Dual Phase Decompression Theory and Bubble Dynamics

23th Capita Selecta Duikgeneeskunde

Amsterdam, 03/17/2018:

21st. Century Decompression Theory

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Dual Phase Decompression Theory and Bubble Dynamics

Agenda (1):

Basics of dual phase theory and its application in diving.

- What is “Dual Phase”?
- (only short) Overview on Bubble Models
- basic bubble physics, kavitation and tribonucleation,
- bubble dynamics and evolution:
- Why does a bubble exist and why does it grow or shrink?
- The critical diameter concept
- The role of bubble seeds (gas nuclei)
- How does a bubble exchange gases with its environment?
- Is a spherical bubble real or does it look more like a “cigar”?
- …

Dual Phase Decompression Theory and Bubble Dynamics

<u>Agenda (2):</u>

Basics of dual phase theory and its application in diving.

- Basics of the “Varying Permeability Model” (VPM)
- VPM in a nut-shell
- The shortcomings @ VPM
- “Colors” of VPM
- BVM(3) (Bubble Volume Model, USN)
- modern Hybrid-Deco-Models: “Copernicus”
- …

Bubble Models

Description of the free gas phase (= bubbles)

3 prominent representatives:

→ <u>VPM</u> (Varying Permeability Model; deterministic)

- **„best fit“ via USN, RNPL, TEKTITE**
- **Implementations in various mix gas computers & free-/share ware programs**

→ <u>RGBM</u> (Reduced Gradient Bubble Model; deterministic)

- **cryptic …, „VPM like“**
- **licence models for Suunto® & Mares® computers**
- **relatively great bubbles method … (© ALBI)**

→ <u>BVM(3)</u> (Bubble Volume Model; probabilistic)

- **USN / 3 compartments (HT = 1; 26; 316 min.)**

Bubble Models

Description of the free gas phase (= bubbles)
The prominent deterministic representatives:

→ **<u>these are all DUAL PHASE</u>**
→ **<u>i.e.: FREE phase (gas bubbles)</u>**
→ **<u>AND the</u>**
→ **<u>LIQUID phase (gas in solution)</u>**
→ **this is the perfusion part of the model:**
→ **Start: saturation**
→ **End: de-saturation**

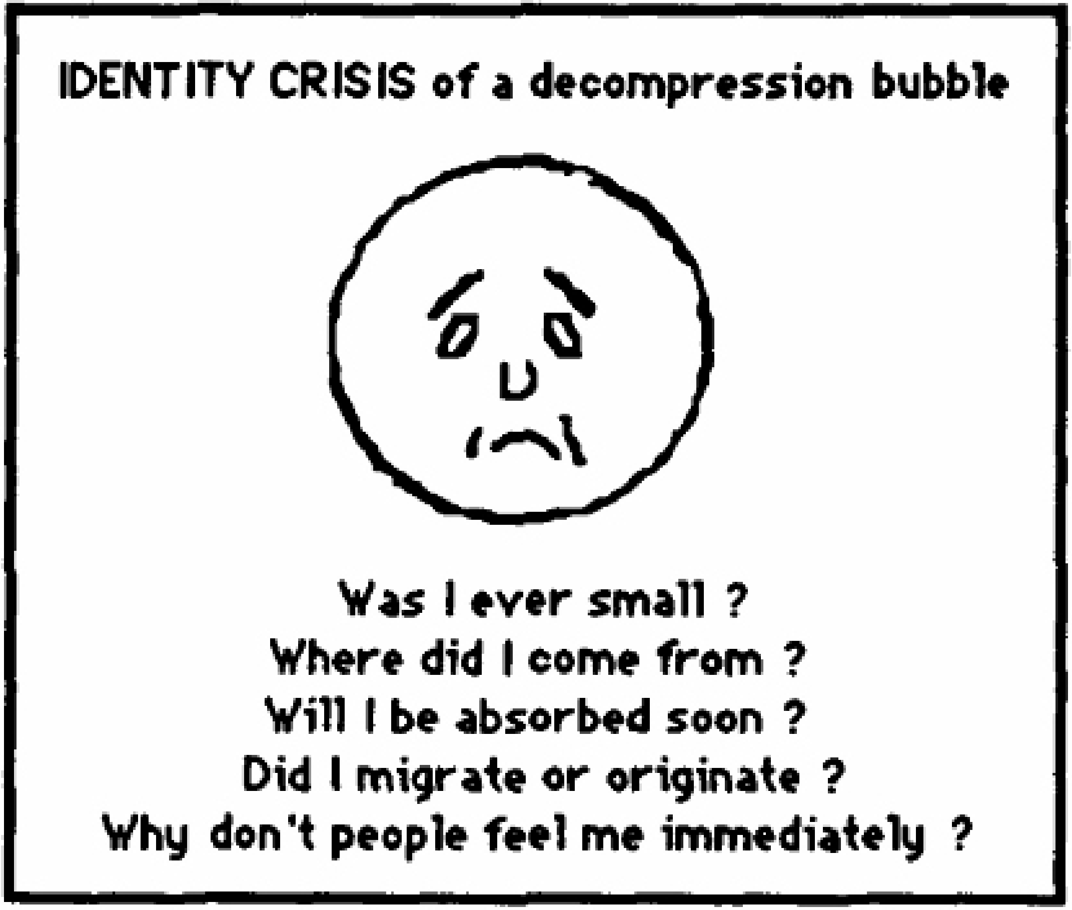
→ **only difference to Haldane, Workman, etc:**
→ **„1 equation“ for „safe ascent“**
→ **constant for all compartments / half-times**
→ **constant for all depths**

Sources:

- → **VPM: 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**

- → **RGBM: [71] "Reduced Gradient Bubble Model in depth", Bruce R. Wienke, Best Publishing Company, 2003, ISBN 1-930536-11-9**

- → **BVM(3): Gerth WA, Vann RD. Probabilistic gas and bubble dynamics models of decompression sickness occurrence in air and N2-O2 diving. Undersea Hyperb Med. 1997;24:275-92.**



Some important questions about decompression sickness bubbles; see text.

AL-SR-1992-0005

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THE PROCEEDINGS OF THE 1990 HYPOBARIC DECOMPRESSION SICKNESS WORKSHOP

Edited by

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ARMSTRONG LABORAT

CREW SYSTEMS DIRECTORATE
CREW TECHNOLOGY DIVISION
Brooks Air Force Base, TX 78235-5000

June 1992

Final Special Report for Period 16-18 October 1990

Basic Model with Bubble Seed

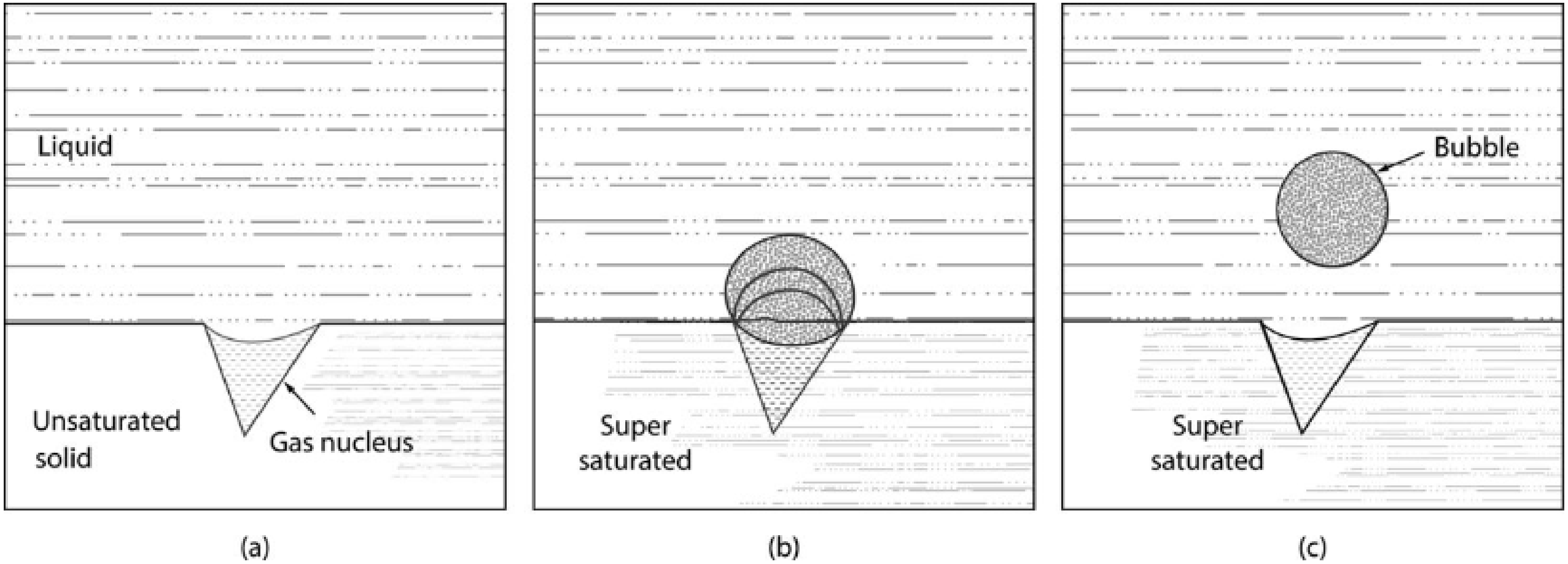

Figure 10.6 Depiction of a gas micronucleus resident in a crevice on a blood vessel wall. In the unsaturated state (a), the nucleus is quiescent. When the underlying tissue becomes supersaturated (b), gas diffuses into the nucleus and causes it to grow until such time that a bubble breaks off (c), after which the cycle will be repeated.

Source: Edmonds et al., 5.th edition, 2016, p. 129

Kavitation

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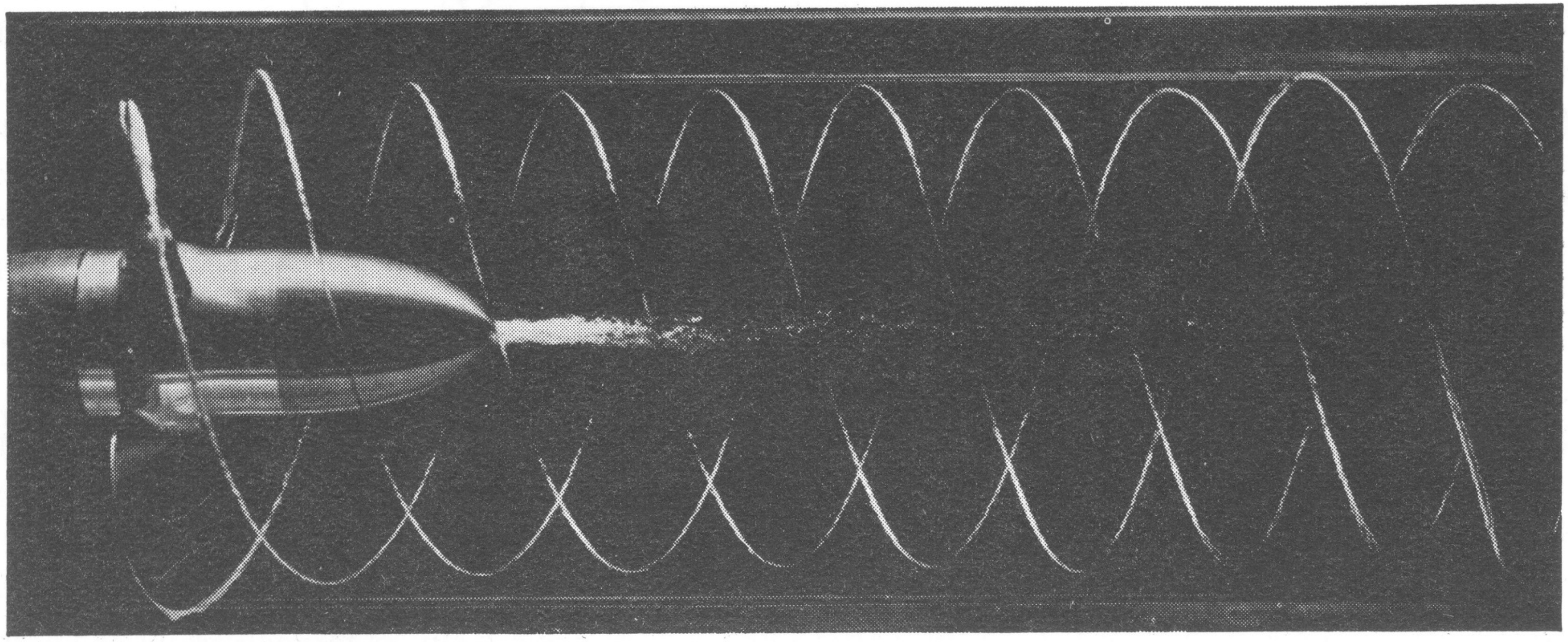

Abb. VII, 54. Kavitationsblasen hinter einem rotierenden Schiffspropeller (Versuchsanstalt für Wasserbau und Schiffbau, Berlin)

Tribonucleation

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Michael Powells Law:

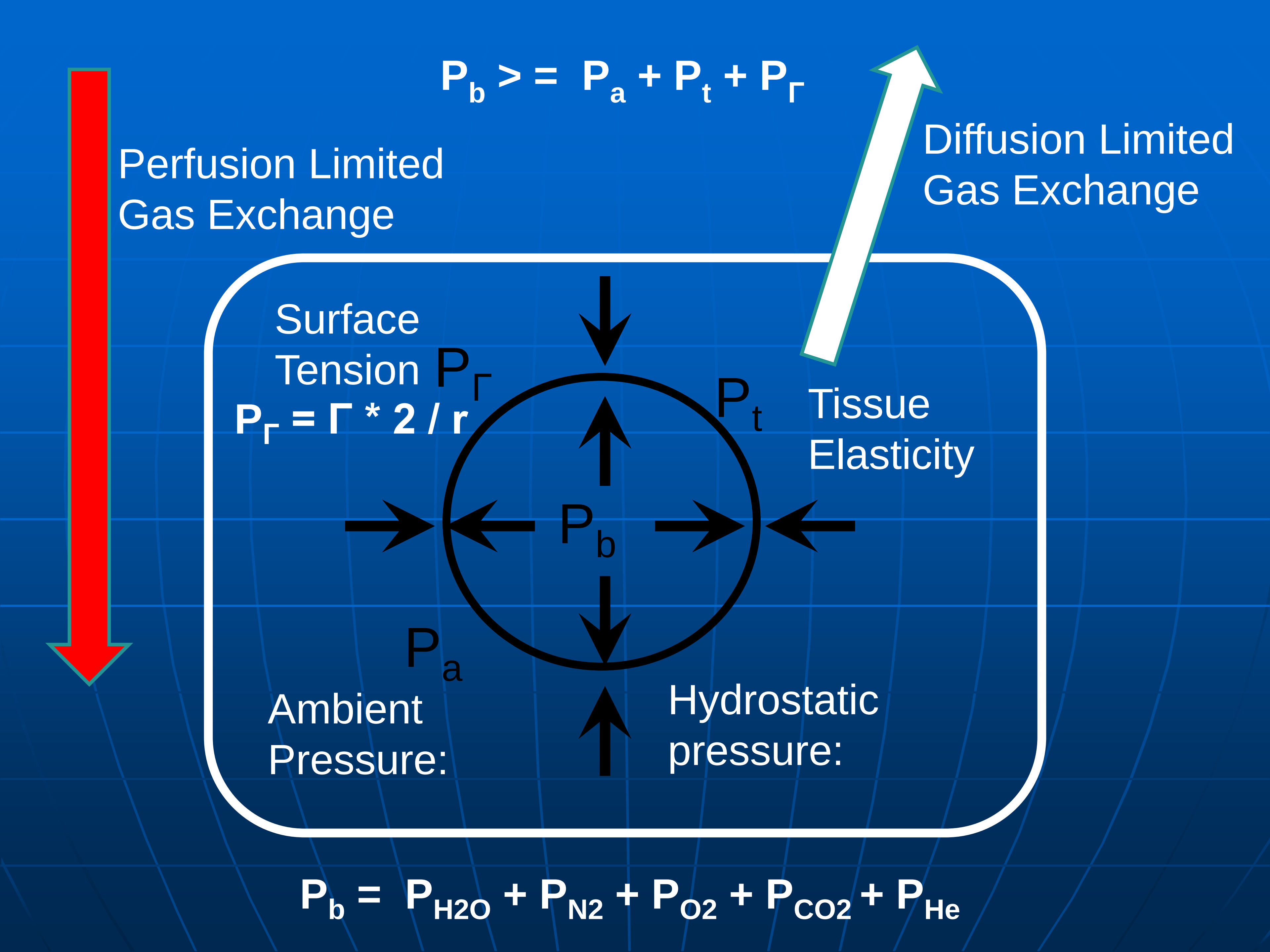
You will form many micronuclei in the gym while lifting weights,

but you will never get DCS!


12 20:28

12 20:55

12 21:03



$P_b >= P_a + P_t + P_\Gamma$
Perfusion Limited Gas Exchange
Diffusion Limited Gas Exchange
Surface Tension P_Γ
$P_\Gamma = \Gamma * 2 / r$
P_t
Tissue Elasticity
P_b
P_a
Ambient Pressure:
Hydrostatic pressure:
$P_b = P_{H2O} + P_{N2} + P_{O2} + P_{CO2} + P_{He}$

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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

Generic example for a small bubble:

Γ = 50 dyn/cm
r = 1 µm, then:
P_Γ = 1 Bar
and thus the internal bubble pressure:
ca. 2 Bar @ P_a = 1 Bar and P_t = 0.

Water / Air e.g.: Γ = ca. 72 mN/m @ ca. 37° C;
Blood / Air e.g.: Γ = ca. 58 mN/m @ ca. 37° C;
Quicksilver (Hg) / Air: Γ = ca. 485 mN/m @ ca. 20° C
Ether / Air: Γ = ca. 20 mN/m @ ca. 20° C

For a valid doppler-reading required:
r > 40 µm and / or v > 20 cm/sec
depending on site (pre-cordial, sub-clavia, …) &
measuring frequency (1- 6 MHz)

The critical radius r_c

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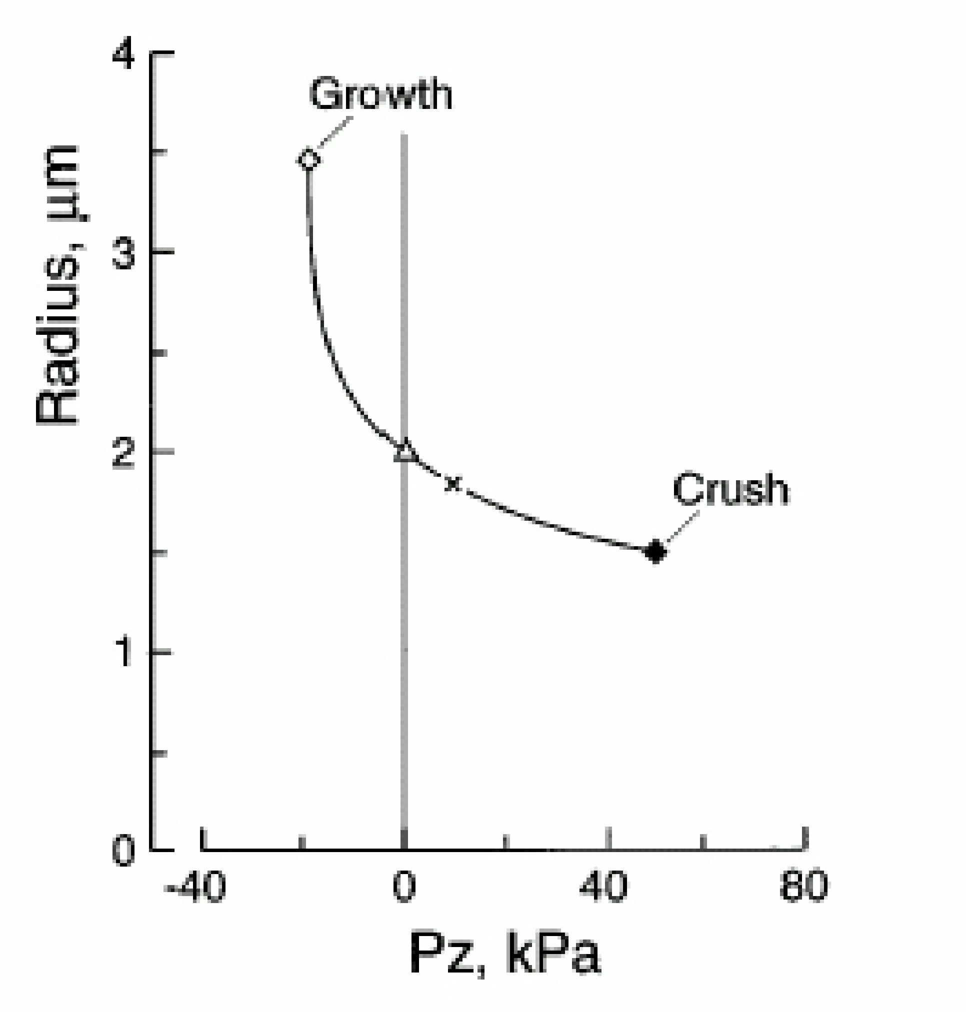

The critical radius r_c

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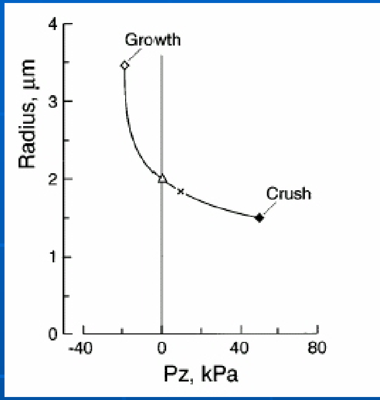
Metastable state, bubble either:
→ crushes
→ expands



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

$P_t = 0$, 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 $P_{SS} = P_b - P_a$

For P_{SS}, please see as well slides # 27, 34/35, 41/43

The critical radius r_c

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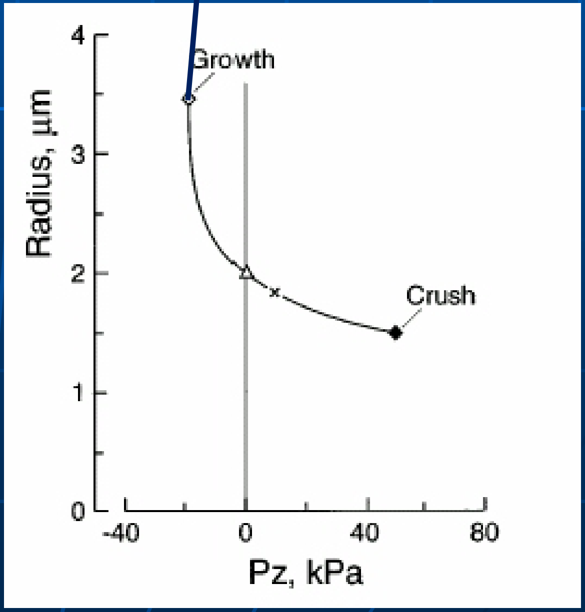
But that's only (linear) theory!!!

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 …]



The critical radius r_c

practical
Application of Murphy's Law:

Linear Models
produce simple, beautiful
and easy
to understand
wrong answers ….

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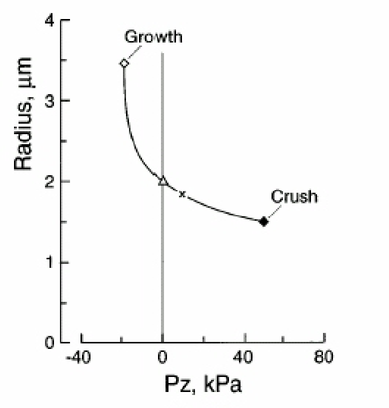
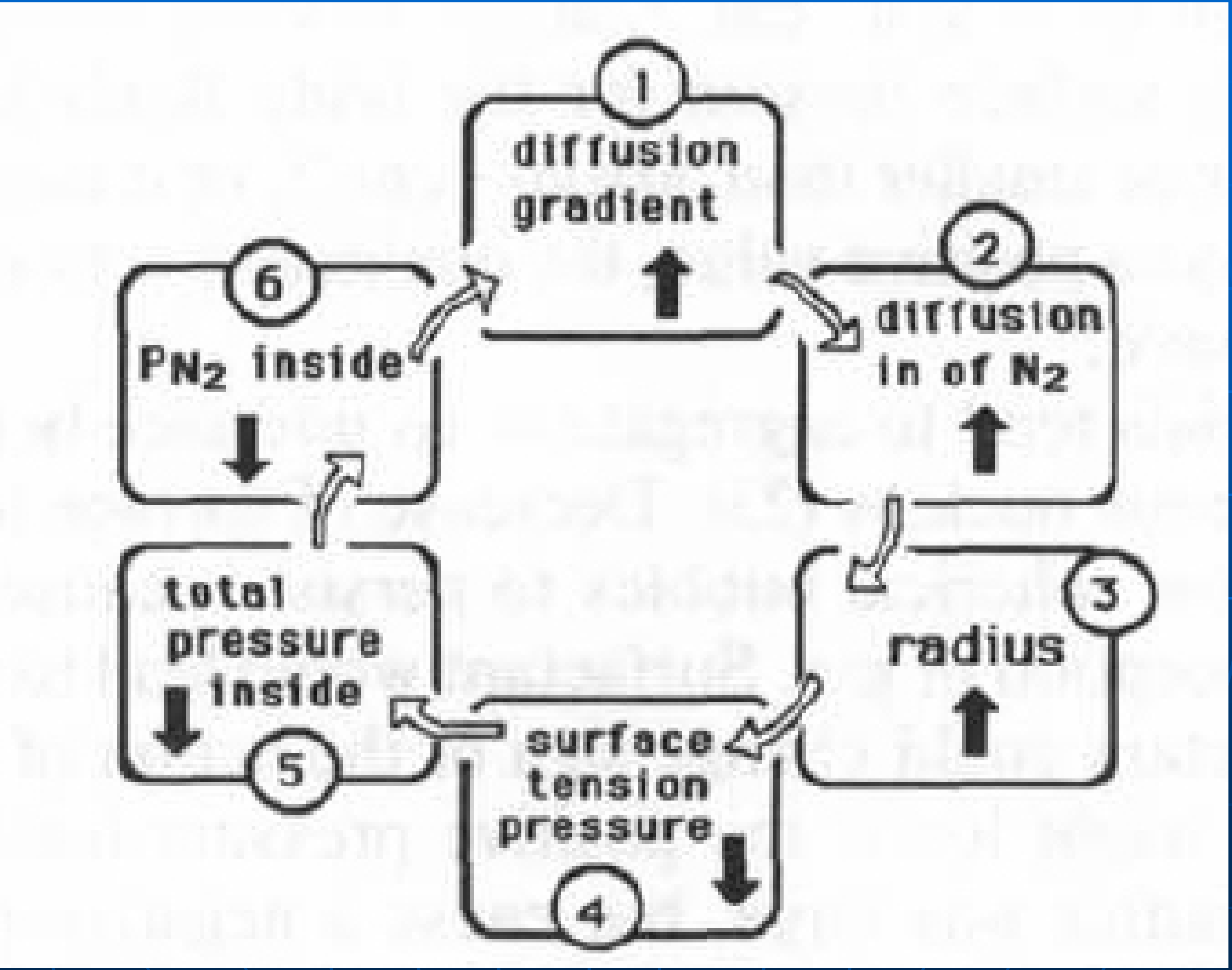


Feedback Loop



Model for a „Bubbler“:

Source: Vve Fourny & Fils, Champagne Rose brut

a „real“ bubble:

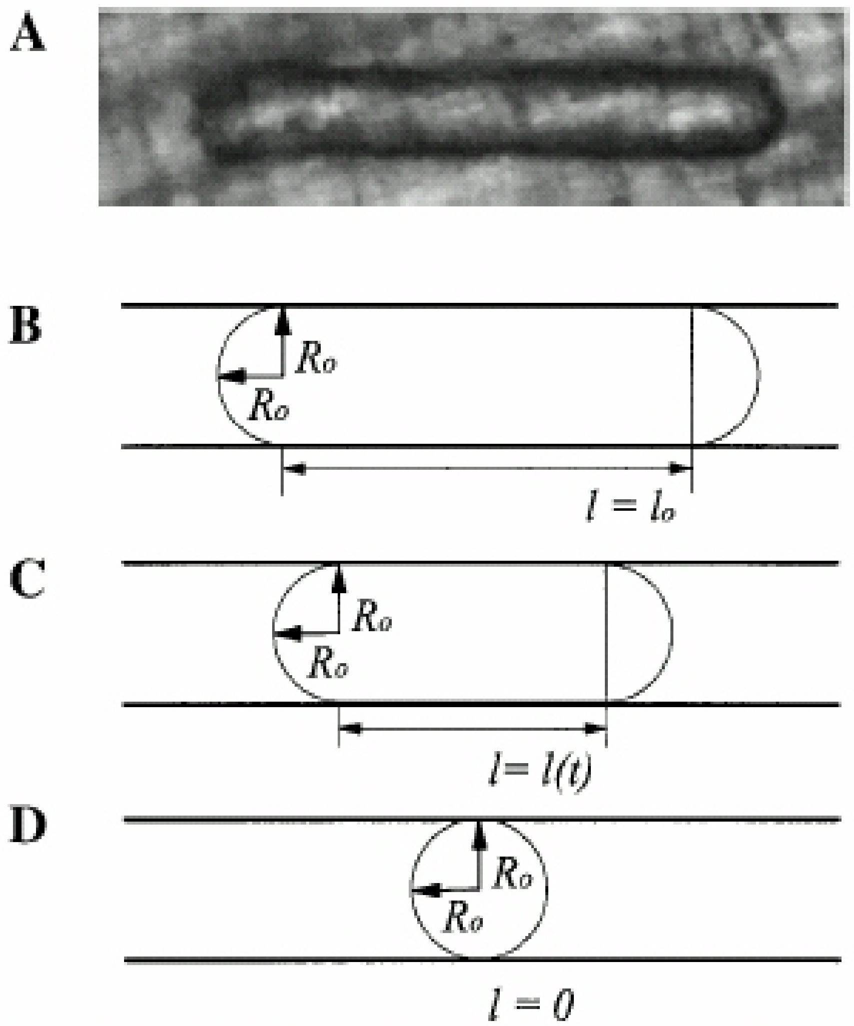
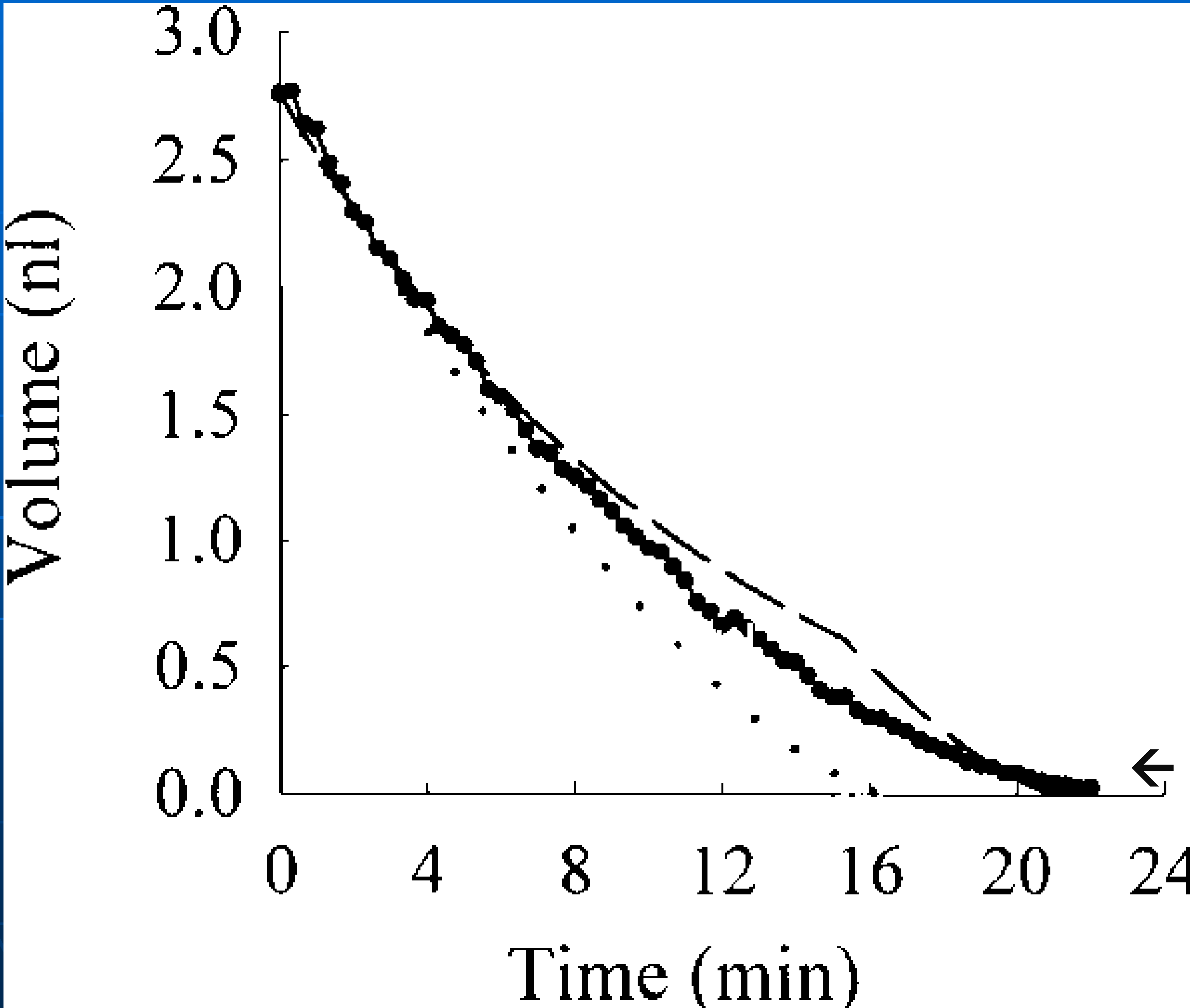


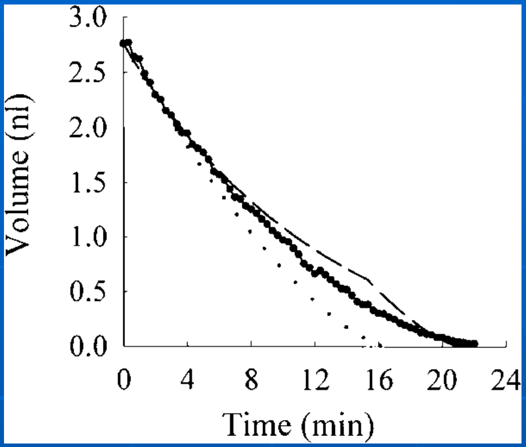
Fig. 1. In vivo and model intravascular gas bubble geometries. *A*: microscopic view of air bubble entrapped in rat cremaster arteriole. Bubble dimensions are length at *time 0* (l_0) = 368 µm and radius at *time 0* (R_0) = 33 µm. *B*: model air embolism geometry at time $t = 0$. *C*: model bubble shape for $0 < t < T_1$, where T_1 is time taken for collapse of cylindrical portion, after partial gas absorption. *D*: model air embolism configuration at $t = T_1$.

lifetime of bubbles?



“Cigar“ / Zeppelin

lifetime of bubbles?



Measured and predicted absorption times for bubble having initial volume of 2.8 nl.

In vivo measurement (large dotted line),
prediction using initial in vivo bubble dimensions (dashed line), and
prediction assuming spherical bubble of same initial volume (small dotted line) are shown.

Sources:

Franklin Dexter, MD, PhD, and Bradley J. Hindman, MD: Recommendations for Hyperbaric Oxygen Therapy of Cerebral Air Embolism Based on a Mathematical Model of Bubble Absorption, Anesth Analg 1997;84:1203-7

Branger, Annette B., and David M. Eckmann. Theoretical and experimental intravascular gas embolism absorption dynamics. J. Appl. Physiol. 87(4): 1287–1295, 1999

Bubble Models

VPM in a nutshell (1):

Bubble-Counts at Knox-Gelatin

- Bubble seeds, ca. 1 µm
- Bubbe Growth through Δp and Diffusion
- Bubble Distribution: exponential (many small, less big)
- Criteria for „safe“ Decompression:
- Initial hypothesis:
  - constant # of Bubbles (= const. „deco stress“):
  - good for saturation dives, failed for short dives!

- Later on, modified hypothesis:
- (dynamical) critical net volume of free gas $V < V_{crit}$
  - How can we keep V small?
  - High Pressure! Ergo: deeper stops than USN!

Microscopic Study of Bubble Formation Nuclei 127

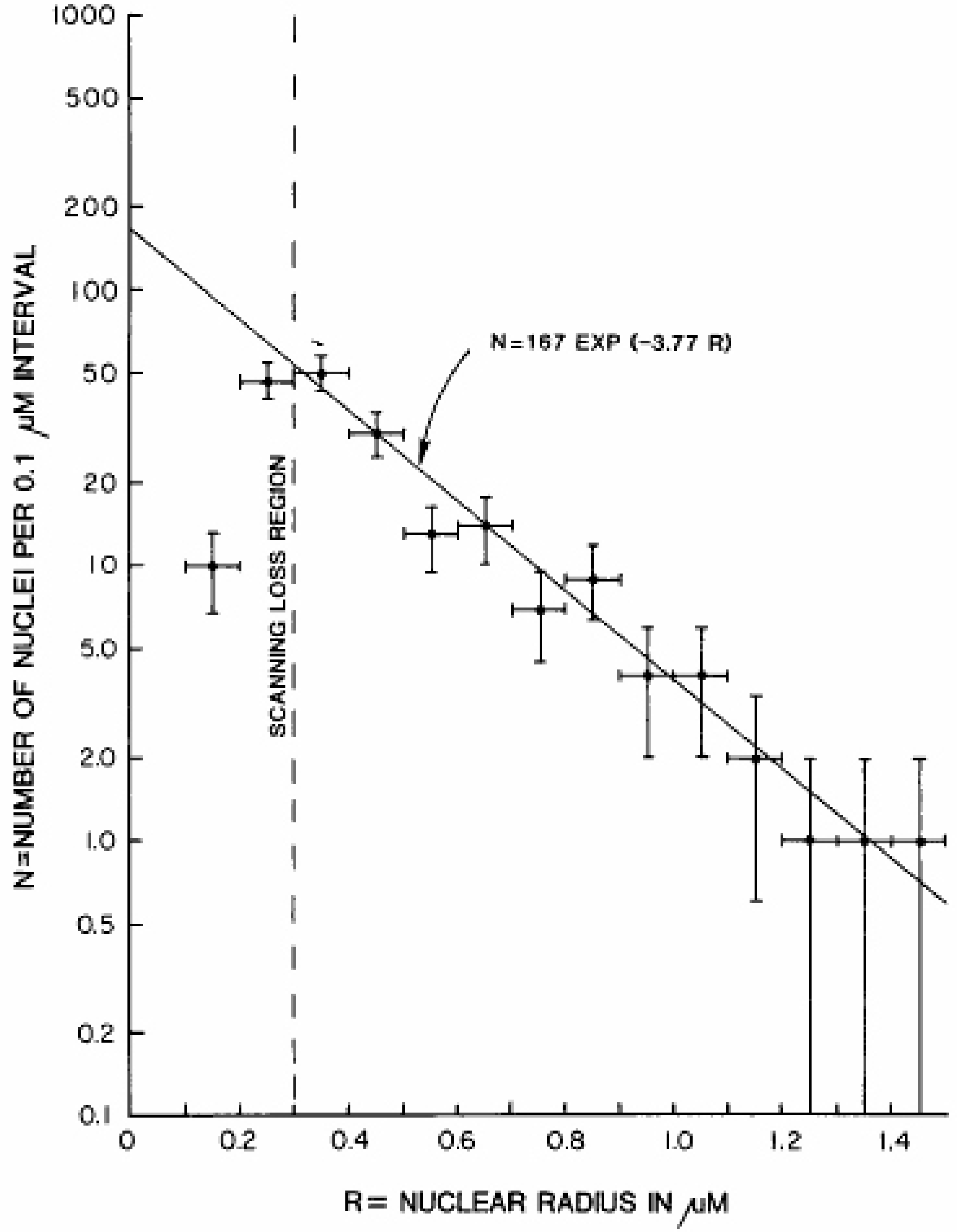


Fig. 6. Differential radial distribution of gas cavitation nuclei in agarose. The scanning efficiency deteriorates rapidly below 0.3 μm, and data in this region should be disregarded. Above 0.3 μm, the results can be described by a decaying exponential.

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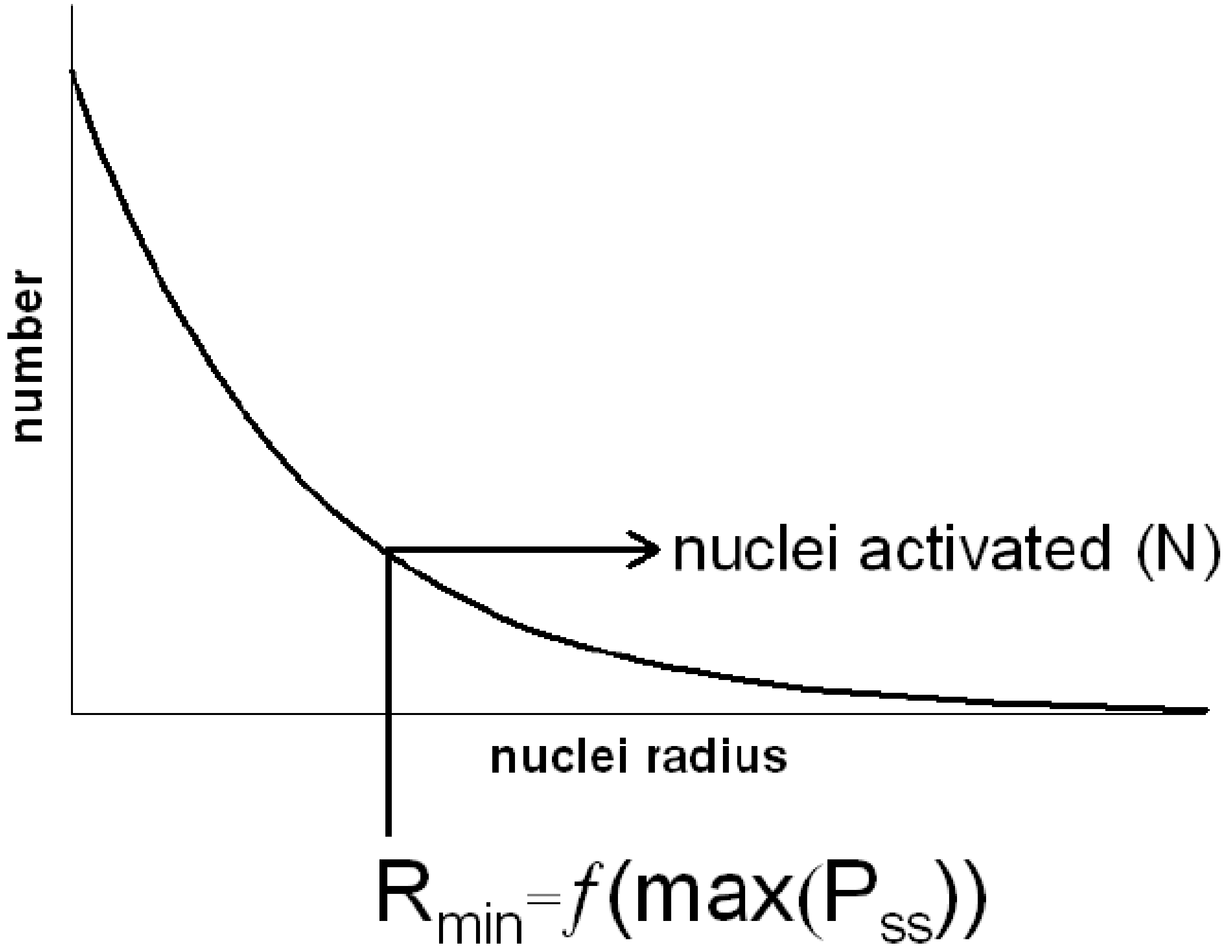
Bubble Distribution (1)

Bubble Distribution (2)

Exponential distribution of gas nuclei radii. The number of gas nuclei activated into growth as bubbles (N) is all nuclei of R_{min} and larger. R_{min} is a function of the maximum supersaturation (P_{ss}).



Bubble Models

VPM in a nutshell (1a, history)

PROCEEDINGS OF THE SIXTH SYMPOSIUM
ON UNDERWATER PHYSIOLOGY

Sponsored by

Institute for Environmental Medicine,
University of Pennsylvania Medical Center

Undersea Medical Society

U.S. Office of Naval Research

U.S. National Oceanic and Atmospheric Administration

Edited by C. W. Shilling and M. W. Beckett

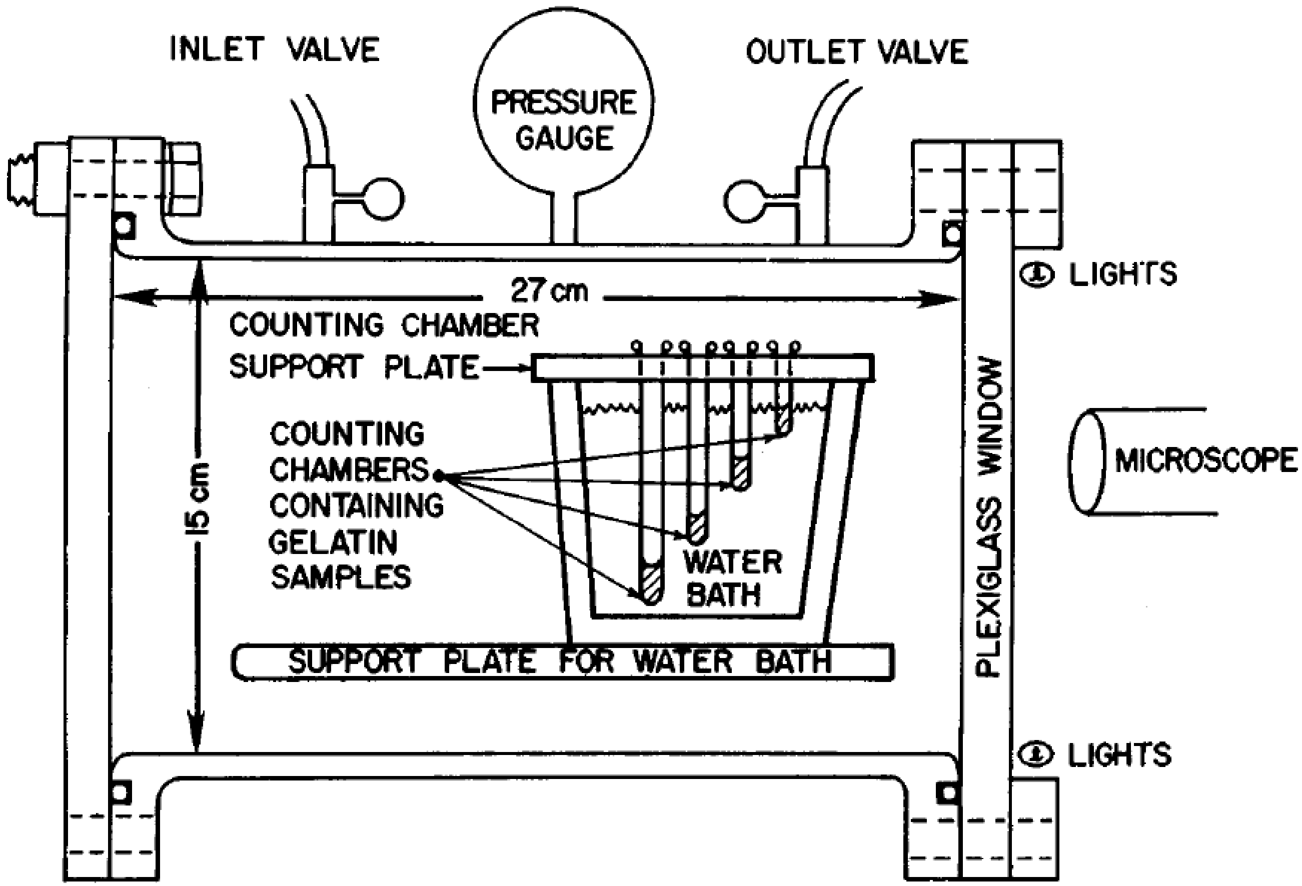


Fig. 1. Pressure vessel and counting chambers used to study decompression of gelatin.

Bubble Models

VPM in a nutshell (1b, history)

PROCEEDINGS OF THE SIXTH SYMPOSIUM
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Fig. 2. Photograph of a counting chamber and gelatin sample taken a few minutes after decompression; bubbles in the upper 1 mm were noticeably smaller and more numerous than elsewhere; only those in the lower 3 mm were counted (this corresponds to a fiducial volume of about 3 mm × 6 mm × 27 mm).

Bubble Models
VPM in a nutshell (2)

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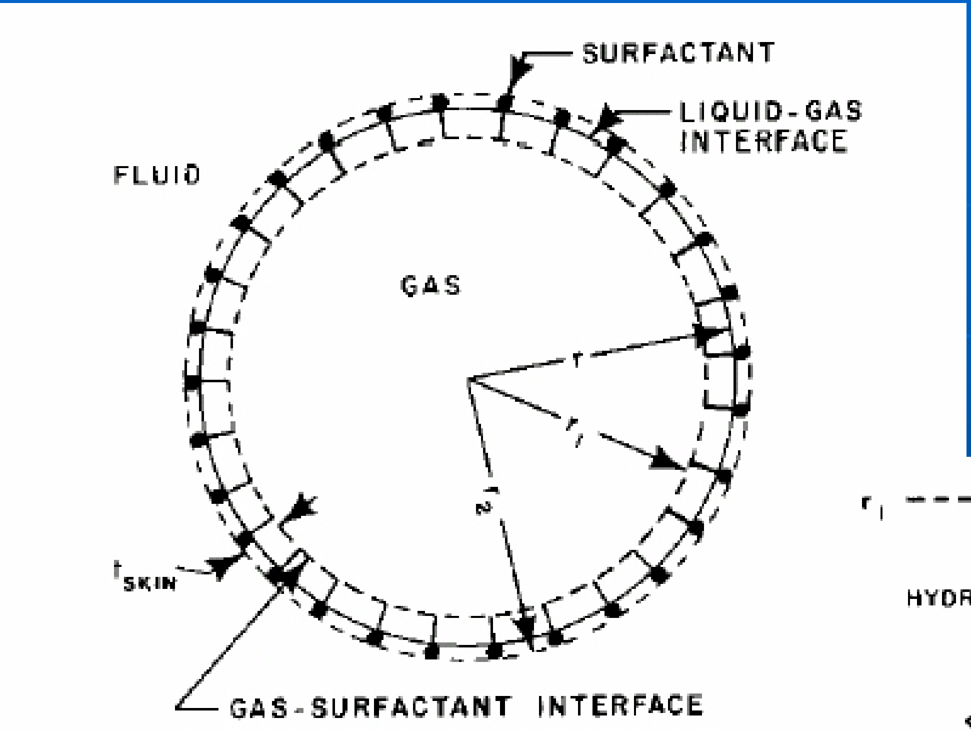
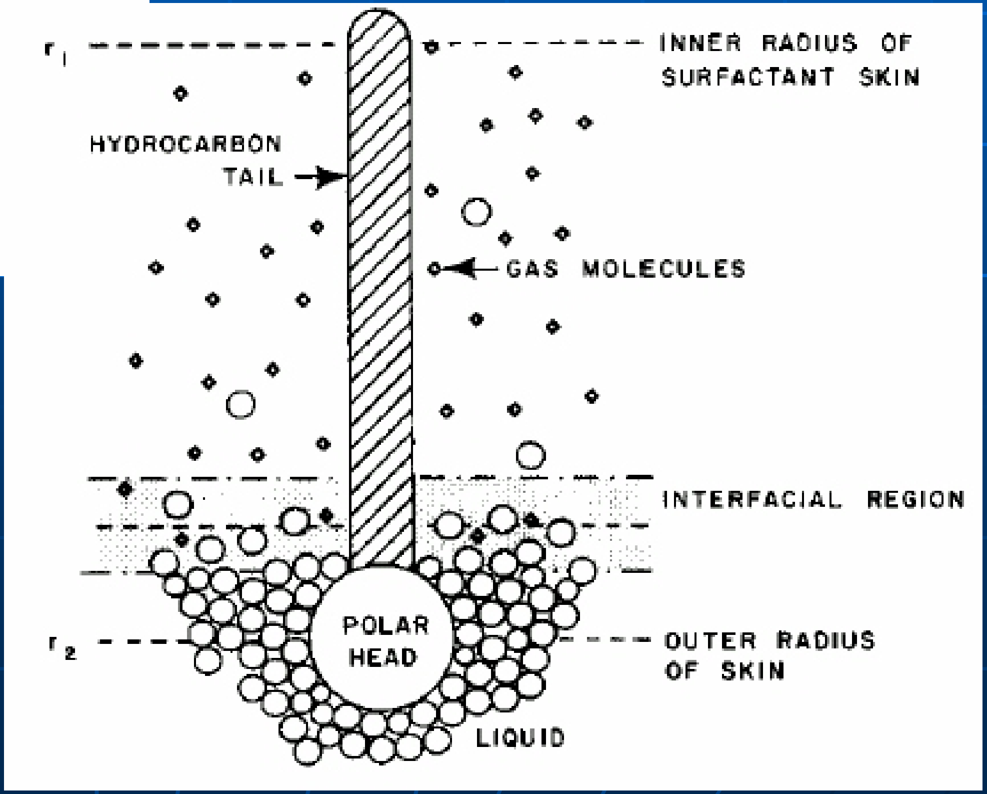




Bubble Models

VPM in a nutshell (3):

- 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)

VPM in a nutshell (4):

Comparison with „OLD USN“:

(new ones from 2008
and 12/2016
look different:
no more 10 feet stops!
longer stops
@ 20 feet and deeper)

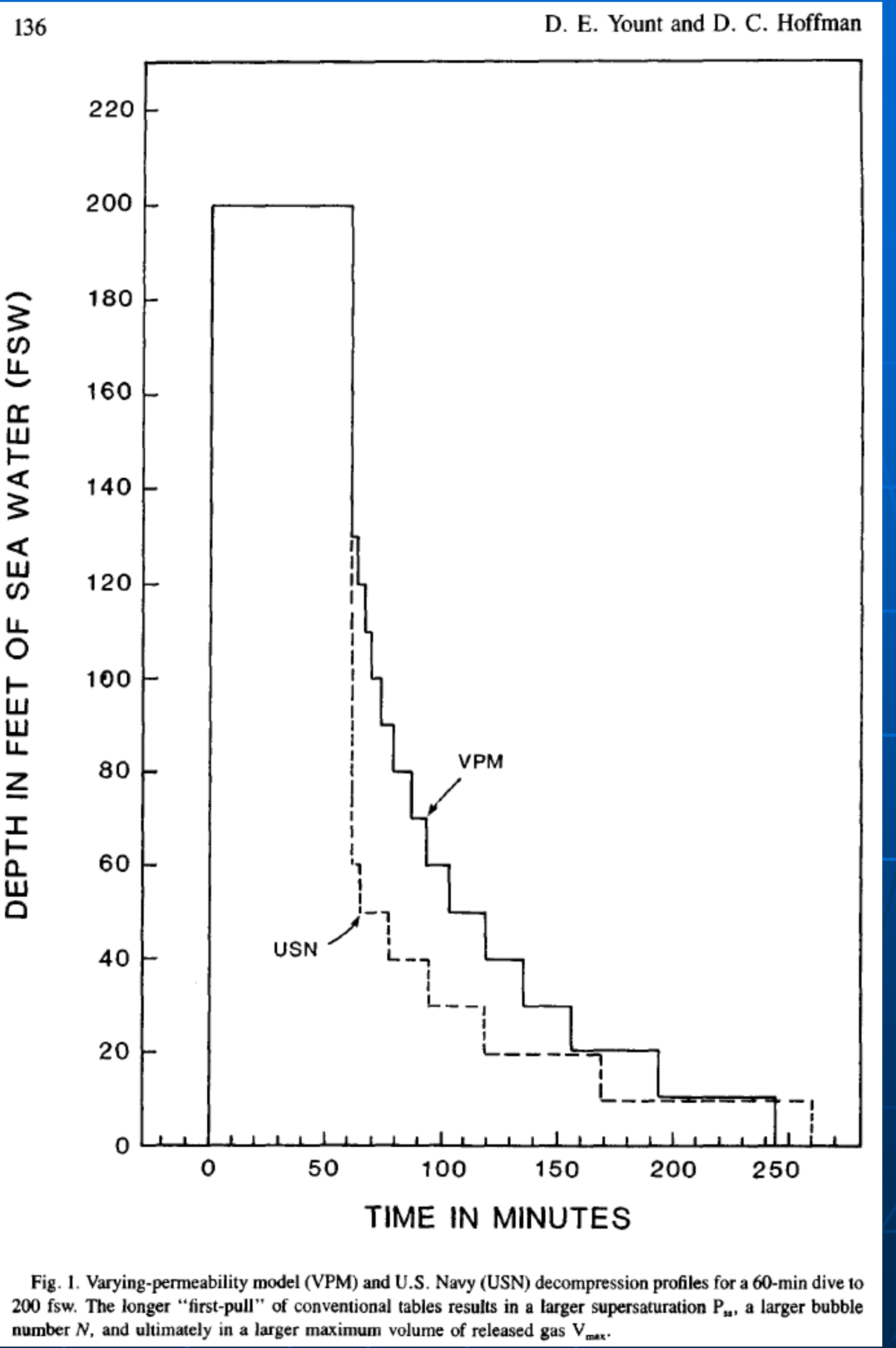
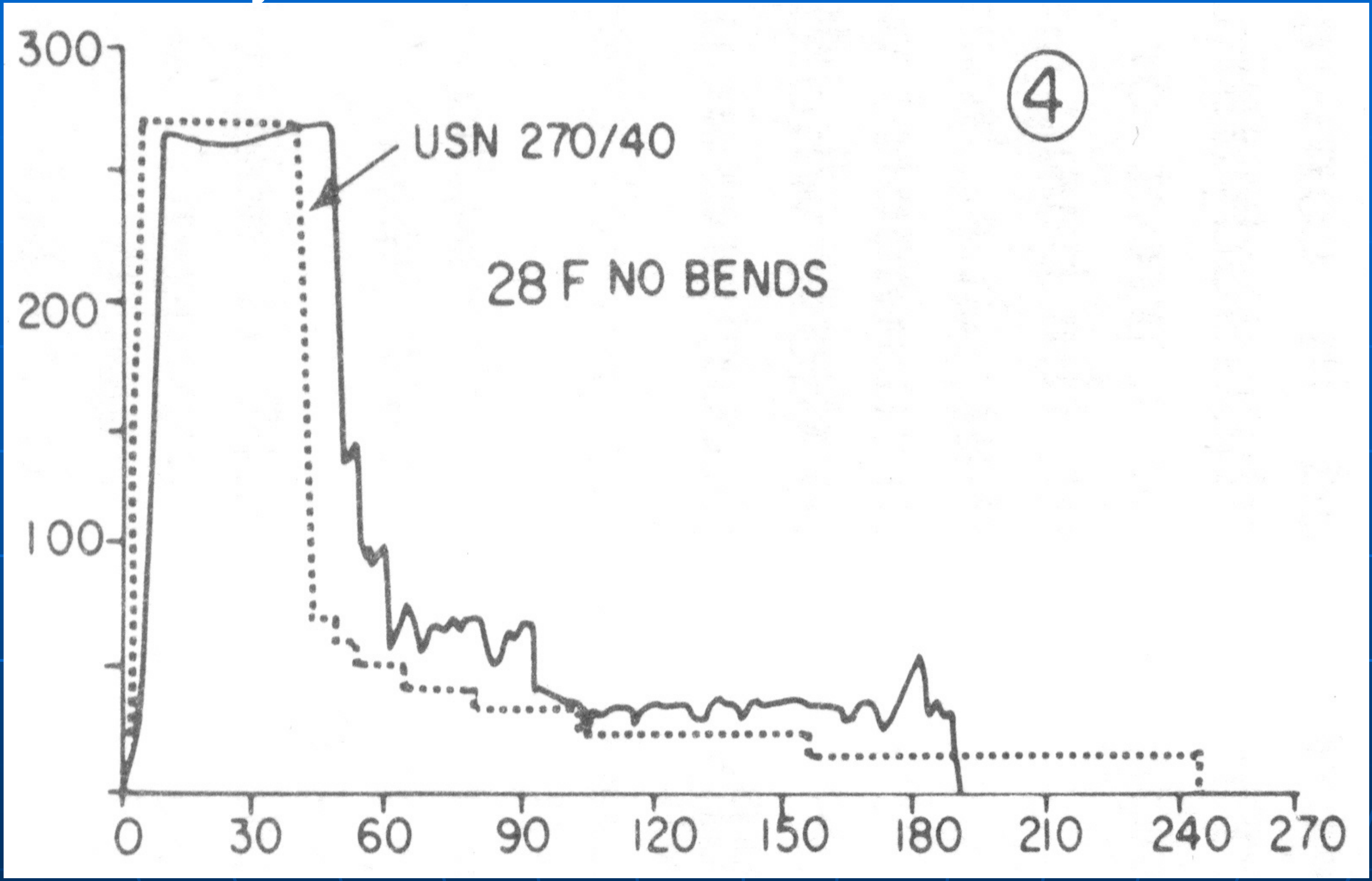

136 D. E. Yount and D. C. Hoffman

Fig. 1. Varying-permeability model (VPM) and U.S. Navy (USN) decompression profiles for a 60-min dive to 200 fsw. The longer "first-pull" of conventional tables results in a larger supersaturation P_{ss}, a larger bubble number N, and ultimately in a larger maximum volume of released gas V_{max}.

Thermodynamic Model:



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

Shortcomings (1) etc.:

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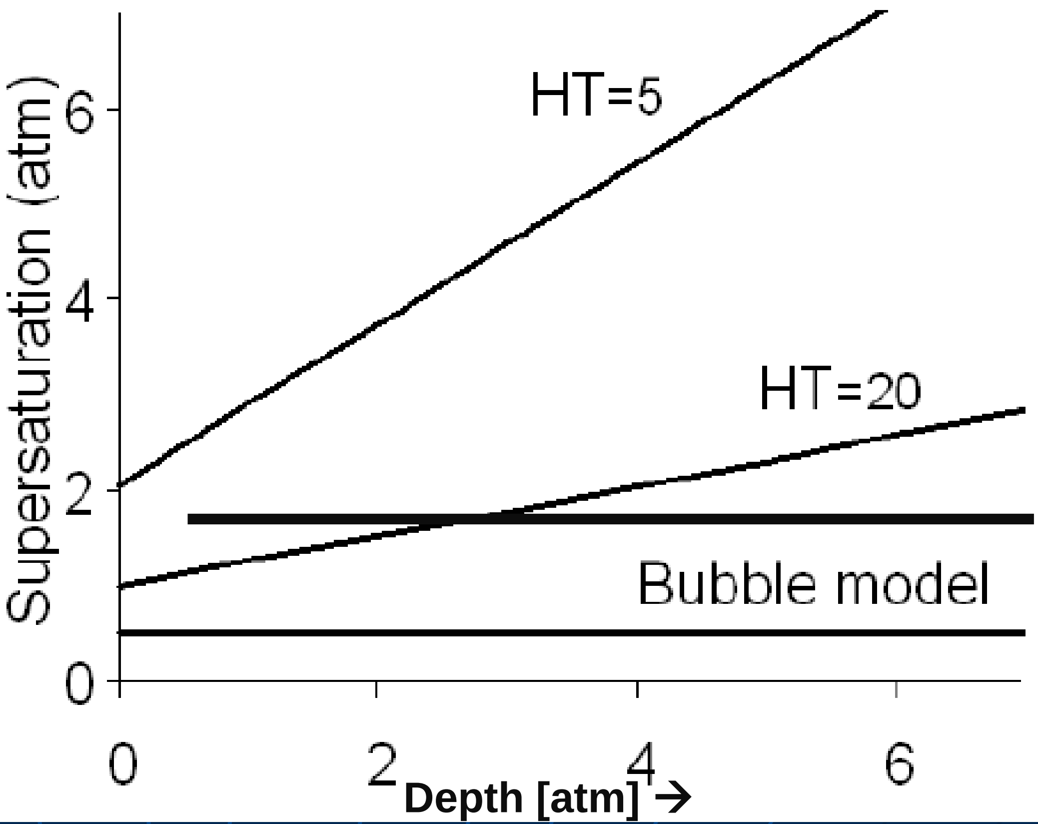
- → Saturation &
- → De-Sat. Calculation
- → same as Perfusion-
- → models
- → no tissue compliance
- → Bubble Distribution?
- → i.e. r_{Bubble} & #
- → Parameter Fit …

- → thus:
- → many
- → „Colours“ of the VPM

Ascent rules expressed as allowed supersaturation in atmospheres absolute at different depths during decompression expressed in atmospheres gauge. In content models, different half-time compartments typically have a different rule (e.g., HT=5, HT=20). In bubble models allowed supersaturation is independent of depth (bubble).



Shortcomings (2) etc.:

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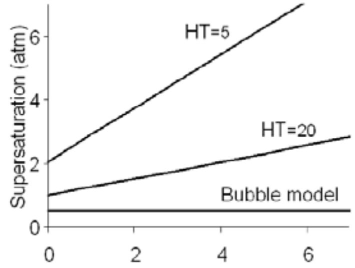
→ as per nearly ALL perfusion models:

→ only one pressure step (Box Profiles);
→ i.e.: NO multi-level tests !
→ up to now (2018):
→ not seriously challenged with Trimix / Heliox

Ascent rules expressed as allowed supersaturation in atmospheres absolute at different depths during decompression expressed in atmospheres gauge. In content models, different half-time compartments typically have a different rule (e.g., HT=5, HT=20). In bubble models allowed supersaturation is independent of depth (bubble).



→ ! The original algorithm by D.C. Hoffman was never intended for Trimx: only one inert gas is possible; i.e. only Air/ EAN or Heliox!
→ ! Neither the bubble radii, the exp. distribution, nor the 5 parameters have been verified in experiments scalable to human beings!

Shortcomings (3) etc.:

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…, thus the many „Colours“ of the VPM (1):

➔VPM-B: B = Boyle; includes the expansion of the bubbles at ascent

➔ VPM-B/E: additional manual input of conservativism for Extreme dives

➔VPM-CVA: Critical Volume Algorithm

➔ VPM-B/FBO: Fast Bail Out option

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Colours of the VPM (2):

➔VPM-B/GFS: regularly the deep stops are too long and the shallow to short; thus a parallel ZH-L with Gradient Factor Surfacing (GF Hi = GF Lo = 0,9) is calculated and the more conservative profile is displayed for the shallow stops

➔VPM-BS: there is only one critical radius for each gas: ca. 0,6 µm for N_2 and ca. 0,5 µm for He;

now each compartment gets its own value:
N_2: 0,35 µm fastest compartment → 2,0 µm slowest compartment
He: 0,25 µm fastest compartment → 1,9 µm slowest compartment

Shortcomings (4)

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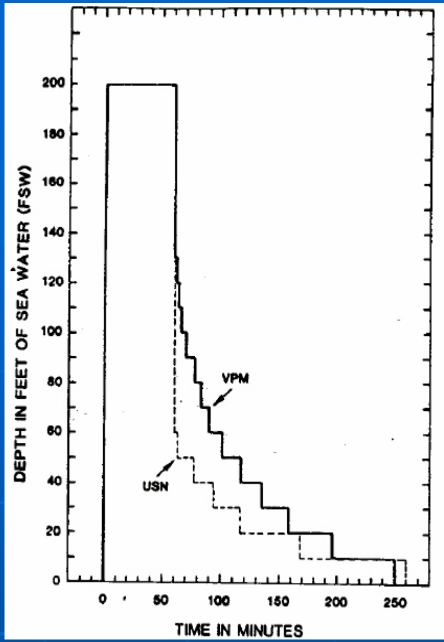
In the own words of Yount & Hoffman;
(Source: l.c., p. 144):

Another criticism is that we have said very little about the physiological processes that presumably underlie our mathematical equations. We take oxygen and carbon-dioxide into account and assume a reasonable range of tissue half times, but many other details are overlooked. We make no distinction, for example, between "fatty, loose tissue" and "watery, tight tissue" (14), nor do we state explicitly where the bubbles form or how they grow, multiply, or are transported. Finally, we say nothing about such factors as solubility, diffusion versus perfusion, tissue-deformation pressure, or tissue-specific differences in surface tension. Our response to criticisms of this type is that most of the omitted processes are poorly understood, and their inclusion at this stage would serve only to complicate the model and increase the number of undetermined parameters.

VPM in a nutshell (5):



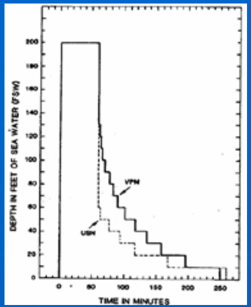
more sources:

36th. UHMS workshop p. 48

and, as well:

Yount DE, Hoffman DC.
Decompression theory:
a dynamic critical-volume hypothesis.
In:
Bachrach A J, Matzen MM, eds.
Underwater physiology VIII:
proceedings of the eighth symposium on underwater physiology.
Bethesda: Undersea Medical Society, 1984:131-46.

VPM in a nutshell (7): The REAL Source!



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

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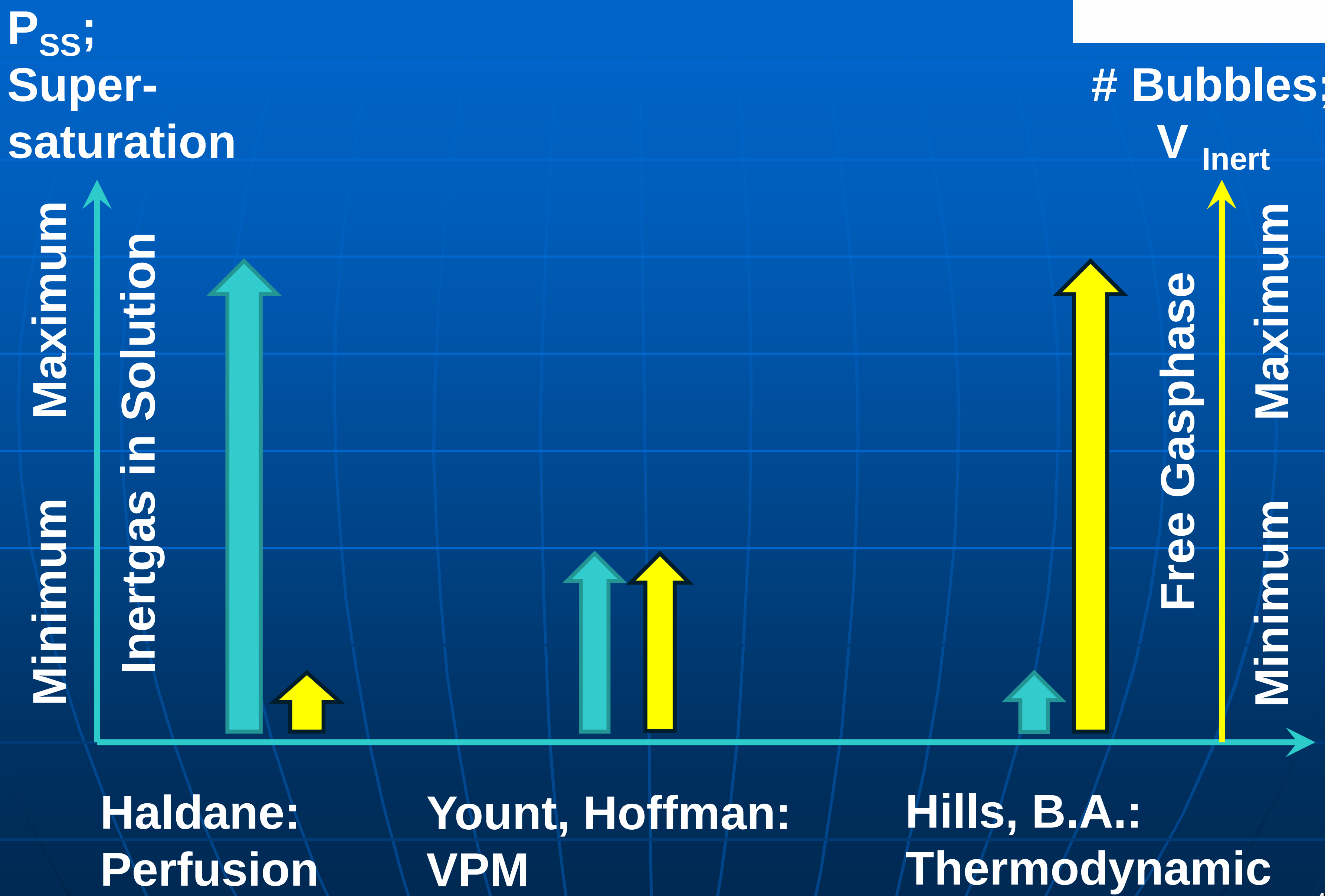

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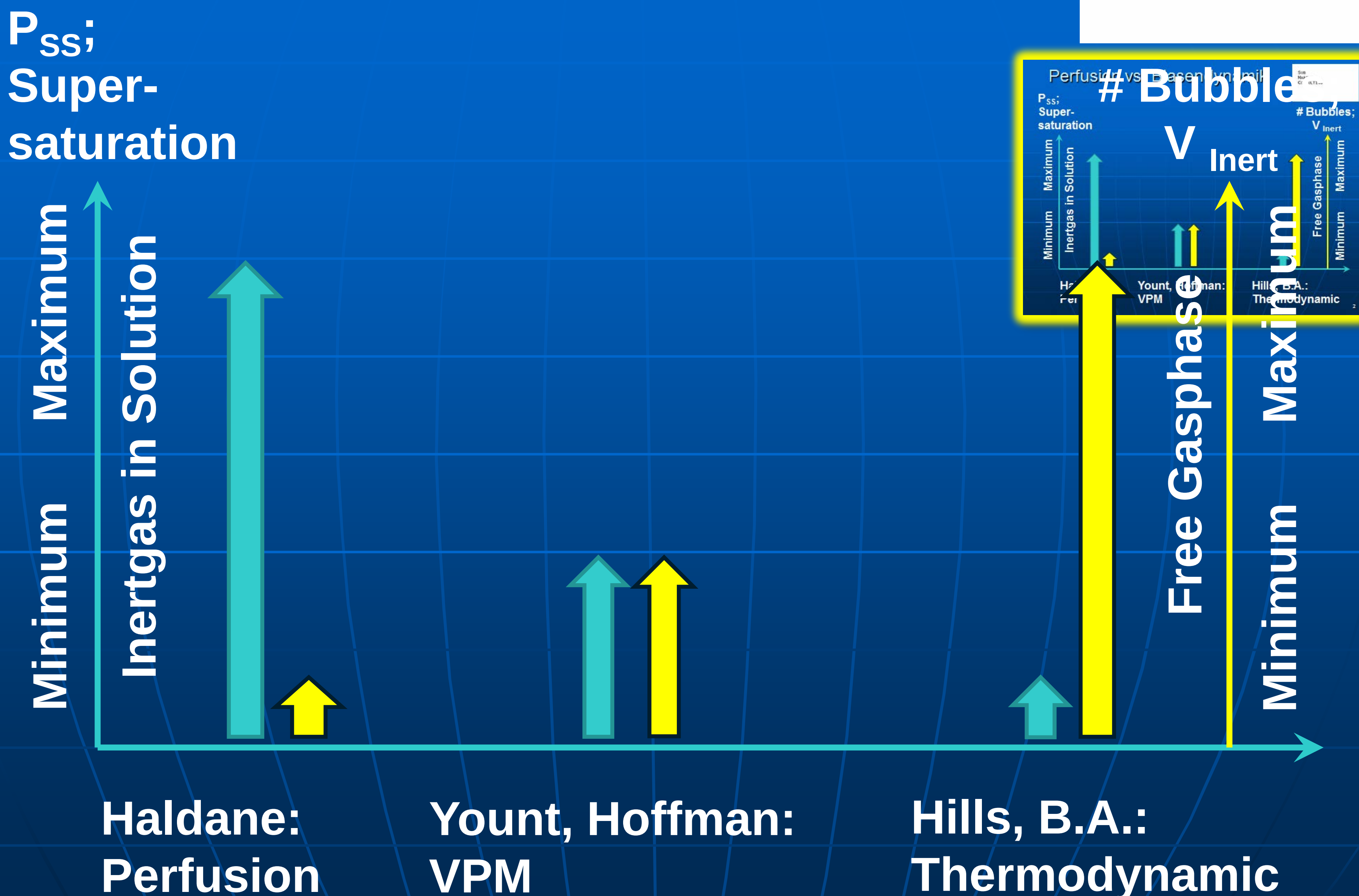

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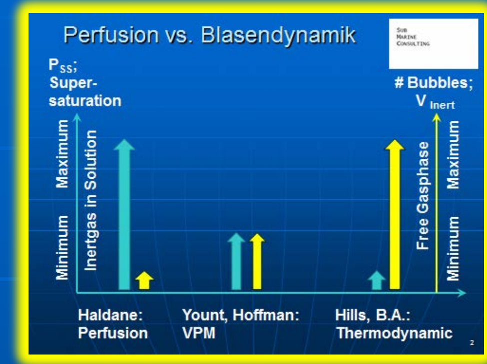

Complexity:

Linear;
M-type eq.

2 Inertgas
iterated t_D

Haldane:
Perfusion

Quadratic;
iterated P_{ss} & t_D

Yount, Hoffman:
VPM

Bessel: $J_0 J_1$ $Y_0 Y_1$
(Gauss-Legendre)^2

Hills, B.A.:
Thermodynamic

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Copernicus: Original Charts from Alf Brubakk @ ntnu.no

Copernicus (1)

- Copernicus consists of:
  - *The model itself*. A descriptive model of the mechanisms behind the occurence of serious (CNS) DCS (evolution of vascular bubbles)
  - *A control algorithm*. It calculates a procedure that control the model according to our request (Dynamic optimization algorithm)

Copernicus (2)

- Copernicus consists of:
- Validation strategy through bubble measurement rather than DCS/NO-DCS endpoint
- The model will have two distinct applications:
  - Use the model as a simulator to compare and evaluate procedures and logged dives
  - Use accepted risk/bubble scores as threshold for calculating optimal decompression schedules

Physiological model

- Individually adaptive
- Input:
  - Weight
  - Height
  - Fitness (fat percentage)
  - Gender
  - Cardio-pulmonary performance
  - Workload

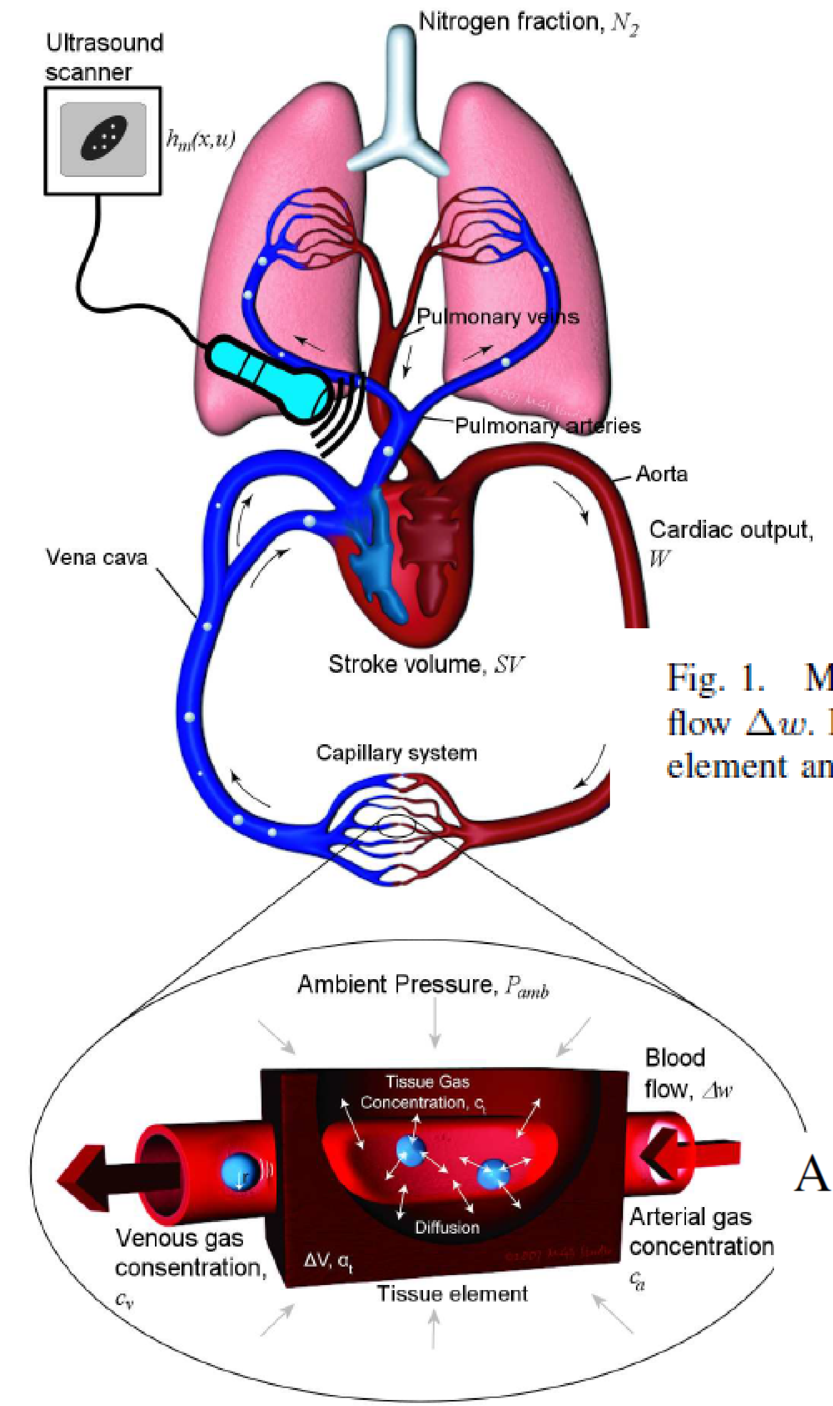

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Fig. 1. Model of a small volume element ΔV, perfused with a small blood flow Δw. Inert gas dissolved in the artery blood will exchange with the tissue element and the N_b bubbles.

Source:

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

Christian R. Gutvik, and Alf O. Brubakk

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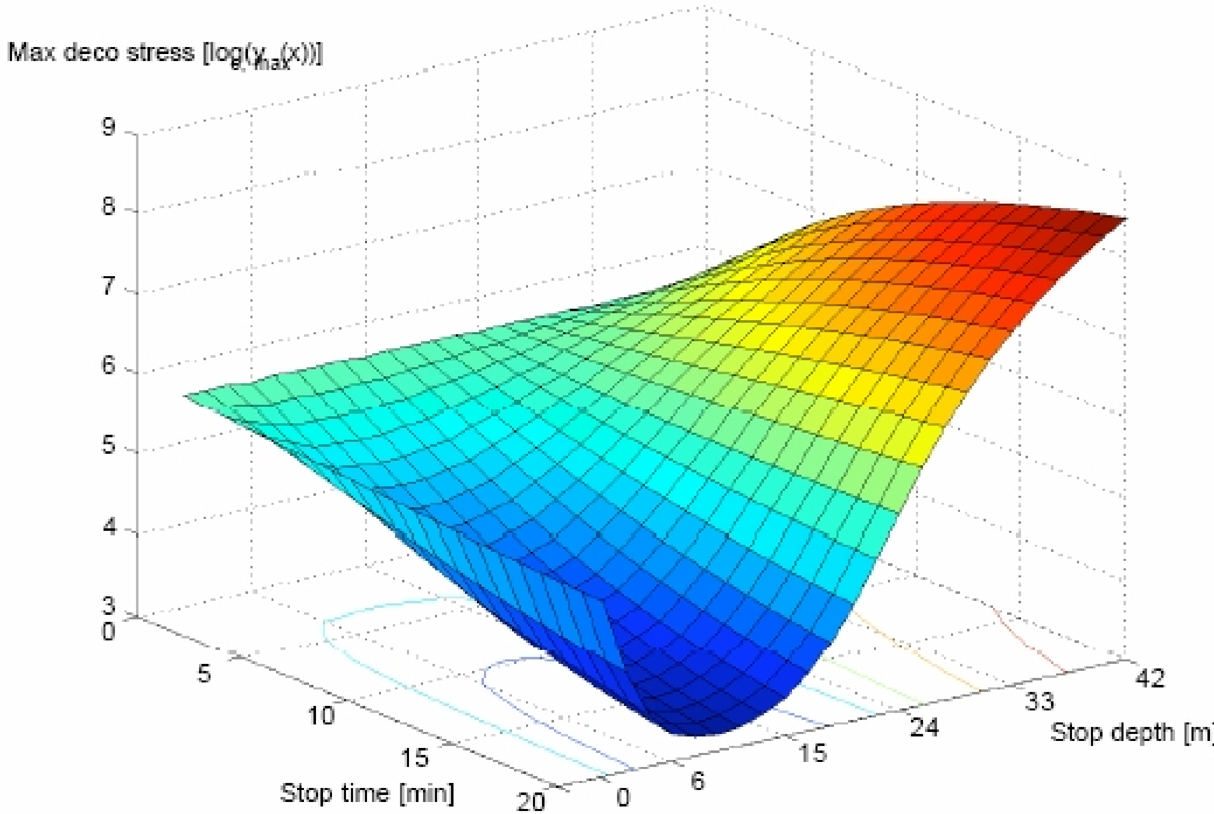

COPERNICUS

Source:

Optimal Decompression of Divers

Procedures for Constraining Predicted Bubble Growth

CHRISTIAN R. GUTVIK, TOR A. JOHANSEN, and ALF O. BRUBAKK

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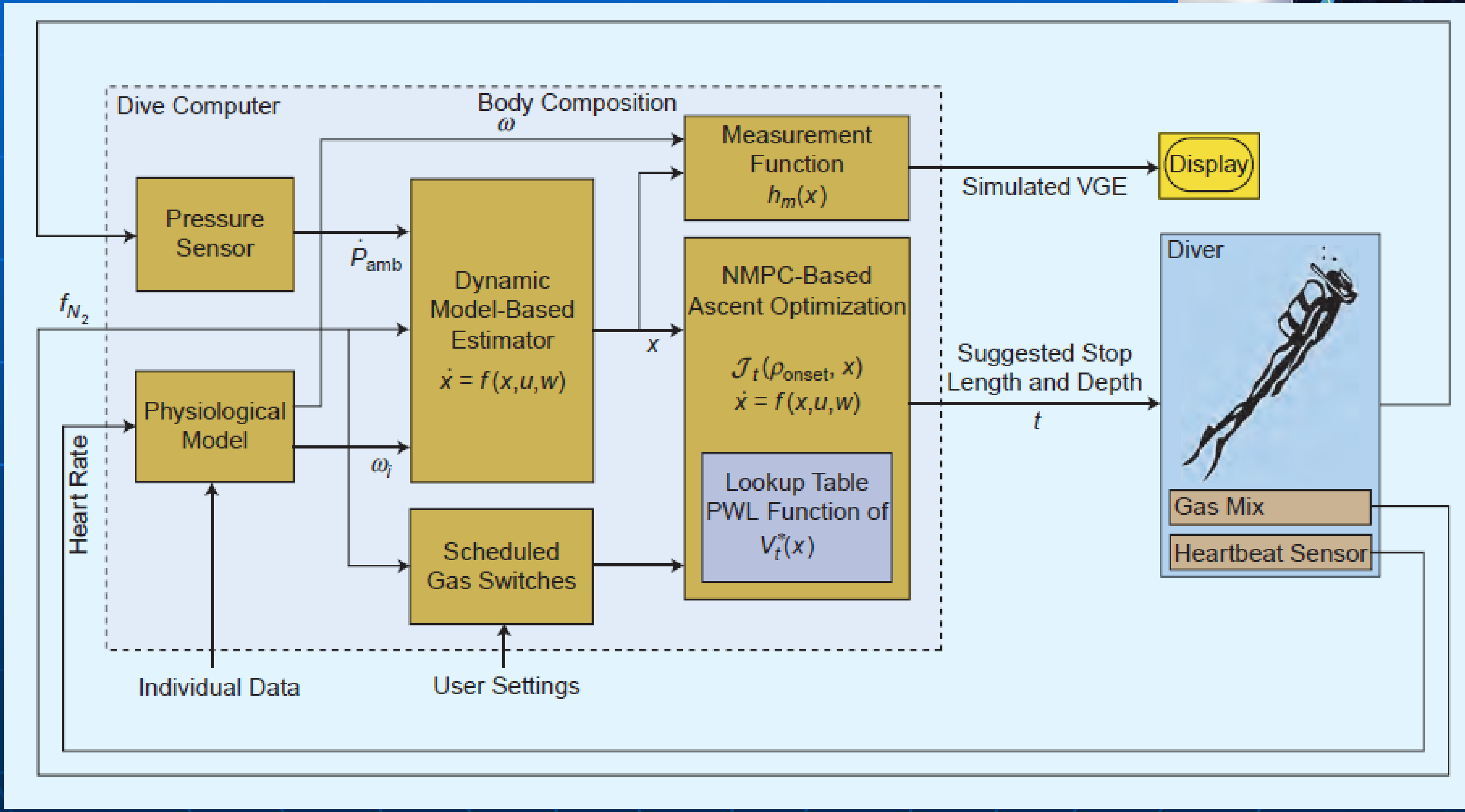
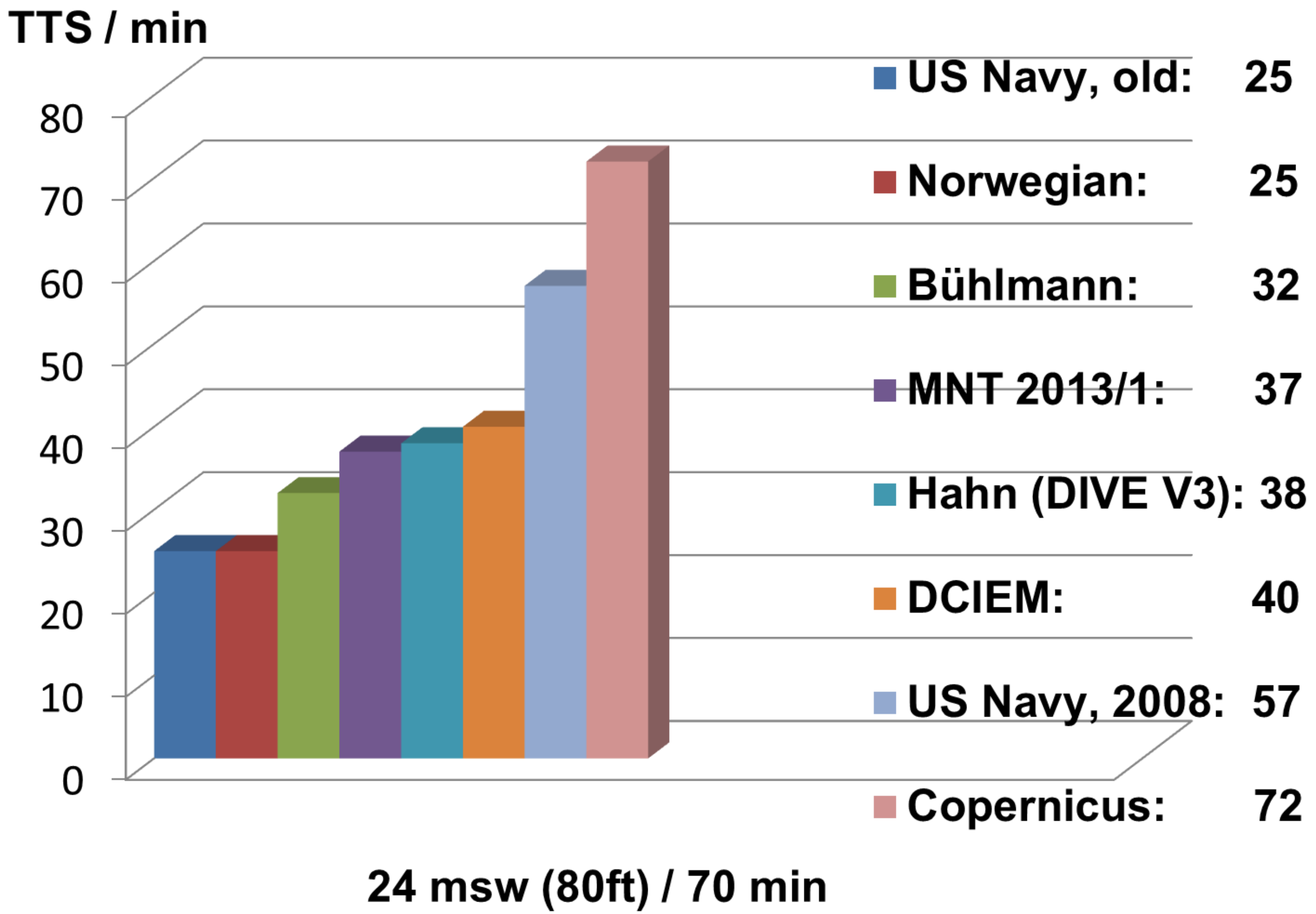


Hybrid Model (Copernicus, 3.)

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



Possible, tentative and surprising conclusion

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

Take home (1):

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- → **VPM is a MODEL**
- → **not better or worse than any other (→ next slide …)**
- → **many simplifications**
- → **5 free parameters, with:**
- → **“best fit” through traditional diving tables**
- → **many different implementations**

- → **Which one is “true”?**
- → **ALL AD HOC**
- → **NONE Tested**
- → ***<u>Recap: “Shortcomings” (Slides # 37 – 41!!!)</u>***

- → **Don’t use a single source!**
- → **Compare always with established tables!**
- → ***see next lecture !!!***

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Take home (2):

→ *not better or worse than any other …*

→ **No epidemiologic evidence!**

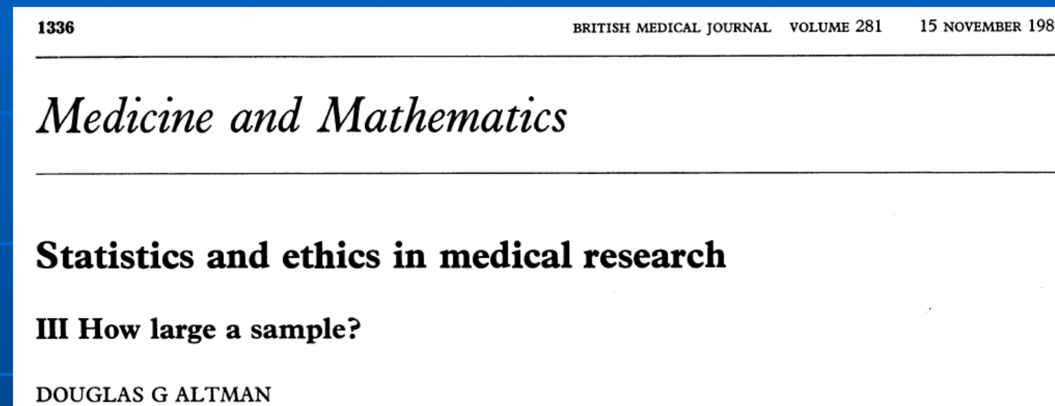
→ **that is: statistically viable**

→ **Requirement:**

→ **“Power” > 0.8, … 0.85**

→ **i.e.: a certain quality!**

→ **i.e.: sample > 180!**



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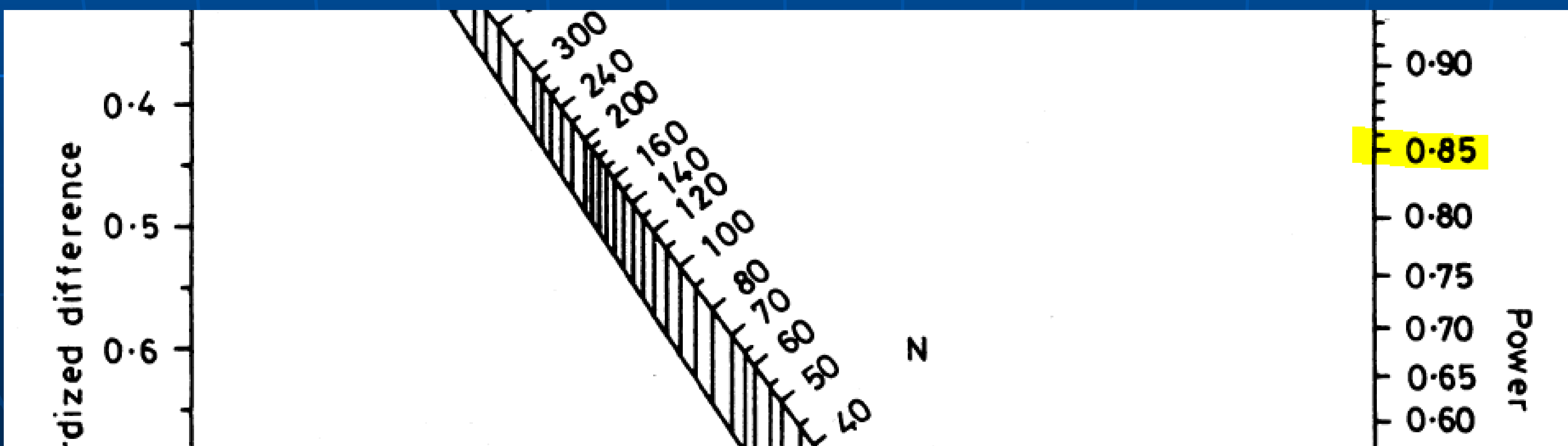
Medicine and Mathematics

Statistics and ethics in medical research

III How large a sample?

DOUGLAS G ALTMAN



21st century decompression?

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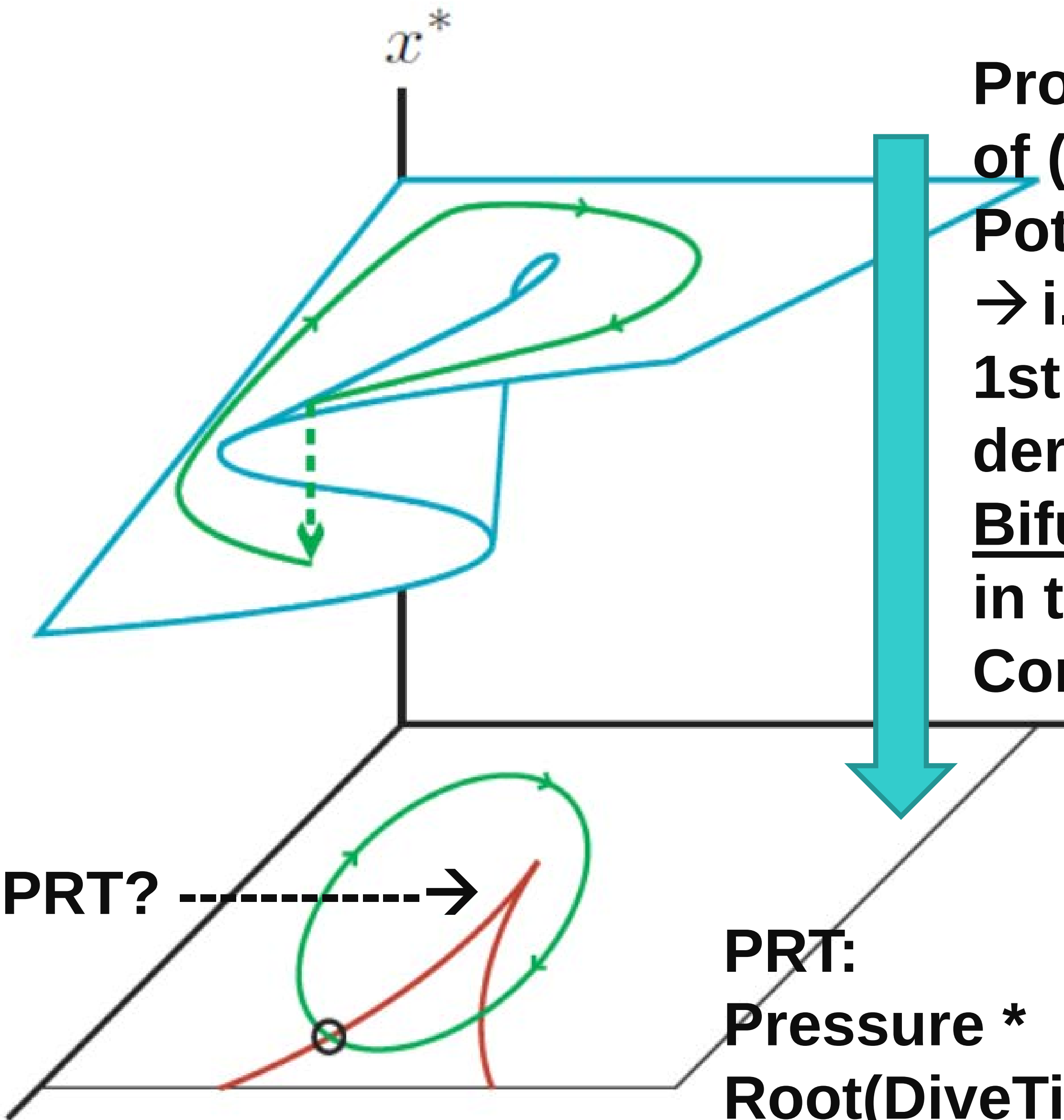
"Note:
The senior (elder) author believes that
the only explanation for most cases of DCS
lies in the random application
of Chaos Theory,
which he also does not understand,
or String Theory
which no-one understands."

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

Not Chaos -, but: Catastrophe Theory???



Projection of (Energy) Potentialfunction:
→ i.e.:
1st. & 2nd. derivative:
<u>Bifurcation Set</u> in the plane of Control Variables

PRT: Pressure * Root(DiveTime)