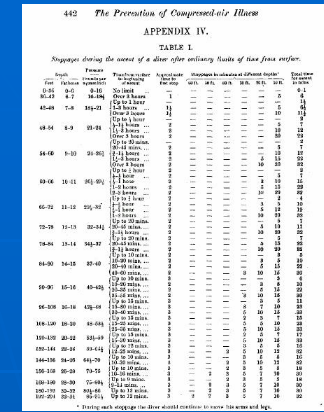
TABLE I.

Stoppages during the ascent of a diver after ordinary limits of time from surface.

Depth: Feet	Depth: Fathoms	Pressure — Pounds per square inch	Time from surface to beginning of ascent	Approximate time to first stop	Stoppages in minutes at different depths*: 60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	Total time for ascent in mins.
0–36	0–6	0–16	No limit ...	—	—	—	—	—	—	—	0–1
36–42	6–7	16–18¼	Over 3 hours	1	—	—	—	—	—	5	6
42–48	7–8	18¼–21	Up to 1 hour	—	—	—	—	—	—	—	1½
			1–3 hours ...	1½	—	—	—	—	—	5	6½
			Over 3 hours	1½	—	—	—	—	—	10	11½
48–54	8–9	21–24	Up to ½ hour	—	—	—	—	—	—	—	2
			½–1½ hours ...	2	—	—	—	—	—	5	7
			1½–3 hours ...	2	—	—	—	—	—	10	12
			Over 3 hours	2	—	—	—	—	—	20	22
54–60	9–10	24–26½	Up to 20 mins.	—	—	—	—	—	—	—	2
			20–45 mins. ...	2	—	—	—	—	—	5	7
			¾–1½ hours ...	2	—	—	—	—	—	10	12
			1½–3 hours ...	2	—	—	—	—	5	15	22
			Over 3 hours	2	—	—	—	—	10	20	32
60–66	10–11	26½–29¼	Up to ½ hour	2	—	—	—	—	—	—	2
			½–¾ hour ...	2	—	—	—	—	—	5	7
			¾–1 hour	2	—	—	—	—	3	10	15
			1–2 hours ...	2	—	—	—	—	5	15	22
			2–3 hours ...	2	—	—	—	—	10	20	32
66–72	11–12	29¼–32	Up to ½ hour	2	—	—	—	—	—	2	4
			½–¾ hour ...	2	—	—	—	—	3	5	10
			¾–1 hour ...	2	—	—	—	—	5	12	19
			1–2 hours ...	2	—	—	—	—	10	20	32
[illegible]	12–13	32–34½	Up to 20 mins.	2	—	—	—	—	—	5	7
			20–45 mins. ...	2	—	—	—	—	5	10	17
			¾–1½ hours ...	2	—	—	—	—	10	20	32
[illegible]	[illegible]14	34½–37	Up to 20 mins.	2	—	—	—	—	—	5	7
			20–45 mins. ...	2	—	—	—	—	5	15	22
			¾–1¼ hours ...	2	—	—	—	—	10	20	32
[illegible]	[illegible]	37–40	Up to 10 mins.	2	—	—	—	—	—	3	5
			10–20 mins. ...	2	—	—	—	—	3	5	10
			20–40 mins. ...	2	—	—	—	—	5	15	22
			40–60 mins. ...	2	—	—	—	3	10	15	30
[illegible]	[illegible]	[illegible]	Up to 10 mi[illegible]	3	—	—	—	—	—	3	6
			10–20 mi[illegible]	2	—	—	—	—	3	5	10
			20–35 [illegible]	2	—	—	—	—	5	15	22
			[illegible]	2	—	—	—	3	10	15	30
[illegible]	[illegible]	[illegible]	[illegible]	3	—	—	—	—	3	5	11
			[illegible]	3	—	—	—	8	7	10	28
			[illegible]	3	—	—	—	5	10	15	33
[illegible]	[illegible]	[illegible]	[illegible]	3	—	—	—	2	3	7	15
			[illegible]	3	—	—	—	5	5	10	23
			[illegible]	3	—	—	—	5	10	15	33
[illegible]	[illegible]	[illegible]	[illegible]	3	—	—	—	2	5	7	17
			[illegible]	3	—	—	—	5	10	15	33
152[illegible]	[illegible]	[illegible]	[illegible]	3	—	—	—	3	5	5	16
			[illegible]	3	—	—	2	5	10	12	32
144–1[illegible]	[illegible]	[illegible]	[illegible]	3	—	—	—	3	5	5	16
			[illegible]	3	—	—	2	5	10	12	32
[illegible]	[illegible]	[illegible]	[illegible]	3	—	—	2	3	5	5	18
			[illegible]	3	—	2	3	5	7	10	30
[illegible]	[illegible]	[illegible]	[illegible]	3	—	—	2	3	5	5	18
			[illegible]	3	—	2	3	5	7	10	30
180–192	[illegible]	[illegible]	[illegible]	3	—	2	3	5	7	10	30
192–204	32–34	86–91½	Up to 12 mins.	3	2	2	3	5	7	10	32

* During each stoppage the diver should continue to move his arms and legs.

The first diving table of the world with staged decompression (1907), Table I, p. 442: ***became wildly successful !!!***



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0–36	0–6	0–16	No limit ...	—	—	—	—	—	—	—	0–1
36–42	6–7	16–18¼	Over 3 hours	1	—	—	—	—	—	5	6
42–48	7–8	18¼–21	Up to 1 hour	—	—	—	—	—	—	—	1½
			1–3 hours ...	1½	—	—	—	—	—	5	6½
			Over 3 hours	1½	—	—	—	—	—	10	11½
48–54	8–9	21–24	Up to ½ hour	—	—	—	—	—	—	—	2
			½–1½ hours ...	2	—	—	—	—	—	5	7
			1½–3 hours ...	2	—	—	—	—	—	10	12
			Over 3 hours	2	—	—	—	—	—	20	22
54–60	9–10	24–26½	Up to 20 mins.	—	—	—	—	—	—	—	2
			20–45 mins. ...	2	—	—	—	—	—	5	7
			¾–1½ hours ...	2	—	—	—	—	—	10	12
			1½–3 hours ...	2	—	—	—	—	5	15	22
			Over 3 hours	2	—	—	—	—	10	20	32
60–66	10–11	26½–29¼	Up to ¼ hour	2	—	—	—	—	—	—	2
			¼–½ hour ...	2	—	—	—	—	—	5	7
			½–1 hour	2	—	—	—	—	3	10	15
			1–2 hours ...	2	—	—	—	—	5	15	22
			2–3 hours ...	2	—	—	—	—	10	20	32
66–72	11–12	29¼–32	Up to ¼ hour	2	—	—	—	—	—	2	4
			¼–½ hour ...	2	—	—	—	—	3	5	10
			½–1 hour ...	2	—	—	—	—	5	12	19
			1–2 hours ...	2	—	—	—	—	10	20	32
72–78	12–13	32–34¾	Up to 20 mins.	2	—	—	—	—	—	5	7
			20–45 mins. ...	2	—	—	—	—	5	10	17
			¾–1½ hours ...	2	—	—	—	—	10	20	32
78–84	13–14	34¾–37	Up to 20 mins.	2	—	—	—	—	—	5	7
			20–45 mins. ...	2	—	—	—	—	5	15	22
			¾–1½ hours ...	2	—	—	—	—	10	20	32
84–90	14–15	37–40	Up to 10 mins.	2	—	—	—	—	—	3	5
			10–20 mins. ...	2	—	—	—	—	3	5	10
			20–40 mins. ...	2	—	—	—	—	5	15	22
			40–60 mins. ...	2	—	—	—	3	10	15	30
90–96	15–16	40–42½	Up to 10 mins.	3	—	—	—	—	—	3	6
			10–20 mins. ...	2	—	—	—	—	3	5	10
			20–35 mins. ...	2	—	—	—	—	5	15	22
			35–55 mins. ...	2	—	—	—	3	10	15	30
96–108	16–18	42½–48	Up to 15 mins.	3	—	—	—	—	3	5	11
			15–30 mins. ...	3	—	—	—	3	7	10	23
			30–40 mins. ...	3	—	—	—	5	10	15	33
108–120	18–20	48–53¼	Up to 15 mins.	3	—	—	—	2	3	7	15
			15–25 mins. ...	3	—	—	—	5	5	10	23
			25–35 mins. ...	3	—	—	—	5	10	15	33
120–132	20–22	53¼–59	Up to 15 mins.	3	—	—	—	2	5	7	17
			15–30 mins. ...	3	—	—	—	5	10	15	33
132–144	22–24	59–64½	Up to 12 mins.	3	—	—	—	3	5	5	16
			12–25 mins. ...	3	—	—	2	5	10	12	32
144–156	24–26	64½–70	Up to 10 mins.	3	—	—	—	3	5	5	16
			10–20 mins. ...	3	—	—	2	5	10	12	32
156–168	26–28	70–75	Up to 10 mins.	3	—	—	2	3	5	5	18
			10–16 mins. ...	3	—	2	3	5	7	10	30
168–180	28–30	75–80½	Up to 9 mins.	3	—	—	2	3	5	5	18
			9–14 mins. ...	3	—	2	3	5	7	10	30
180–192	30–32	80½–86	Up to 13 mins.	3	—	2	3	5	7	10	30
192–204	32–34	86–91½	Up to 12 mins.	3	2	2	3	5	7	10	32

* During each stoppage the diver should continue to move his arms and legs.

Since the introduction into the British Navy twelve years ago of the method of decompression embodied in the tables, with the corresponding regulations as to air supply and testing of the pumps, deep diving has been conducted with comfort and safety to the divers, so that compressed-air illness has now practically disappeared except in isolated cases where from one cause or another the regulations have not been carried out. When a medical compressed-air chamber is available, it is justifiable to cut down the time for the last wearisome stages of the decompression, and so extend the time on the bottom. This has been cautiously tried under Commander Damant's supervision, but the result was that the divers began to suffer from "bends." These could easily

Source: Haldane, J S. Respiration, p. 350, Yale University Press, 1922 / 27

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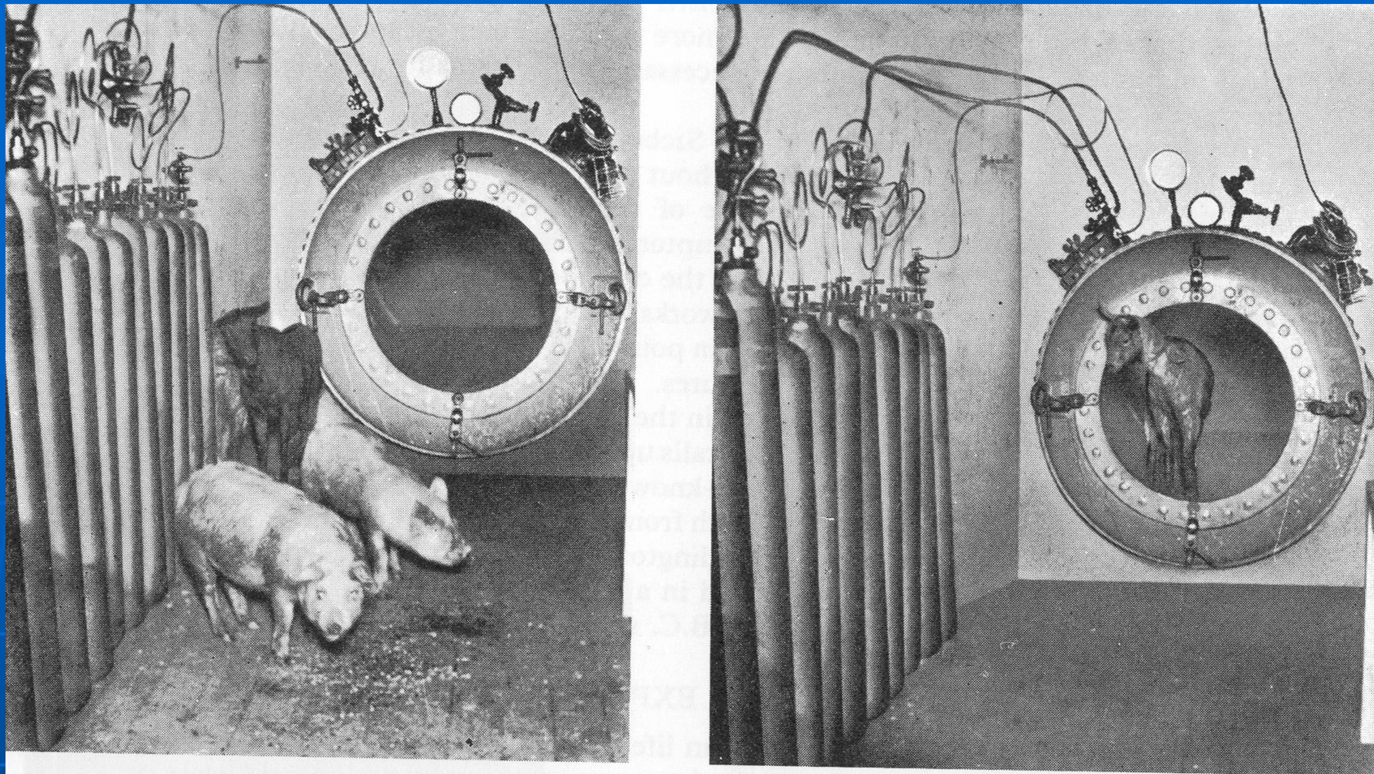

Fig. 10 Experimental Subjects Fig. 11

The pigs look a little apprehensive! "Lavender" takes a last look round!

Quelle: Robert Henry Davis: Deep Diving and Submarine Operations: A Manual for Deep Sea Divers and compressed Air workers [89], S. 22

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.

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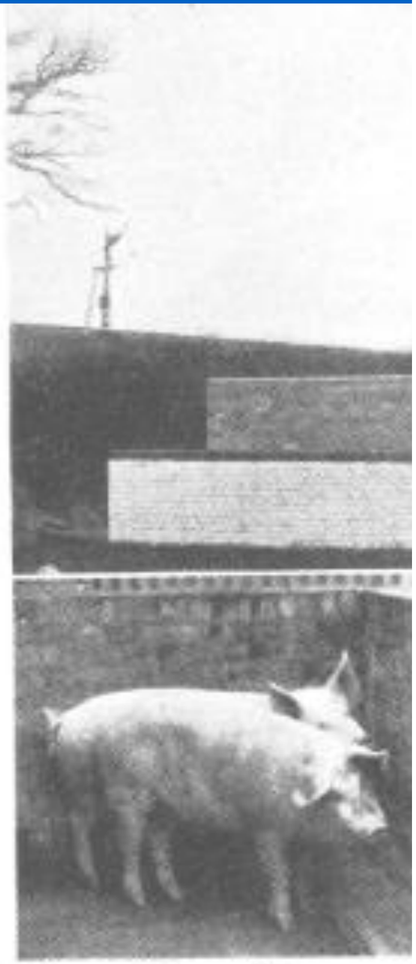

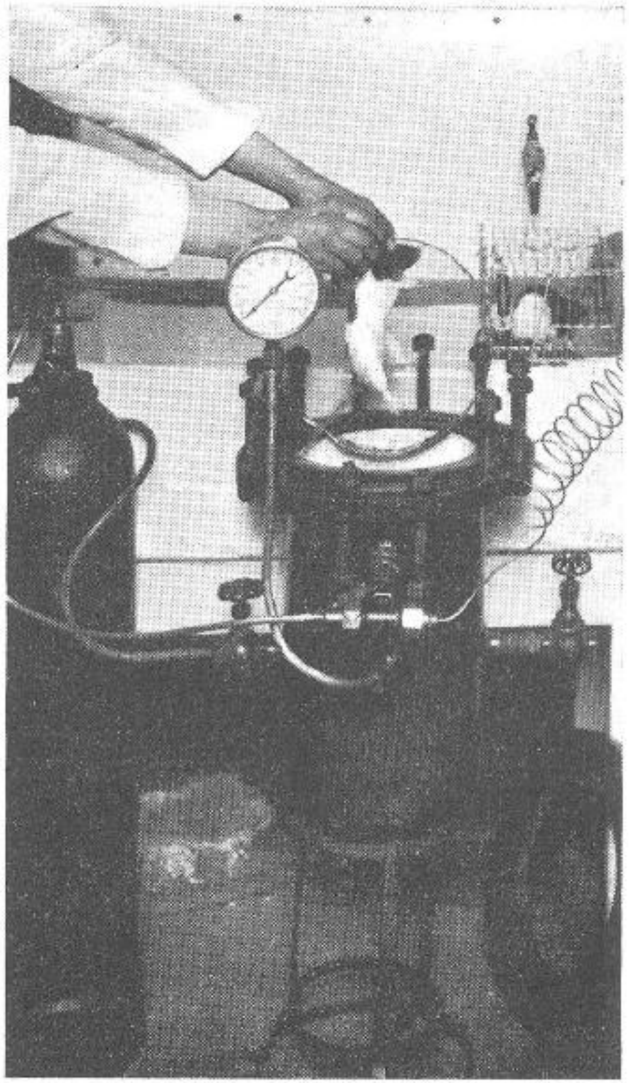

Fig. 15. Apparatus for tests on guinea-pigs, rats and other small animals

Fig. 5. Goat House and Pig Sties at Siebe, Gorman & Co.'s Works (insets: some of the subjects for experiment)

Divers are often men with a sense of humour, hence the christening of strong-smelling goats with fragrant names such as "Lavender", "Rosemary", etc.

Quelle: Robert Henry Davis:
Deep Diving and Submarine
Operations:
A Manual for Deep Sea Divers and
compressed Air workers [89], S. 15

The landscape: „ …my model is better than yours!“

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→ **Perfusion: Haldane – Workman - Schreiner- Hamilton – Ruff & Müller – Thalmann – Bühlmann & Hahn - …**
- **# compartments, half times (HT, τ), M_0**

→ **Diffusion: BSAC (Hempleman), DCIEM (Kidd-Stubbs, Nishi), …**
- **various geometries (slab, (Krogh-) cylinder, …)**

→ **Thermodynamic: Hills, B.A.**

→ **Dual Phase: („Bubble Models“): VPM (Yount, Hoffman), …**

→ **Hybrid-Models: COPERNICUS (Brubakk), …**

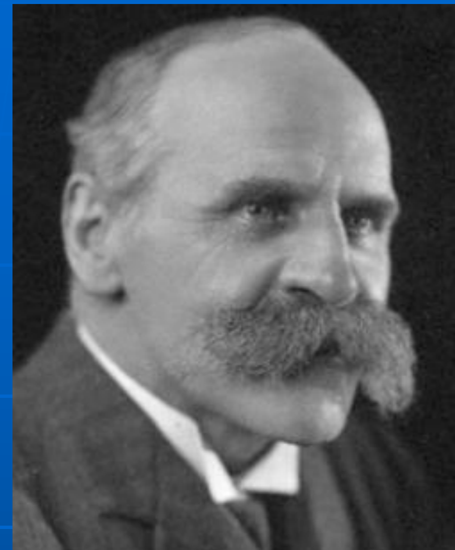
→ **Deterministic versus Statistic Models**
- **maximum likelihood, BVM(3), …**

WARNING: this is not a concluding list!

the landscape …

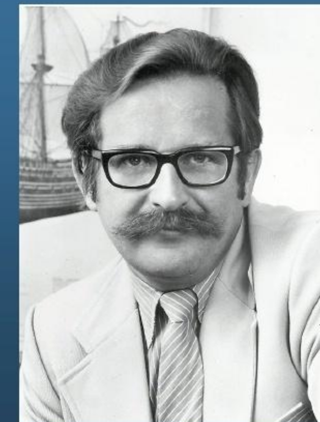
Robert D. Workman, 1968-1969*

Capt. Dr.
Robert Dean
Workman
(1922 – 1998)



(1860 – 1936)

Heinz R. Schreiner, 1970-1971*



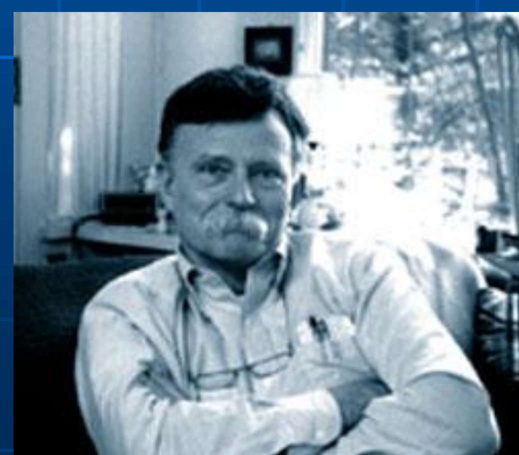
-??-

Prof. Drs.:
Ruff, Siegfried und
Müller, Karl Gerhard
-??-

Dr. Max Hahn
(1929 – 2000)

Prof. Dr. med.
Albert Alois Bühlmann
(1923 – 1994)

Capt. Dr. Ed Thalmann
(1945 – 2004)



Dr. Robert William „Bob Bill“ Hamilton
(1930 – 2011)

The landscape

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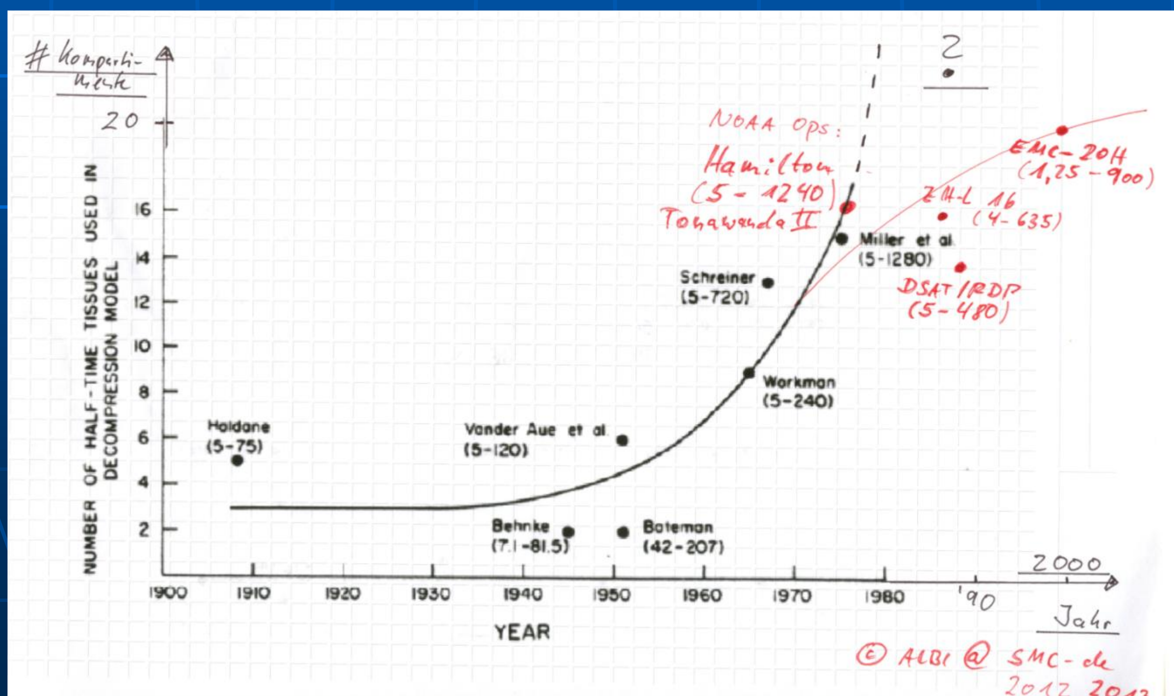
“Physiological models of decompression have traditionally had a bad press. …

The modelers attempted to improve the fit by adding compartments with longer and longer time constants, with no marked improvement.”

Source: Predictions from a mathematical model of decompression compared to Doppler scores.
DR. VALERIE FLOOK, UHM 2011, Vol. 38, No. 3; p. 187



The landscape

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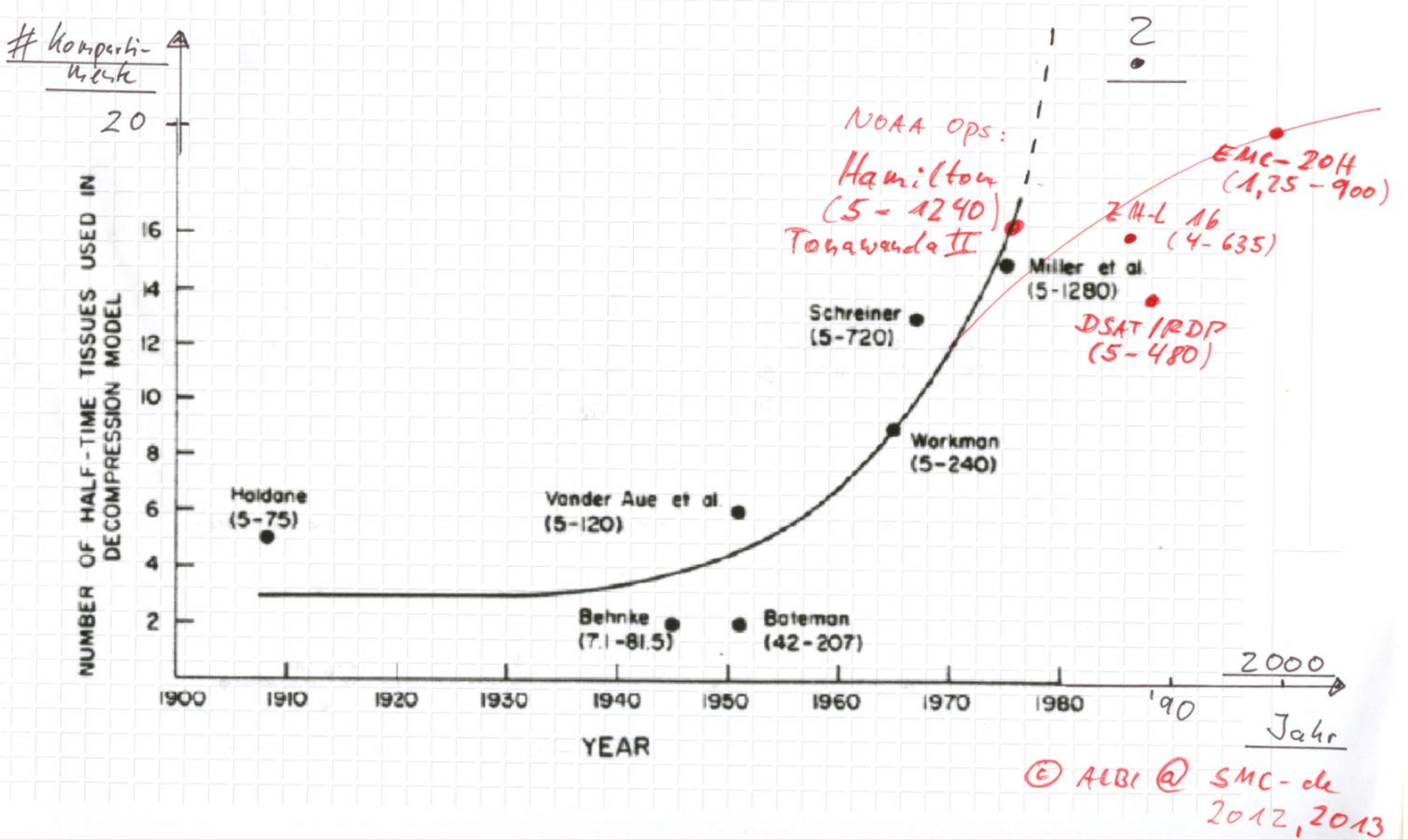

The landscape

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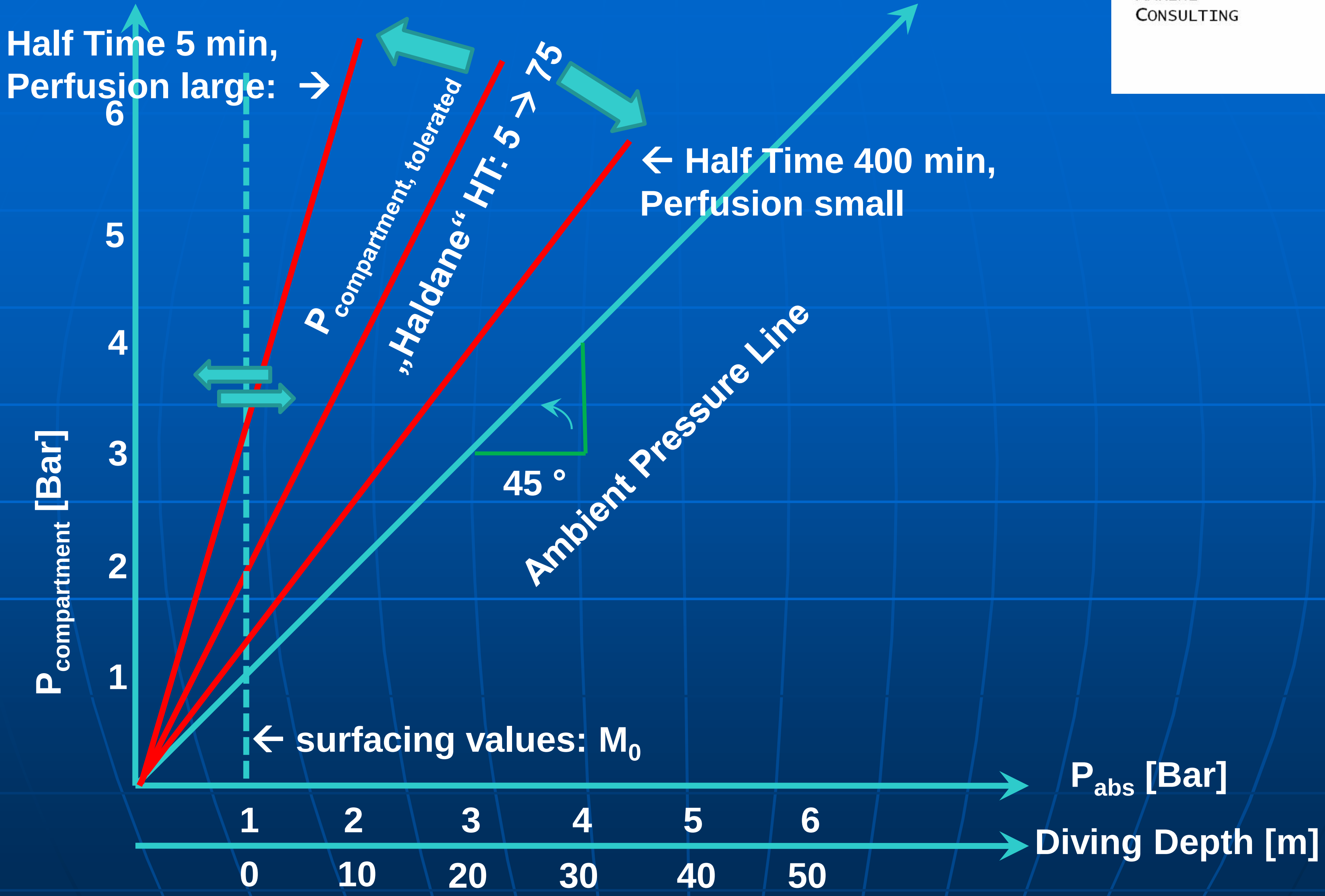

Decompression-Models: Serial versus Parallel

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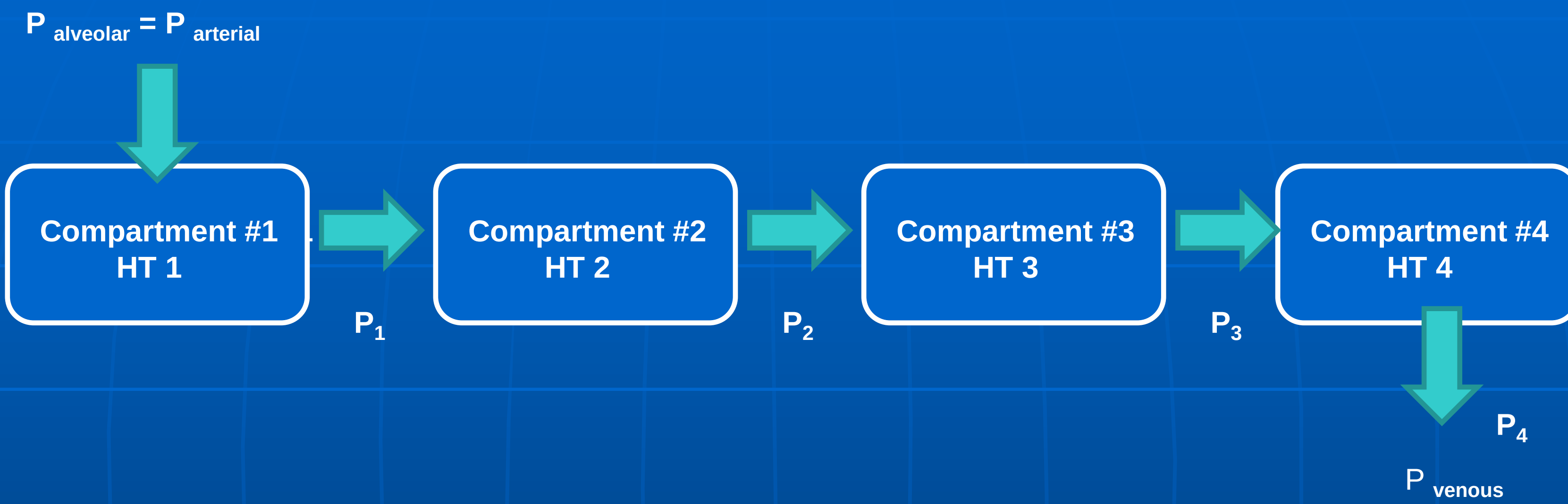
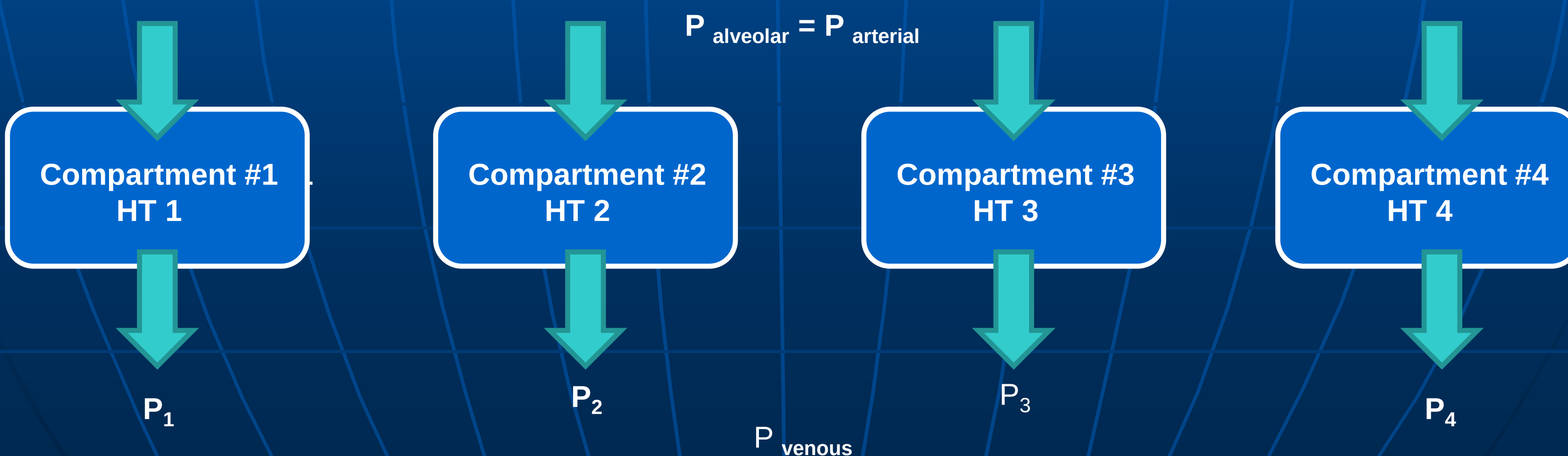
Serial Model



Parallel Model



Experimentelle und theoretische Untersuchung des Druckfall-
problems

Übersicht

Die Gasblase im Organismus wird als die bestimmende Größe für die Konstruktion von beschwerdelosen Dekompressionen erkannt. Auf dieser Grundlage und unter Berücksichtigung des empirischen Materials wird ein Satz von erlaubten Gasspannungen im Gewebe vorgeschlagen. Hieraus lassen sich für beliebige Tauchgänge in Helium-Stickstoff-Gemischen Dekompressionsschemata berechnen. Eine Formel für das Blasenwachstum im Organismus bei einer Dekompression wird entwickelt und zur Diskussion der erlaubten Gasspannungen herangezogen. Im Anhang werden Tauchversuche des Instituts und die Tauchtabellen des "U.S. Diving Manuals" analysiert.

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Covered by oblivion:

Ruff & Müller

Int. Z. angew. Physiol. einschl. Arbeitsphysiol. 23, 251—292 (1966)

Theorie der Druckfallbeschwerden und ihre Anwendung auf Tauchtabellen

S. Ruff

Institut für Flugmedizin der Deutschen Versuchsanstalt für Luft- und Raumfahrt e.V., Bad Godesberg (Leiter: Prof. Dr. S. Ruff)

K. G. Müller

Institut für theoretische Physik der Universität Bonn

Eingegangen am 24. August 1966

Heinz Schreiner et al.

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Schreiner, H.R., and Kelley, P.L. "A Pragmatic View of Decompression," Underwater Physiology Proceedings of the Fourth Symposium on Underwater Physiology, edited by C.J. Lambertsen. Academic Press, New York, (1971) pp. 205-219

Specific rate of tissue perfusion ($\dot{Q}/R$)	Tissue fat fraction (X)				
	min^{-1}	0	0.3	0.7	1.0
	0.3	0	1	2	3
	0.1	4	5	6	7
	0.03	8	9	10	11
	0.0085	12	13	14	15

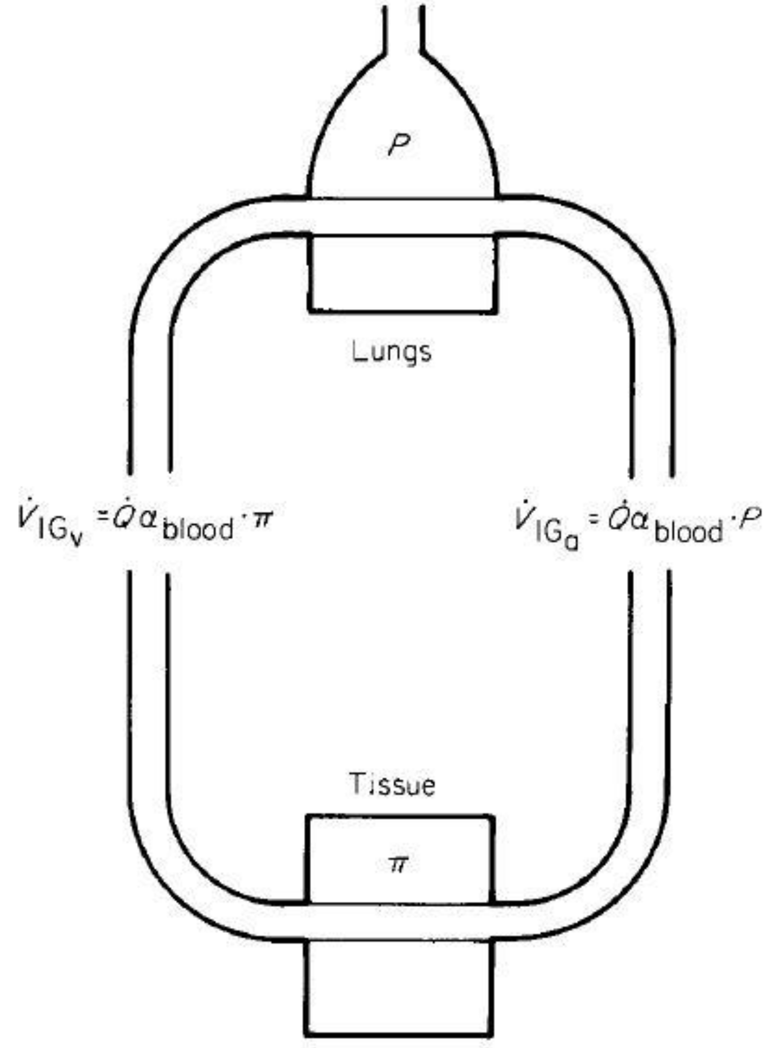

FIG. 1. Schematic presentation of the basic premises of the decompression model.

The landscape:

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→ **Diffusion: BSAC (Hempleman), DCIEM (Kidd-Stubbs, Nishi), … various geometries:**

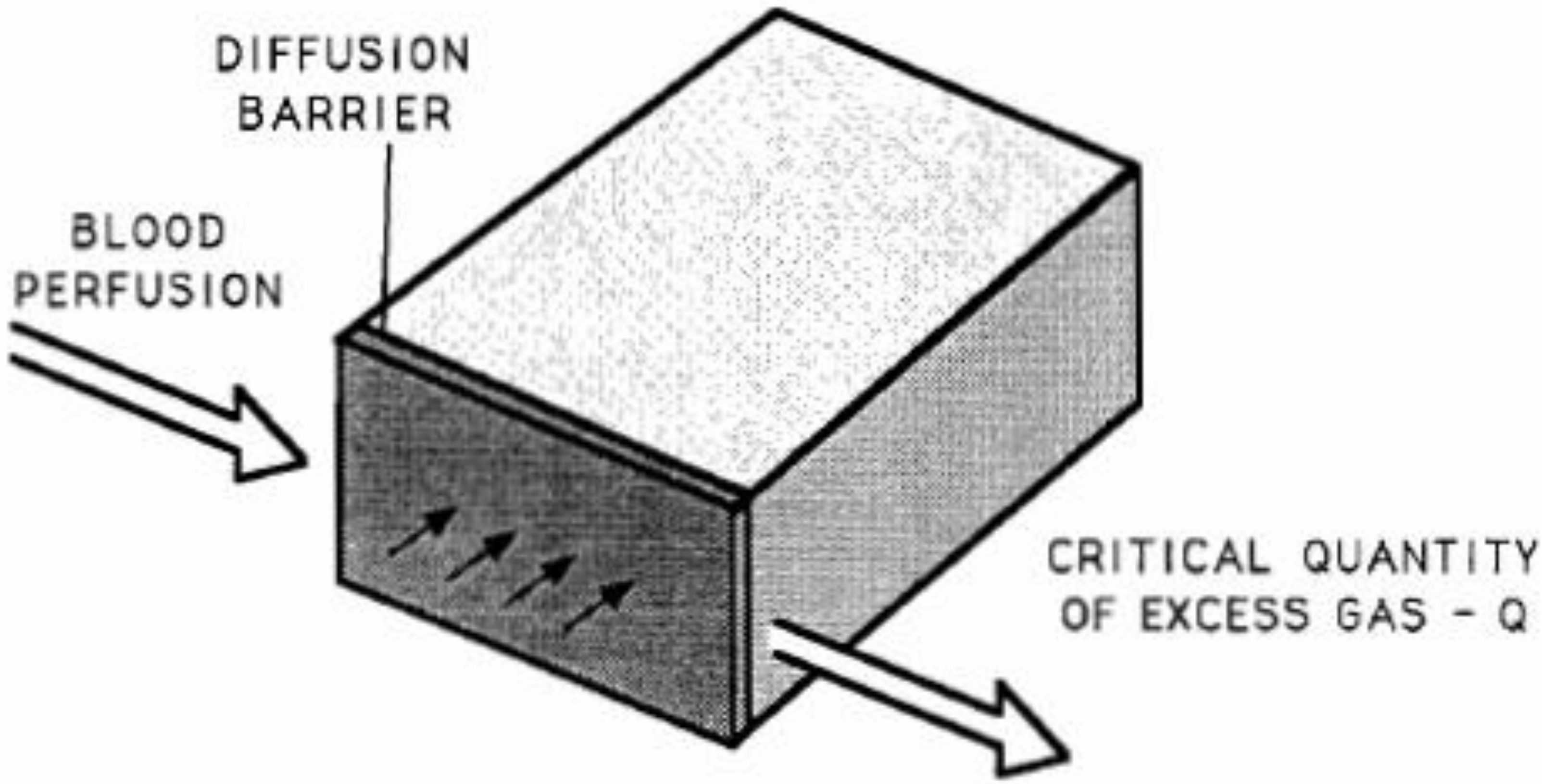

Figure 2.3 - Single Tissue Diffusion Limited Model - Inert gas exchange modeled with linear diffusion from capillaries into semi-infinite tissue slab. The decompression stress is defined by a tolerable quantity of dissolved inert gas -Q (redrawn from Hempleman (88)).

The landscape:

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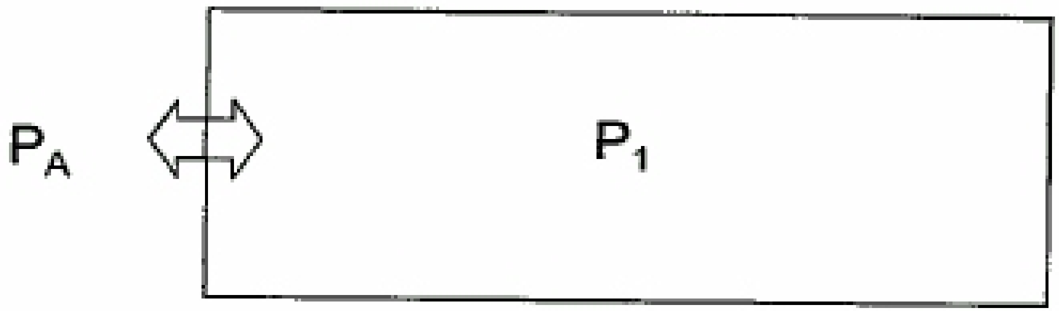
→ **Diffusion: BSAC (Hempleman), DCIEM (Kidd-Stubbs, Nishi), … various geometries:**



$$P_1 = P_A - \frac{8}{\pi^2}(P_A - P_0)\left[e^{-kt} + \frac{e^{-9kt}}{9} + \frac{e^{-25kt}}{25}\right]$$

Fig. 5. Single slab bulk diffusion model (British).

Results: BSAC 88

The landscape:

→ **Diffusion: BSAC (Hempleman), DCIEM (Kidd-Stubbs, Nishi), … various geometries:**

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Sources:

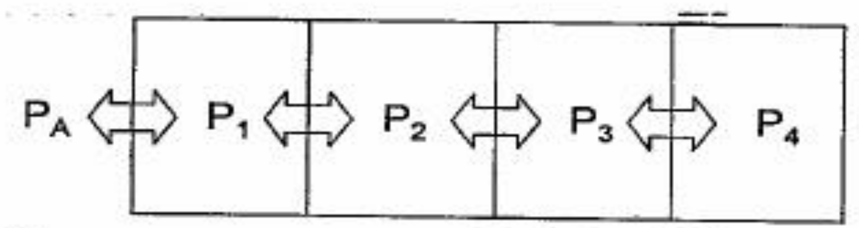
- **The new decompression tables, Appendix I, RNPL; in: A Medical Code of Practice for work in compressed air, 1968, p. 15 – 33**

- **Hempleman, H.V. Decompression procedures for deep, open sea operations; in: Proceedings of the 3rd Symposium on Underwater Physiology, March 1966, p. 255 – 266**

- **Hempleman, H.V. Tissue Inert Gas Exchange and Decompression Sickness; in: Proceedings of the 2nd Symposium on Underwater Physiology, February 1963, p. 6 – 13**

- **Hempleman, H.V. Investigation into decompression tables. Report III, Part A, A new theoretical basis for the calculation of decompression tables. RNPL, June 1952.**

DCIEM



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - Kidd-Stubbs Model (Canadian/ DCIEM).

(Source: DEVELOPMENT OF THE DCIEM 1983 DECOMPRESSION MODEL FOR COMPRESSED AIR DIVING, September 1984, DCIEM No. 84-R-44, R.Y. Nishi, G.R. Lauckner. Defence and Civil Institute of Environmental Medicine 1133 Sheppard Avenue West, P.O. Box 2000, Downsview, Ontario M3M 3B9

DCIEM

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[28] DCIEM Diving Manual, DCIEM No. 86-R-35: Part 1 AIR Diving Tables and Procedures, Part 2 Helium-Oxygen Surface-Suppplied Decompression Procedures and Tables; Defense and Civil Institute of Environmental Medicine, Canada

Perfusion AND (!) Diffusion; exempli gratia: ascent

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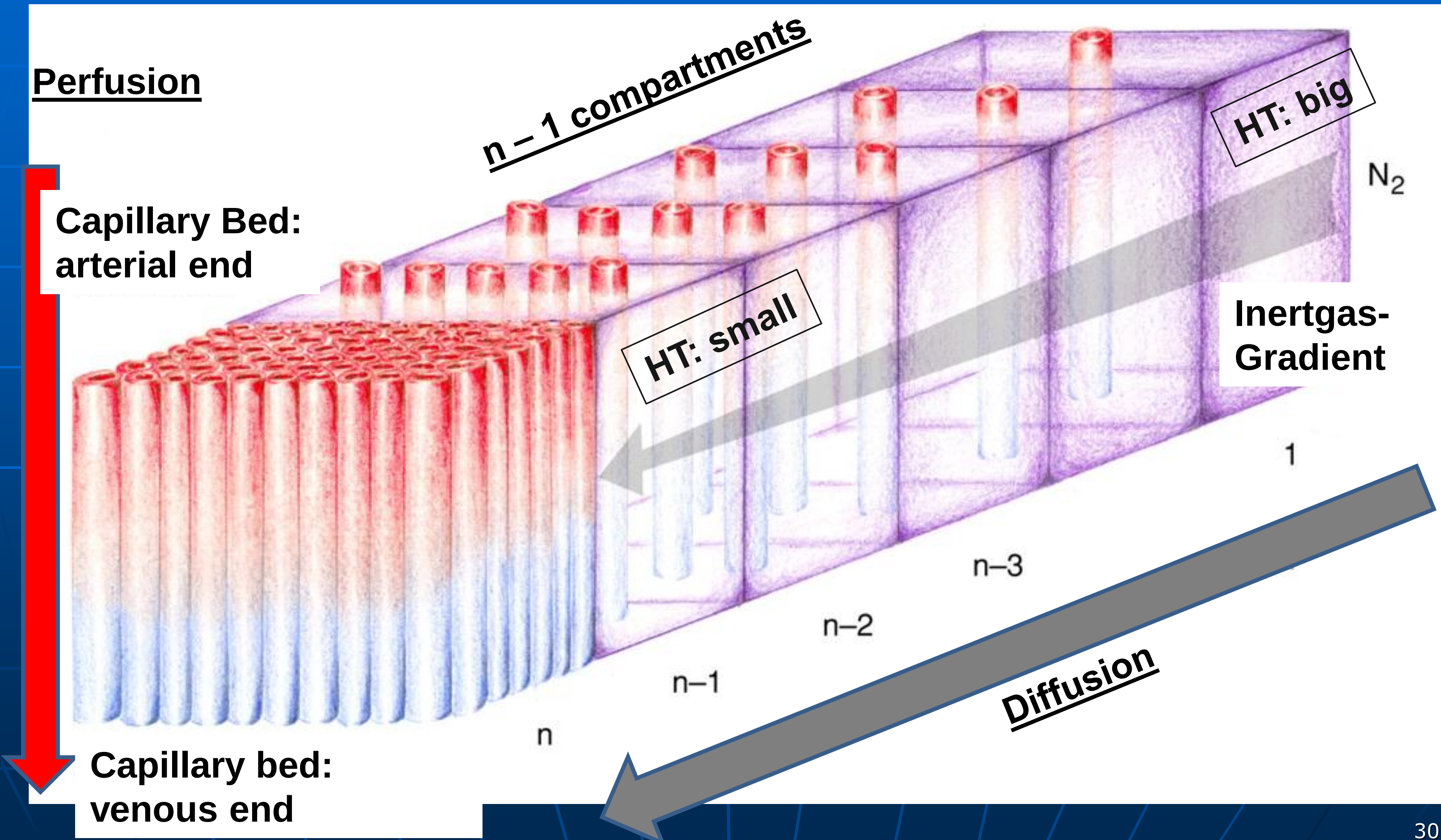

The landscape:

→ **Thermodynamic: Hills, B.A.**

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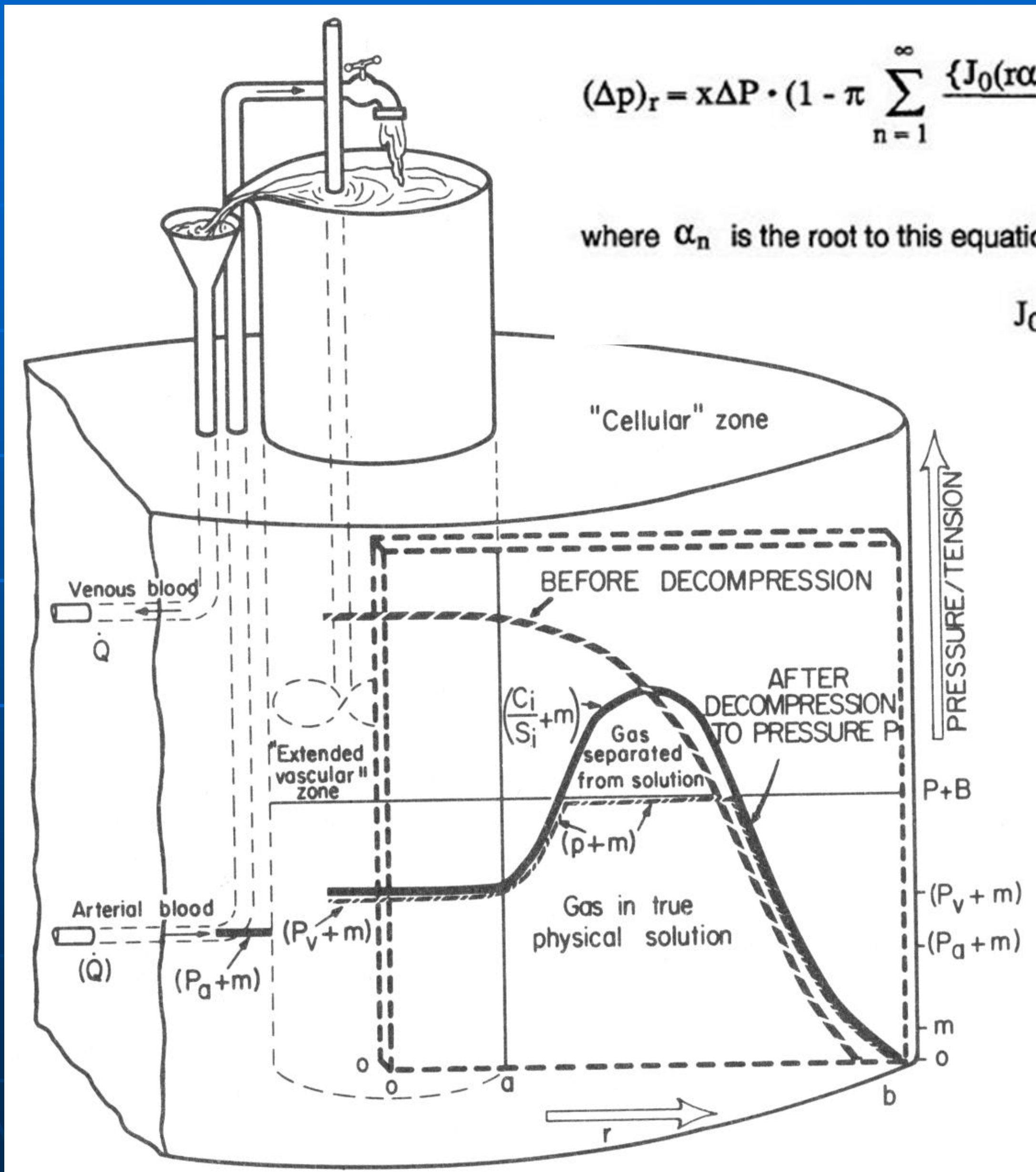
$$(\Delta p)_r = x\Delta P \cdot \left(1 - \pi \sum_{n=1}^{\infty} \frac{\{J_0(r\alpha_n) \cdot Y_0(a\alpha_n) - Y_0(r\alpha_n) \cdot J_0(a\alpha_n)\} \cdot \exp(-\alpha_n^2 \cdot Dt)}{\left[\frac{J_0(a\alpha_n)}{J_1(b\alpha_n)}\right]^2 - 1}\right)$$

where α_n is the root to this equation:

$$J_0(a\alpha_n)\, Y_1(b\alpha_n) - Y_0(a\alpha_n)\, J_1(b\alpha_n) = 0$$



The landscape:

→ **Thermodynamic: Hills, B.A.**

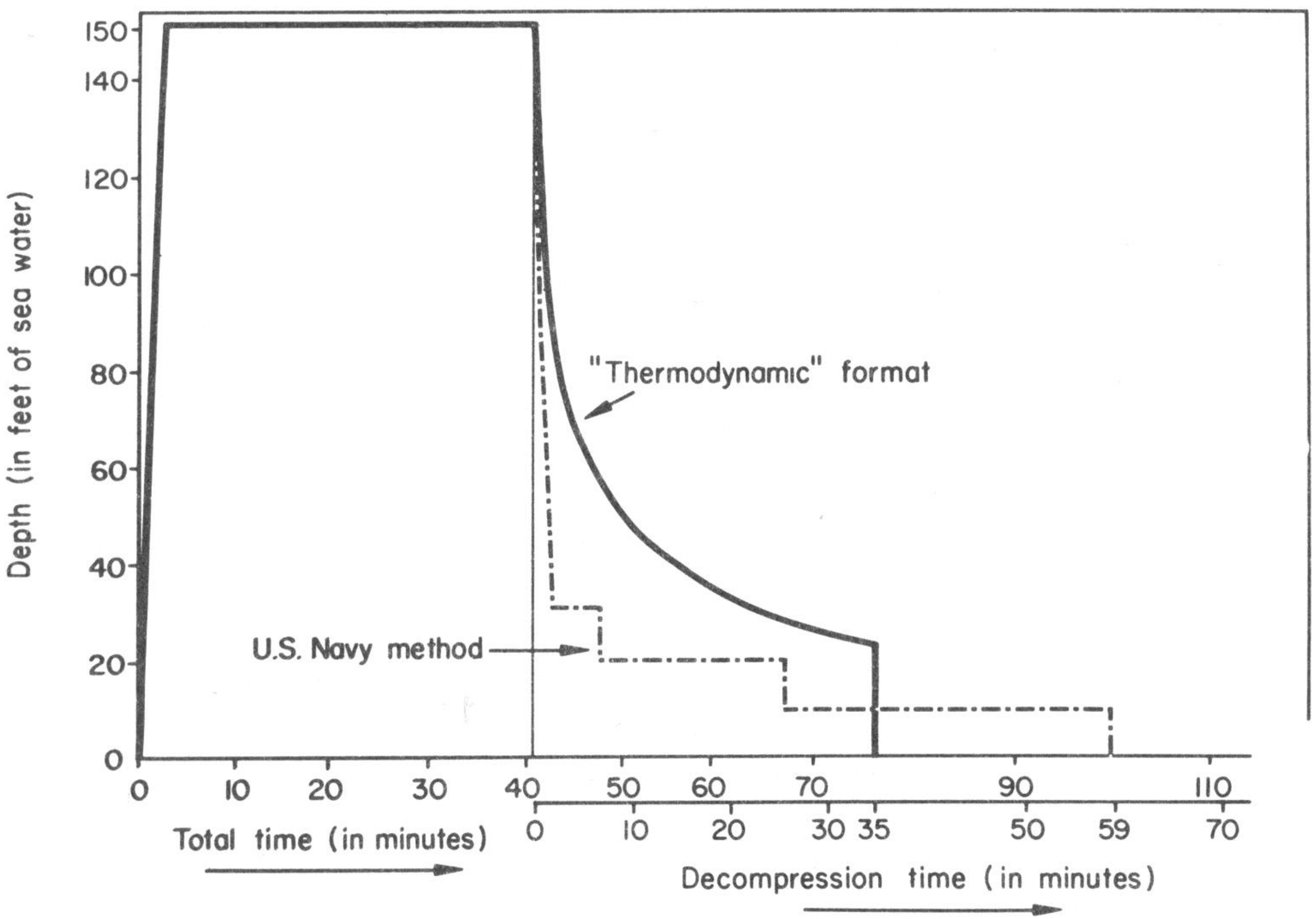


Fig. 85 A typical profile produced by the 'thermodynamic' approach and compared with a U.S. Navy profile for the same air exposure, both schedules being cut off at the total decompression time for equal bends incidence on the same goats. Redrawn from Hills (1966)

The landscape:

→ **Thermodynamic: Hills, B.A.**

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Sources:

→[102] **Hills, Brian Andrew (1977), Decompression Sickness, Volume 1, The Biophysical Basis of Prevention and Treatment, John Wiley & Sons, Ltd.. ISBN 0 471 99457 X, p. 260**

→**9th. UHMS workshop, p. 100 – 118**

Opinion:

"It is therefore possible that the "success" of these diving techniques could easily fall within the statistical confidence limits of conventional Haldane based diving theories."
Source: Gernhardt, ML., Dissertation, p. 23

The landscape:

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Dual Phase: („Bubble Models“):

Perfusion + Description of the free gas phase (= bubbles)

3 prominent representatives:

→ VPM (Varying Permeability Model; deterministic)
„best fit“ via USN, RNPL, TEKTITE
Implementations in various mix gas computers &
free-/share ware programs

→ RGBM (Reduced Gradient Bubble Model; deterministic)
cryptic …, „VPM like“
licence models for Suunto® & Mares® computers
relatively great bubbles method … (© ALBI)

→ BVM(3) (Bubble Volume Model; probabilistic) from USN
3 compartments (HT = 1; 26; 316 min.)

The landscape:

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<u>Dual Phase: („Bubble Models“):</u>
The deterministic representatives work with:

DUAL PHASE
i.e.: FREE phase (gas bubbles)
AND the LIQUID phase (gas in solution)
this is the perfusion part of the model:

Start: saturation
End: de-saturation

only difference to Haldane, Workman, etc:
„1 equation“ for „safe ascent depth“ (aka “ceiling”)
constant for all compartments / half-times
constant for all depths

The landscape:

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→ **Hybrid-Models: COPERNICUS (Brubakk), …**

A Dynamic 2-phase Model for Vascular Bubble Formation During Decompression of Divers

Christian R. Gutvik, and Alf O. Brubakk

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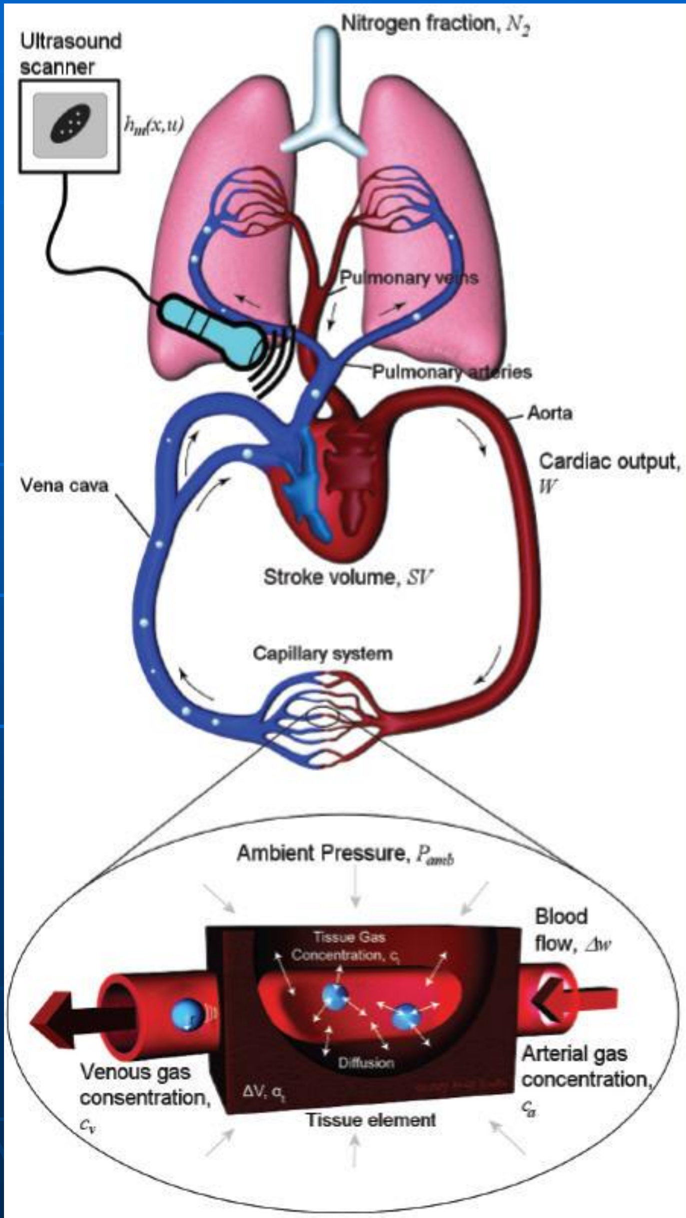

The Copernicus model

Figure 1

Concept illustration derives into:

$$\dot{x} = f(x,u)$$
$$h_m = g(x,u)$$

where:

$$f(x,u) = \begin{bmatrix} \dfrac{\frac{D\alpha_b}{h}\left(x_2 - x_3 - \frac{2\gamma}{x_1} + P_{meta} + c_s\frac{1}{r^3}\right) - \frac{x_1}{3}u_1}{x_3 + \frac{4\gamma}{3x_1} - P_{meta}} \\ \varepsilon_{\tau,i}\frac{\alpha_b}{\alpha_{t,i}}\left(u_2 x_{2+i} - x_{1+i}\right)u_{2+i} + \dot{p}_{r,i}(x) \\ \vdots \\ u_1 \end{bmatrix}$$

$$g(x,u) = \frac{4\pi}{3}\delta k_m \sum_i r_i^3 V_i * \omega_i - V_{dead}$$

$$x = \begin{bmatrix} r_1 & p_{t,1} & r_2 & p_{t,2} & P_{amb} \end{bmatrix}^T$$
$$u = \begin{bmatrix} \dot{P}_{amb} & f_{N2} & \omega_1 & \omega_2 \end{bmatrix}^T$$

Optimal Decompression of Divers
Procedures for Constraining Predicted Bubble Growth
CHRISTIAN R. GUTVIK, TOR A. JOHANSEN, and ALF O. BRUBAKK

Copernicus;
source: Alf B. himself

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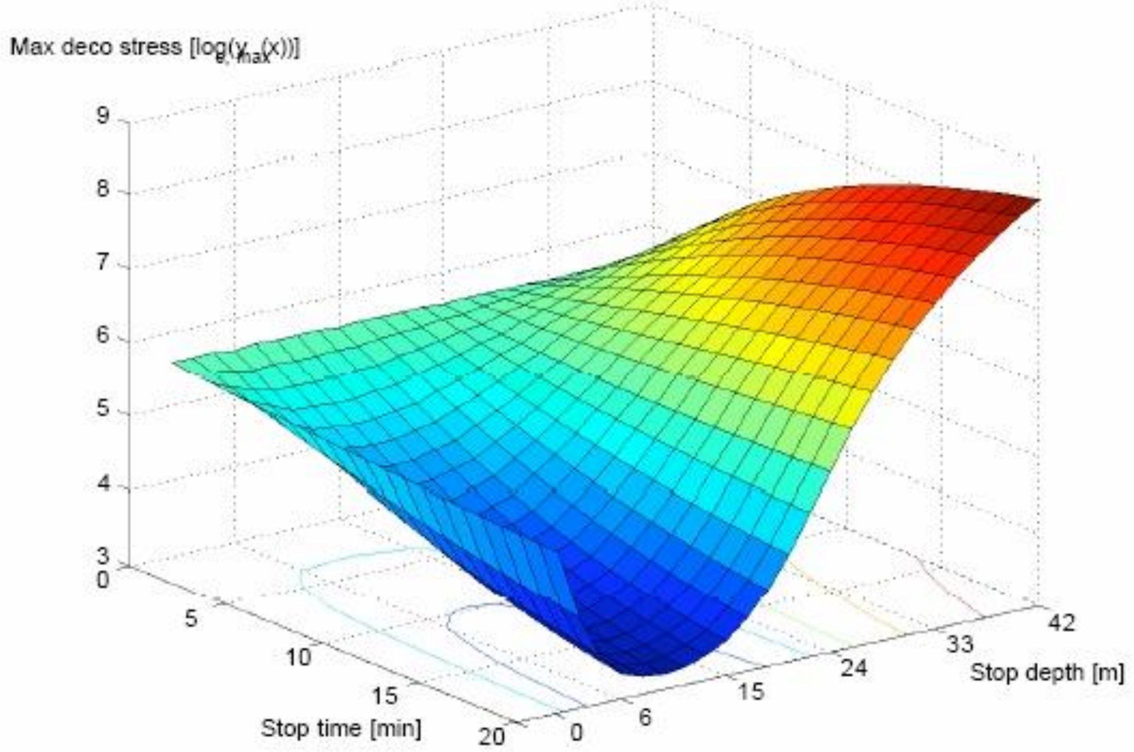
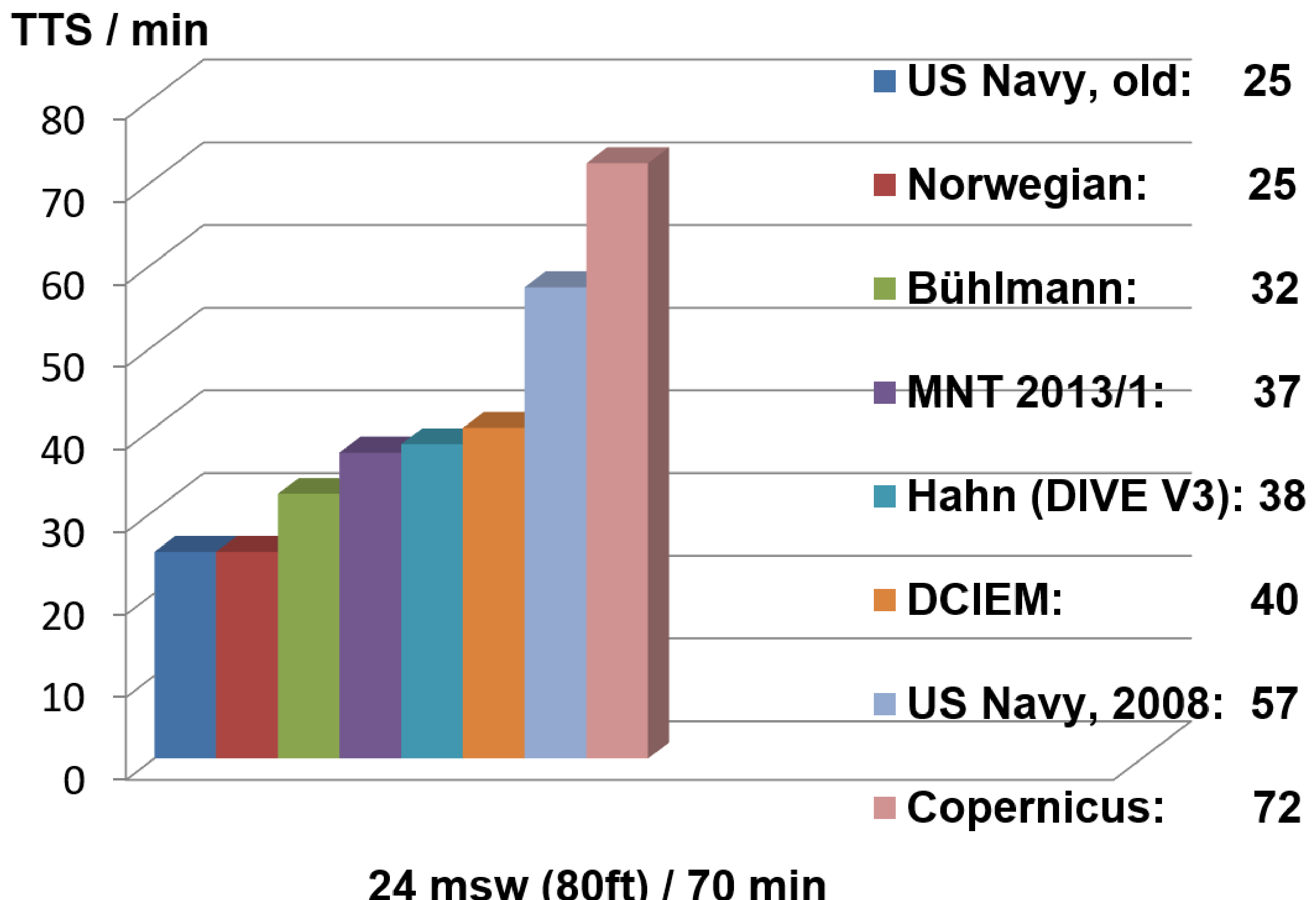


COPERNICUS

www.ntnu.no

Total decompression time + Ascent
Air dives → corr. by ALBI @ SMC



Possible, tentative and surprising conclusion

- Dives with long, > 30 minutes, bottom time <u>may</u> benefit from deep stops
- Dives with short, < 30 minutes, bottom time <u>will not benefit</u> from deep stops.

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P(DCS):
statistical probability (P) of contracting a decompression sickness (DCS)

P(DCS) = 1.0 – P(no DCS)

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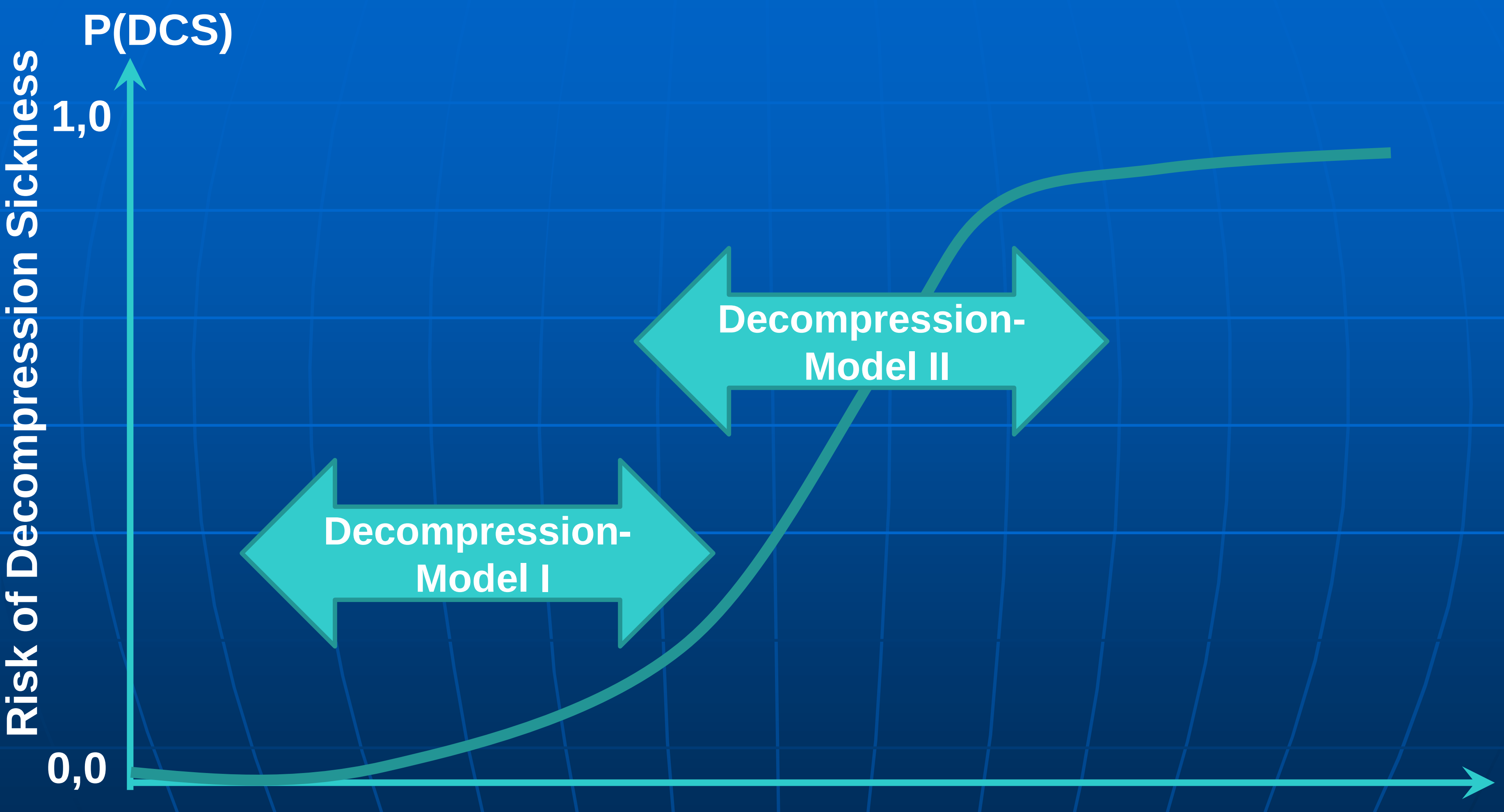
P(DCS): dose- / response curve according to Hill



Inertgas Dose, eg.: Depth * Time; or p * SQRT(t); or: „deco stress“, # bubbles, bubble volume, Doppler Counts, …

„deterministic“ vs. „statistic“

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INPUT:

Dive Parameters:
- → depth
- → time
- → fO_2
- → …

Calibration Database:
- → n * 10^3 dives …
- → biometrics
- → environment
- → DCS outcome /
- → doppler scores …

MODEL TYPE:

deterministic

statistic

OUTPUT:

SAD (safe ascent depth, ceiling)
stop depth & time

P(DCS)
probability of contracting DCS

„deterministic“ vs. „statistic“

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statistic

P(DCS) probability of contracting DCS

Depth feet	m	P(DCS) = 0,05 5% NDL [min]	P(DCS) = 0,01 1% NDL [min]	USN old (= PADI, old) NDL [min]	USN 2008 NDL [min]	RGBM dive #1 NDL [min]	RGBM dive #2 NDL [min]	DSAT RDP (= PADI, new) NDL [min]
25	7,6	-	-	595	1102	-	-	-
30	9,1	240	170	405	371	150	150	-
35	10,7	-	-	310	232	-	110	-
40	12,2	170	100	200	163	110	110	140
50	15,2	120	70	100	92	80	80	80
60	18,2	80	40	60	63	55	55	55
70	21,3	80	25	50	48	40	40	40
80	24,4	60	15	40	39	30	30	30
90	27,4	50	10	30	33	25	n.a.	25
100	30,5	50	8	25	25	20	n.a.	20
110	33,5	40	5	20	20	16	n.a.	17
120	36,6	40	5	15	15	13	n.a.	14
130	39,6	30	5	10	12	10	n.a.	12

„deterministic“ vs. „statistic“

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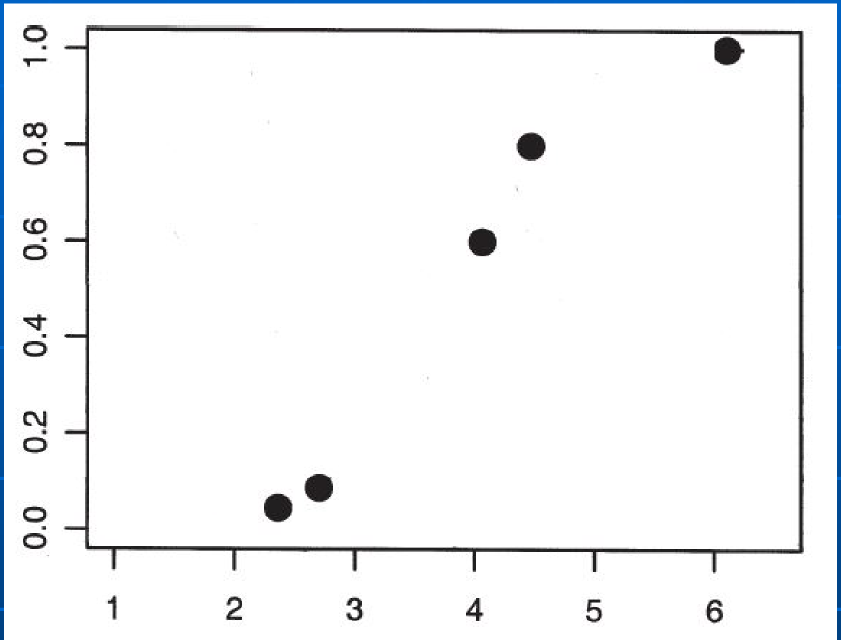

P(DCS) →

saturation pressure, p_{amb} [atm] →

original data from Haldane: experiments with goats

„deterministic“ vs. „statistic“

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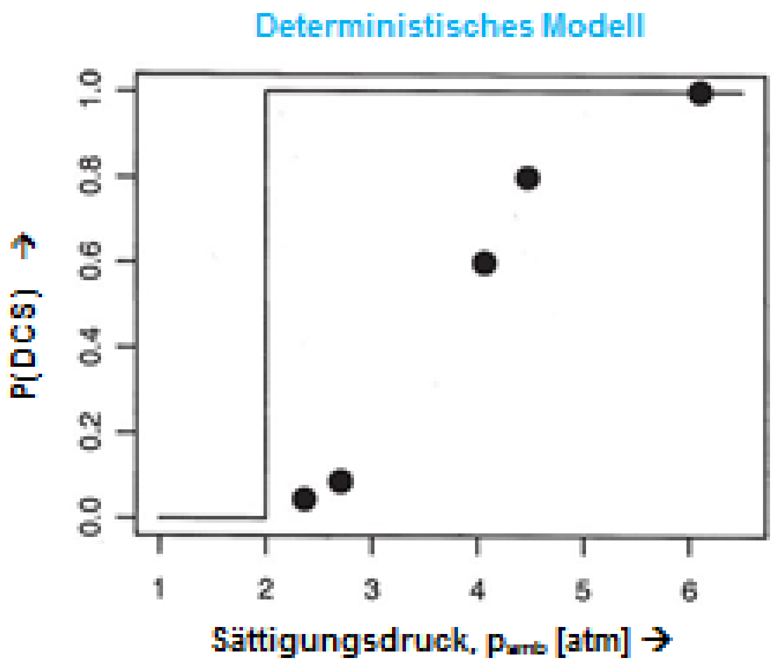

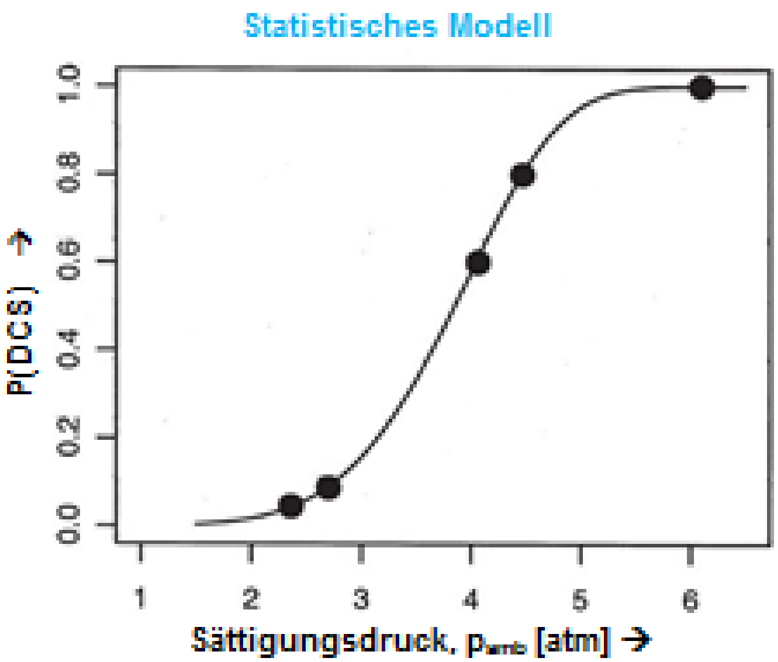

P(DCS) = 1.0 – e^X

mit:

X =(-0,00034 * $(atm)^{5.65}$)

atm sind die Werte an der X-Achse

Source: David J. Doolette, South Pacific Underwater Medicine Society (SPUMS) Journal Volume 35 No. 1 March 2005, S. 28 – 31

„deterministic“ vs. „statistic“

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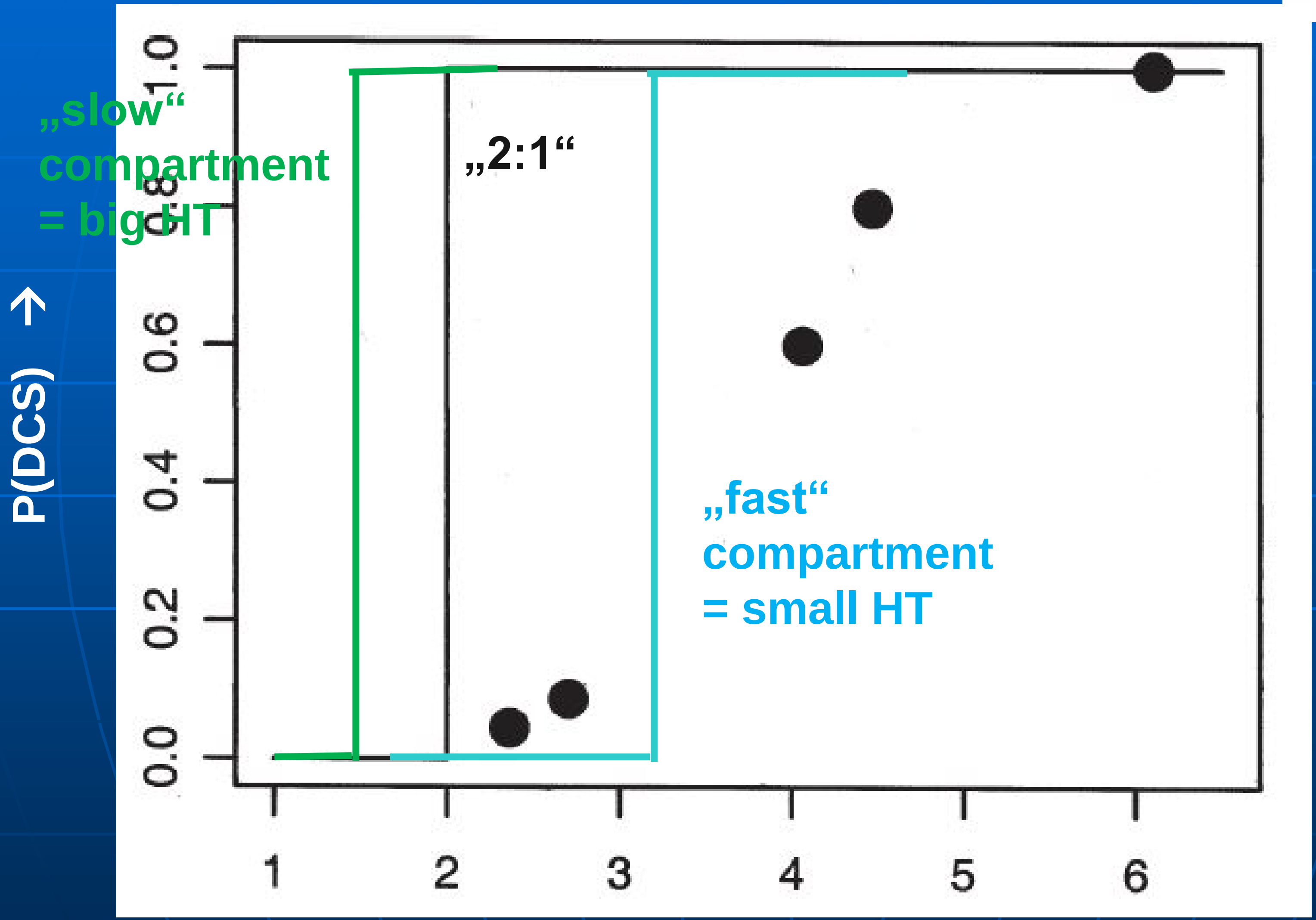

Surfacing Values (M_0), $p_{tiss, tolerated}$ [Bar] →

Prominent representatives of the others and working examples

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- → **Bühlmann:**
  - → **1000 ft experiments (Keller et al.)**
  - → **Max Hahn**
  - → **& Deco-Brain**

- → **United States Navy (USN)**
  - → **New diving manuals: no more 10 feet stops**
  - → **LEM / VVAL18**

Bühlmann

B
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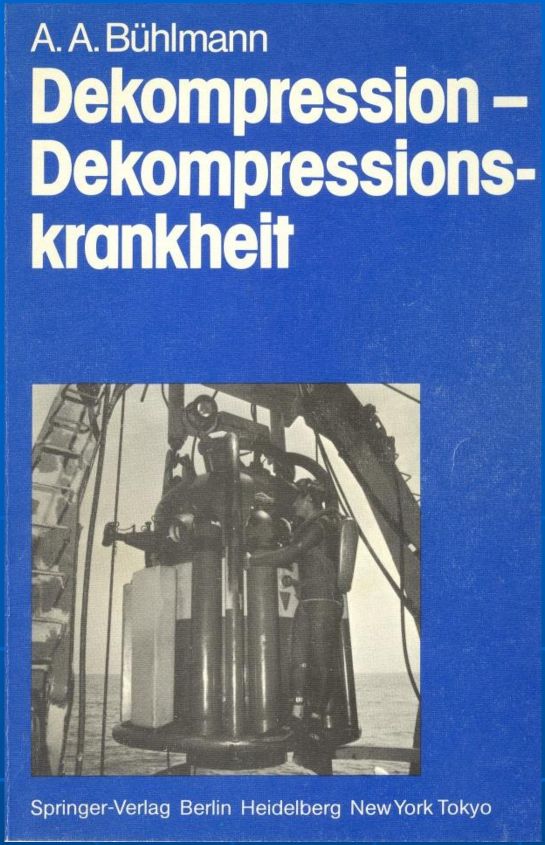

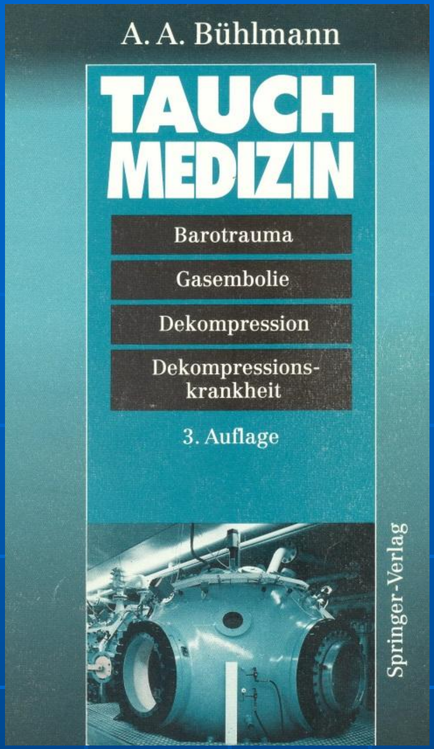

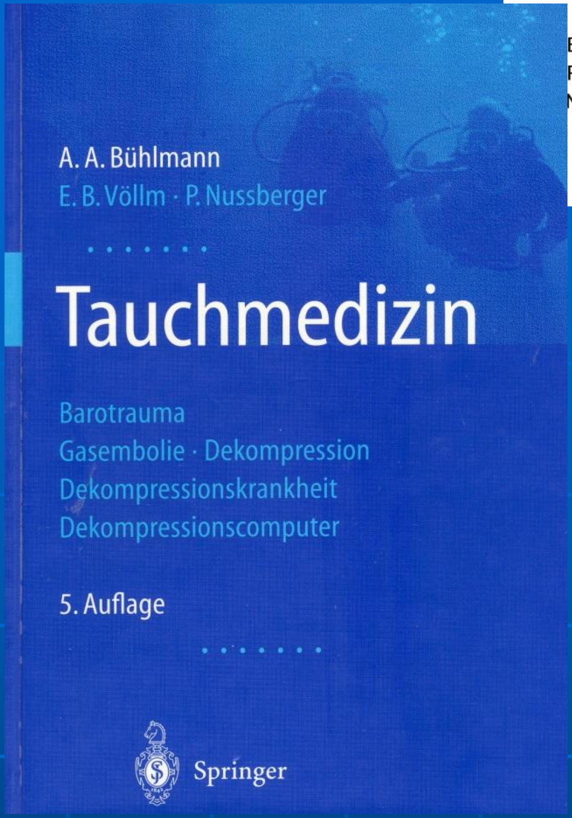

[4] Dekompression - Dekompressionskrankheit, A. A. Bühlmann, Springer, 1983, ISBN 3-540-12514-0

[5] Tauchmedizin (Barotrauma, Gasembolie, Dekompression, Dekompressionskrankheit) A. A. Bühlmann, Springer, 1993, ISBN 3-540-55581-1

[65] "Tauchmedizin", Albert A. Bühlmann, Ernst B. Völlm (Mitarbeiter), P. Nussberger; 5. Auflage in 2002, Springer, ISBN 3-540-42979-4

Bühlmann (1)

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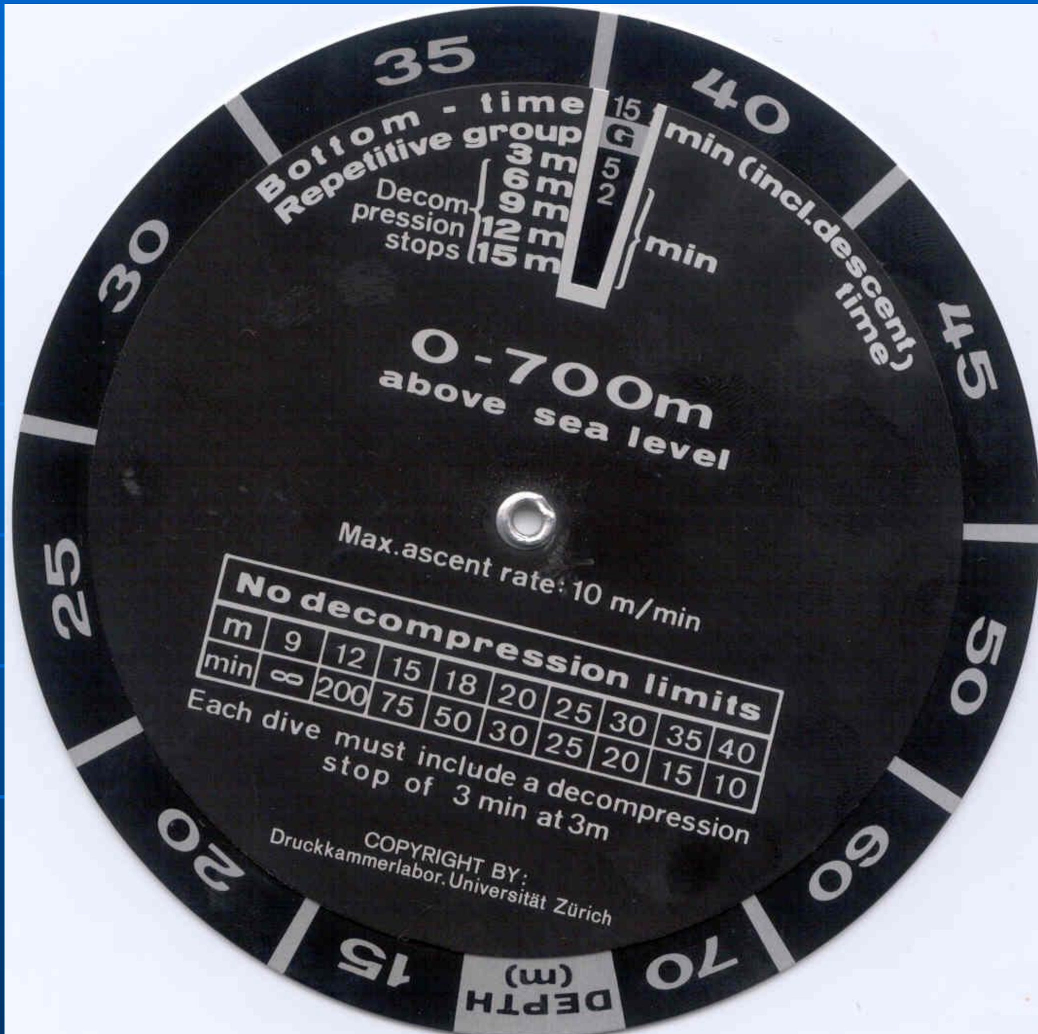

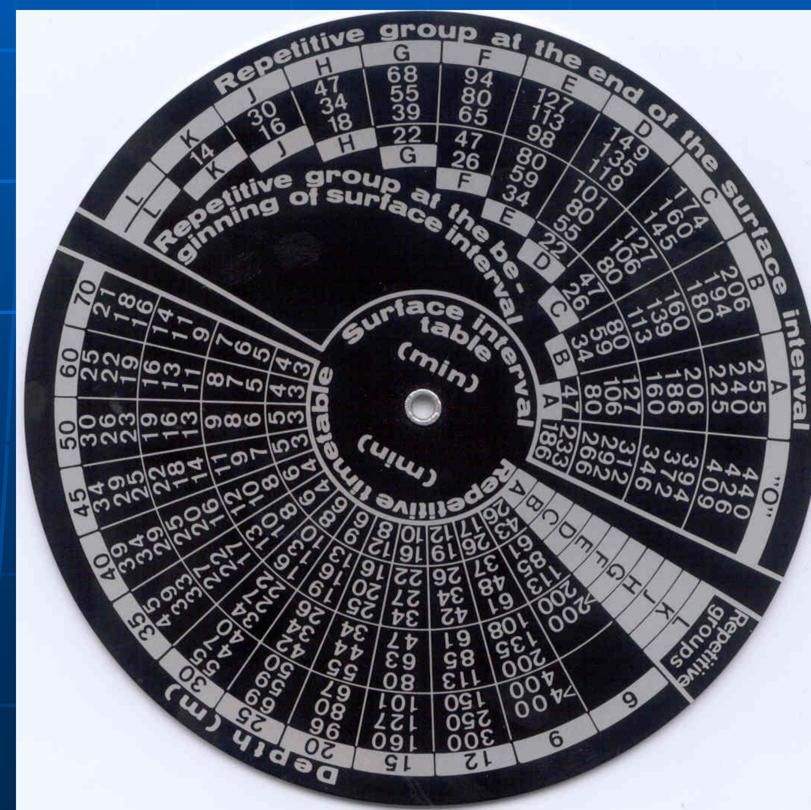

Bühlmann - Hahn

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Tauchtiefe (m) Nullzeit (min)	Grundzeit (min)	Dekopausen 6	Dekopausen 3	Wiederholungsgr.
9 (615')	20			B
	40			C
	80			D
	120			E
12 (174')	15			B
	30			C
	45			D
	60			E
	90			F
15 (93')	15			C
	30			D
	45			E
	60			F
	90			G
18 (63')	10			B
	20			C
	30			D
	40			E
	60			F
	70		4	G
	80		8	G
	90		15	G
21 (38')	10			B
	20			D
	30			E
	40		1	F
	50		3	F
	55		6	G
	60		9	G
	65		12	G
	70		16	G
	75		20	G
24 (26')	10			C
	20			D
	30		1	E
	40		4	F
	45		7	F
	50		11	G
	55		15	G
	60	1	19	G
	65	2	24	G
	70	4	26	G
	75	6	29	G

Tauchtiefe (m) Nullzeit (min)	Grundzeit (min)	Dekopausen 9	Dekopausen 6	Dekopausen 3	Wiederholungsgr.
27 (20')	10				C
	20				D
	25			2	E
	30			3	F
	35			5	F
	40		1	9	F
	45		1	14	F
	50		3	17	G
	55		4	23	G
	60		7	26	G
30 (17')	10				C
	15				D
	20			2	D
	25			4	E
	30		1	5	F
	35		2	10	F
	40		4	14	G
	45		5	19	G
	50		8	24	G
	55	1	11	27	G
	60	2	13	30	G
33 (14')	5				B
	10				C
	15			1	D
	20			4	E
	25		2	5	F
	30		3	8	F
	35		5	14	G
	40	1	6	19	G
	45	2	8	25	G
	50	3	12	28	G
36 (9')	5				B
	10			1	C
	15			2	D
	20		1	4	E
	25		3	7	F
	30	1	4	13	G
	35	2	6	18	G
	40	3	9	24	G
	45	5	12	29	G

Tauchtiefe (m) Nullzeit (min)	Grundzeit (min)	Dekopausen 12	Dekopausen 9	Dekopausen 6	Dekopausen 3	Wiederholungsgr.
39 (7')	5					C
	10				1	D
	15				4	E
	20			3	5	F
	25		1	4	10	G
	30		3	5	16	G
	35	1	3	8	23	G
	40	2	5	12	28	G
42 (5')	5					C
	10				1	D
	15			1	5	E
	20		1	4	6	F
	25		3	5	13	G
	30	1	4	7	20	G
	35	4	4	11	27	G
45 (5')	3					B
	6				1	D
	9				1	E
	12				4	E
	15			3	4	E
	18		1	4	6	F
	21		3	4	10	G
	24	1	3	6	14	G
	27	2	4	6	20	G
	30	3	4	9	25	G
48 (4')	3					C
	6				1	D
	9				3	E
	12			2	4	E
	15		1	3	5	F
	18		3	4	8	F
	21	1	4	4	14	F
	24	2	4	6	18	G
	27	4	4	8	24	G
51 (4')	3					C
	6				1	D
	9				4	E
	12			3	4	F
	15		2	4	6	F
	18	1	3	4	11	F
	21	3	3	6	16	G

Austauchtabelle Bühlmann / Hahn 251–700m ü. N. N.

Aufstiegsgeschwindigkeit 10 m/min

Bühlmann (2)

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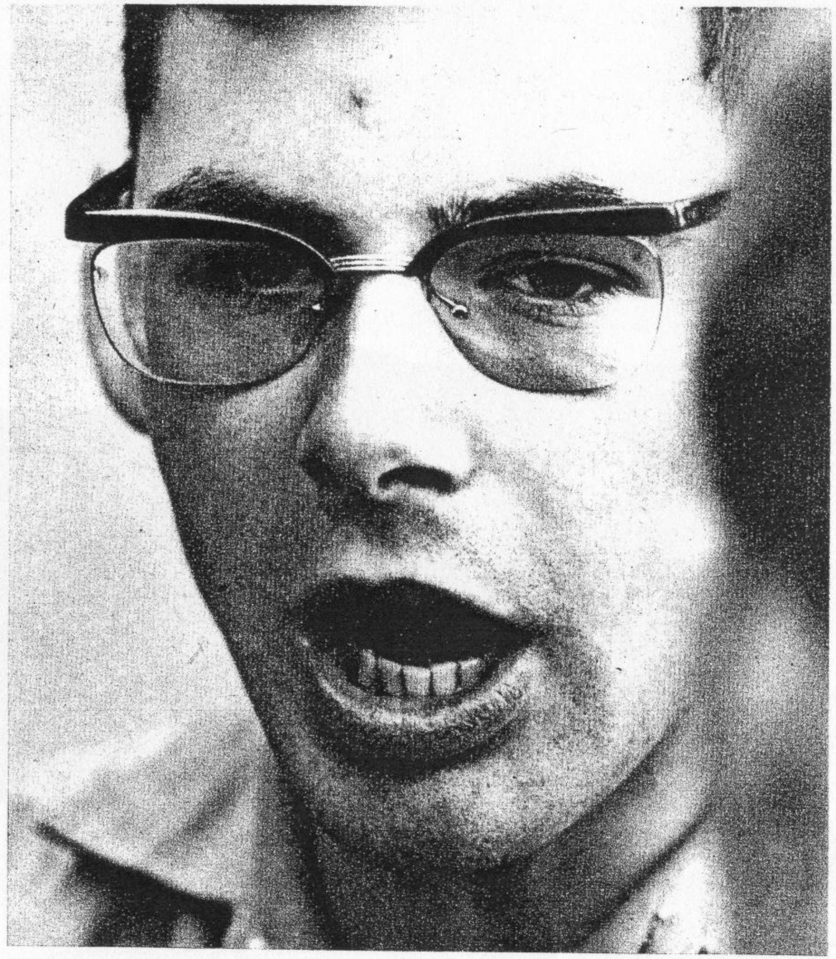
Rekord und Tod



„Mein System hat keinen Fehler!“

So verteidigte sich Hannes Keller (28), Mathematiker aus Winterthur, gegen den Vorwurf, er habe seine Kameraden dem Rekordwahn geopfert. Bisher war er mit 220 Meter Tiefe bereits Rekordtaucher der Froschmänner. Unter seinem System versteht er die von ihm konstruierte Druckkammer und die von ihm benutzte Atemgas-Mischung. Als man ihm vorhielt, daß der berühmte Tiefseetaucher Prof. Piccard ihn gewarnt habe, meinte er: „Auch ein so großer Forscher konnte meine Tauchtechnik nicht beurteilen“

Source: „stern“, december 1962

Bühlmann (3)

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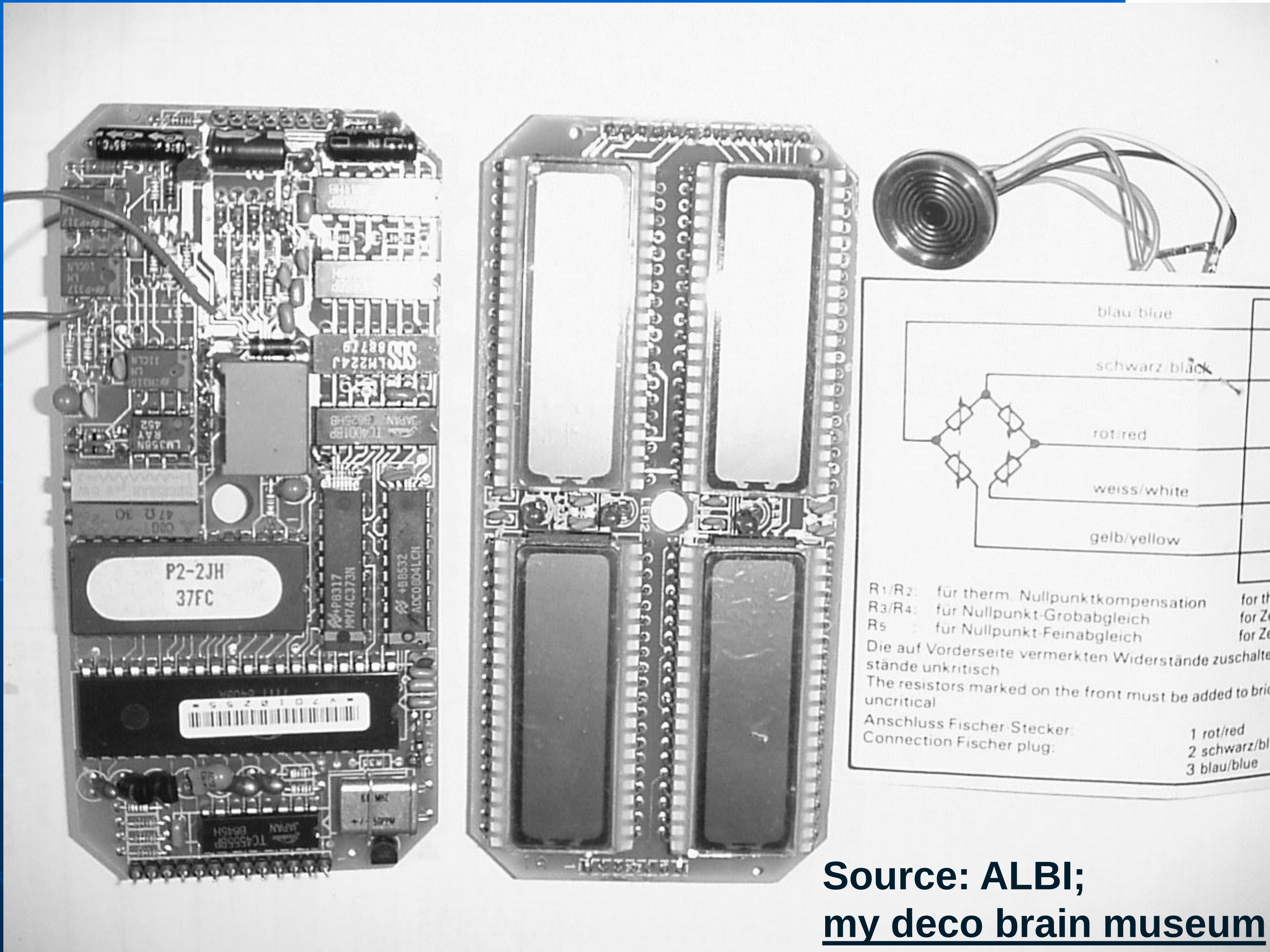

Source: ALBI;
my deco brain museum

Bühlmann (4)

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Source: ALBI;
my deco brain museum

USN (1)

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SS521-AG-PRO-010

0910-LP-115-1921 REVISION 7

U.S. Navy Diving Manual

Volume 1:	Diving Principles and Policies
Volume 2:	Air Diving Operations
Volume 3:	Mixed Gas Surface Supplied Diving Operations
Volume 4:	Closed-Circuit and Semiclosed Circuit Diving Operations
Volume 5:	Diving Medicine and Recompression Chamber Operations

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SUPERSEDES SS521-AG-PRO-010, REVISION 6 CHANGE A, Dated 15 October 2011.

PUBLISHED BY DIRECTION OF COMMANDER, NAVAL SEA SYSTEMS COMMAND

01 DECEMBER 2016
CHANGE A 30 APRIL 2018

Sources:
[14], [15],
[15a], [15b], [15c], [15d]

USN (2)

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Source: Workman R. D. (1965) NEDU Report 6-65

$$M = M_0 + \Delta M * d$$

	N2:				He:		
	HWZ [min]	**M_0 - Wert**	**ΔM Delta M**		**HWZ [min]**	**M_0 - Wert**	**ΔM Delta M**
#		(fswa)				(fswa)	
1	5	104	1,8		5	86	1,5
2	10	88	1,6		10	74	1,4
3	20	72	1,5		20	66	1,3
4	40	56	1,4		40	60	1,2
5	80	54	1,3		80	56	1,2
6	120	52	1,2		120	54	1,2
7	160	51	1,2		160	54	1,1
8	200	51	1,1		200	53	1,0
9	240	50	1,1		240	53	1,0

USN (3)

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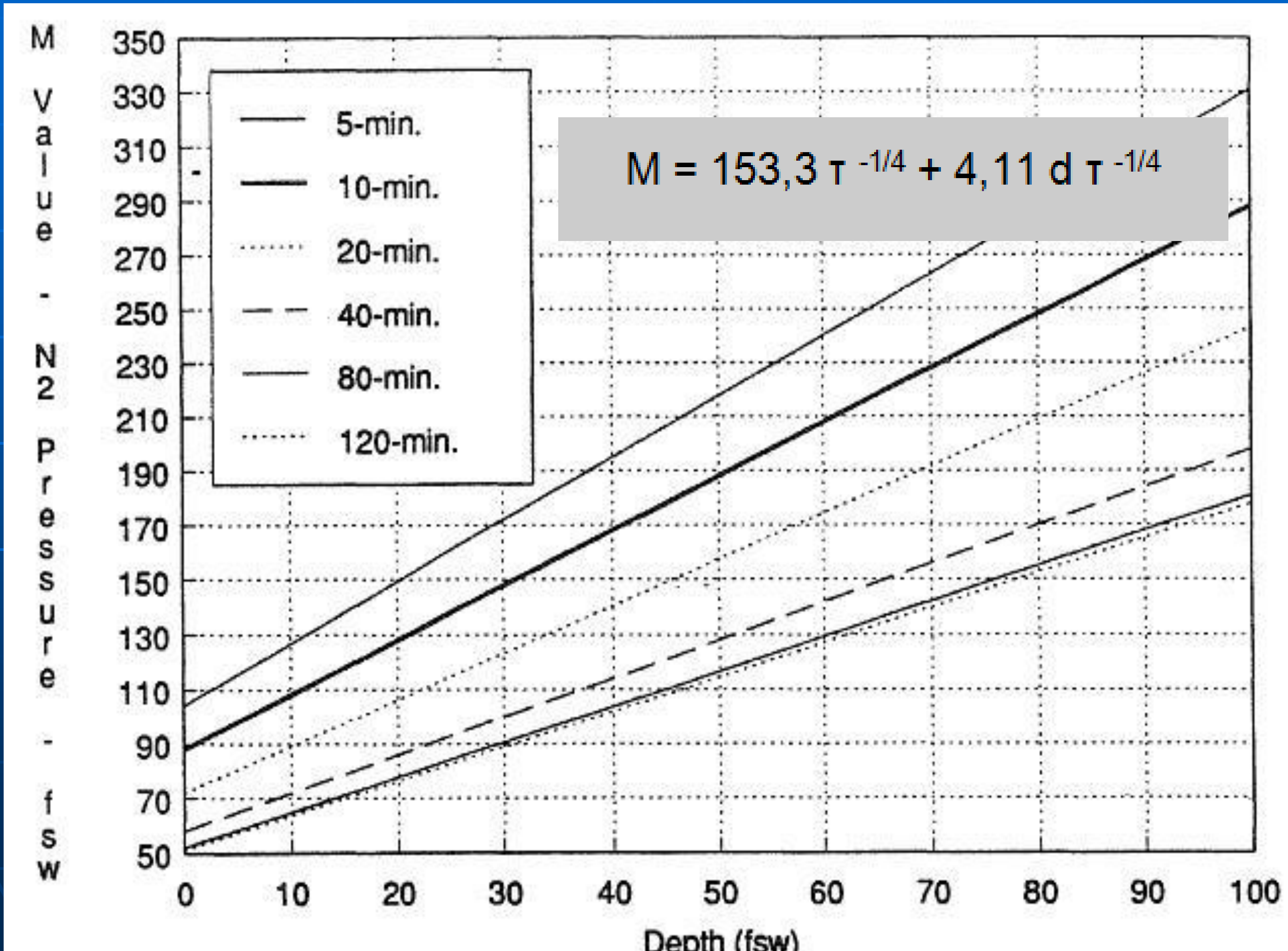

$$M = 153{,}3\,\tau^{-1/4} + 4{,}11\,d\,\tau^{-1/4}$$

Source: THE DYNAMICS OF DECOMPRESSION WORKBOOK, First Edition, 1992 by Karl E. Huggins, p. 3-5

Prominent representatives of the others and working examples

→ **USN (4) / LEM / VVAL18**

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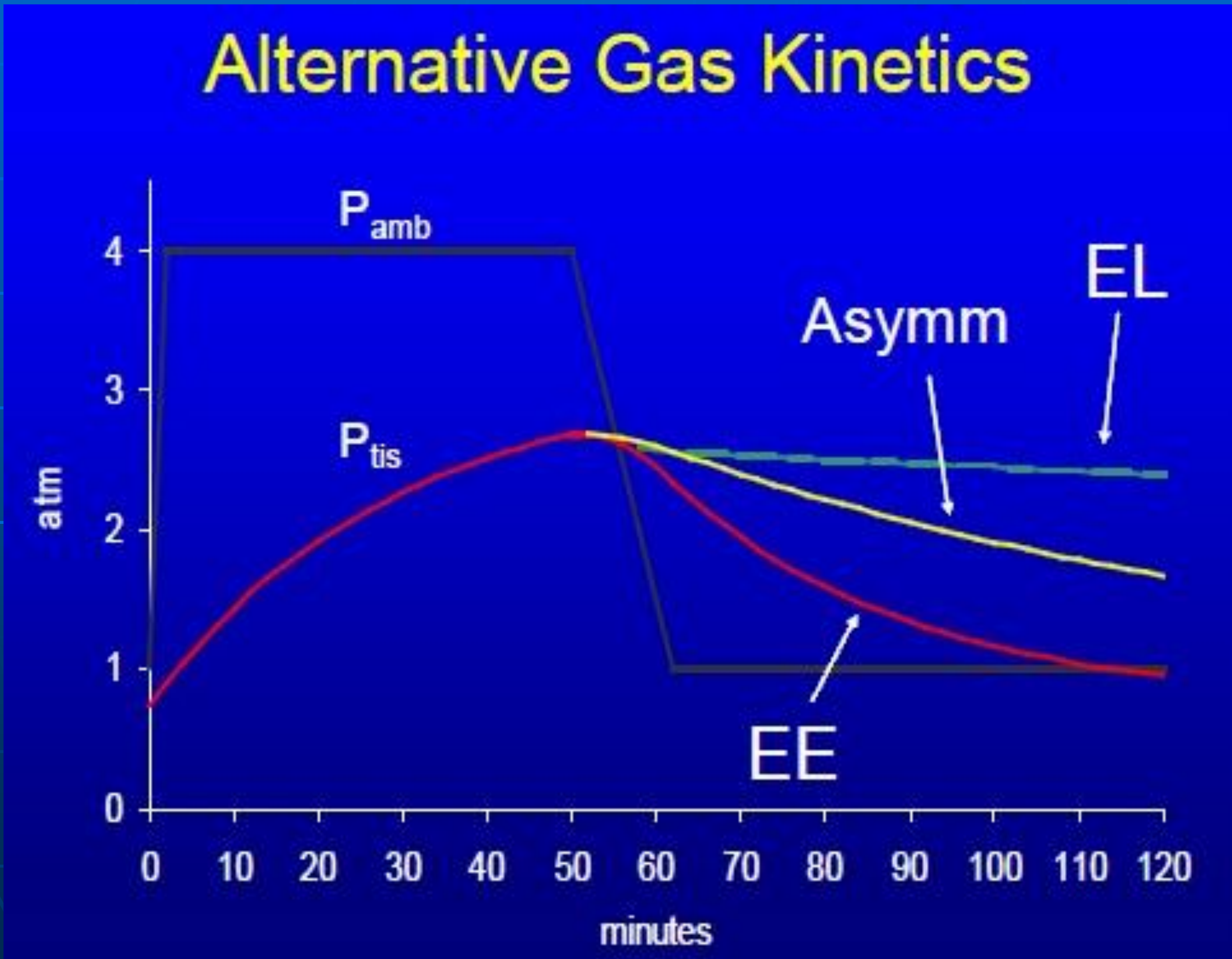

LEM: Linear-Exponential-Multigas
VVAL 18: name of variable in the FTN source code

Coda:

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"Haldane works if you use it properly!"

R.W. Hamilton
17th UHMS workshop, p. 135;
1978

Bonus Material:

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→ **Exotic Models & strange Implementations**

→ **DCS as a „CUSP“ catastrophe?**

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Exotic Models & strange Implementations:

→ ONE compartment (1-tissue model)
→ CMD (Complex Mathematical Decompression)
→ ABM (Articular Bends Model)
→ COMEX (AB-Model, Compagnie Maritime d'Expertises)
→ RGBM (Reduced Gradient Bubble Model, B.R. Wienke)
→ TBDM (Tissue Bubble Diffusion Model, M. L. Gernhardt)
→ Srinivasan & Gerth: plethora of bubble models …
→ Saul Goldman‘s models (Safe Advanced Underwater aLgorithm, or S.A.U.L.); (3CM)
→ PADUA (Pennsylvania Analysis of Decompression for Undersea and Aerospace)
→ GFM (Gas Formation Model)
→ PBPK („physiologically based pharmacokinetic" models); often combinations of parallel and serial compartments
→ Contractors Tables (deep secret … ☺)
→ EXPOSER (DRF, HT 1 s → 2760 min)
→ $\aleph_0$ infinite (∞) many compartments
→ .
→ ..

WARNING: this is not a concluding list!

Not Chaos-, but: Catastrophe-Theory!

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"Note:
The senior (elder) author believes that
the only explanation for most cases of DCS
lies in the random application
of Chaos Theory,
which he also does not understand,
or String Theory
which no-one understands."

[Diving Medicine for Scuba Divers, Edmonds et al.,
ISBN: 978-0-646-52726-0, p. 138]

Not Chaos-, but: Catastrophe-Theory!

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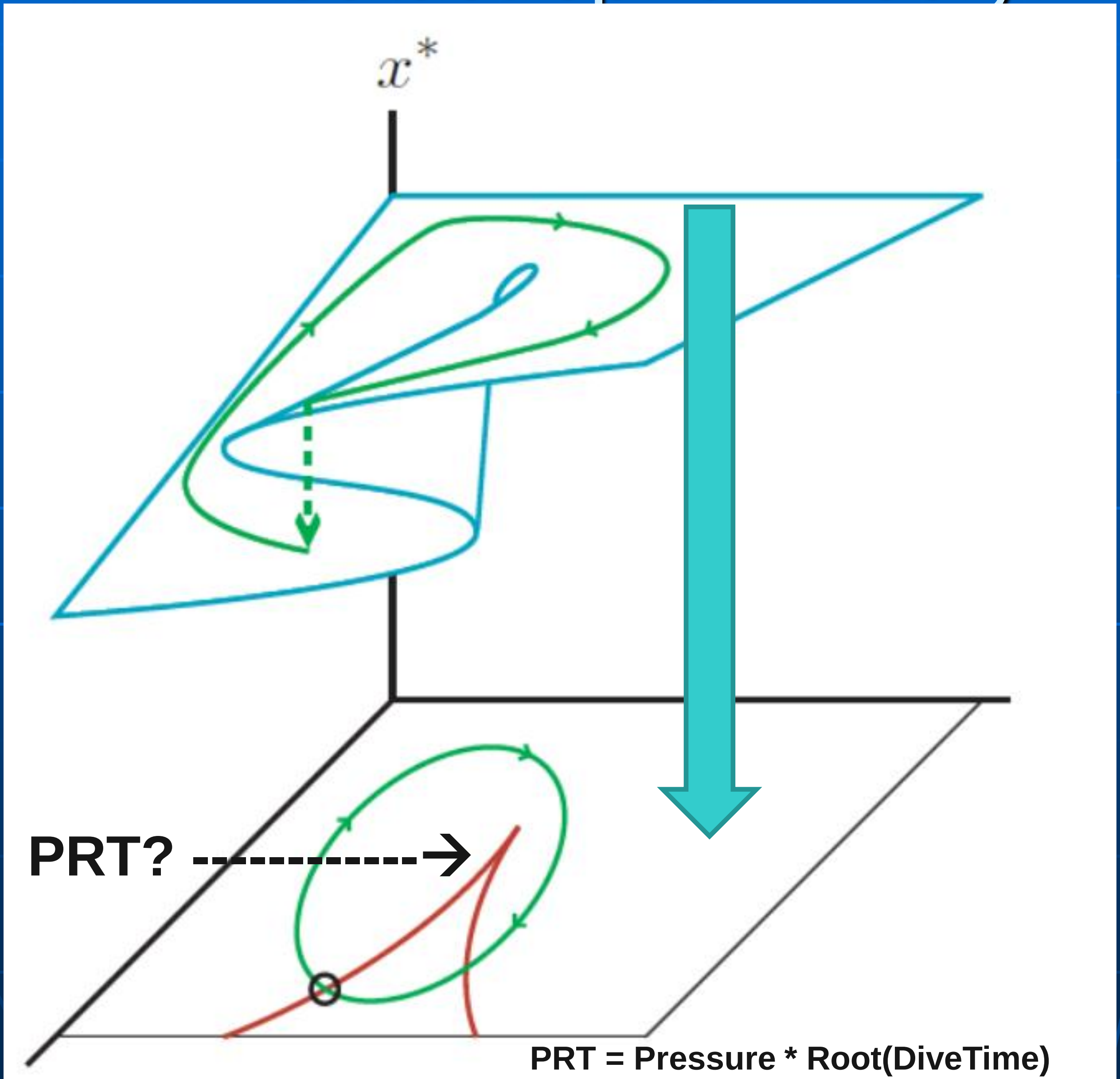
Sources:

→ **Thom, R. (1972)**
Stabilite Structurelle et Morphogenese,
W. A. Benjamin, Reading, MA; English transl.:
Structural Stability and Morphogenesis (by David Fowler), W. A. Benjamin, Reading, MA, 1975.

→ **Gilmore, Robert (1981)**
Catastrophe Theory for Scientists and Engineers
Wiley, ISBN 0-471-05064-4

Not Chaos-, but: Catastrophe-Theory!



Projection of (Energy) Potentialfunction of a „CUSP" catastrophe → i.e.: 1st. & 2nd. Derivative yields:

Bifurcation Set in the plane of Control Variables

Bühlmann Symposium 29./30. März 2019
Universitätsspital Zürich

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History and Development of Decompression Algorithms

Albrecht Salm
Dipl. Phys.
PADI MSDT # 33913
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Q & A ?
Contact: →