

# PHYSIOLOGIE DES APNOETAUCHENS

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Allg. öffentl. Krankenhaus St. Vinzenz Betriebs GmbH Zams

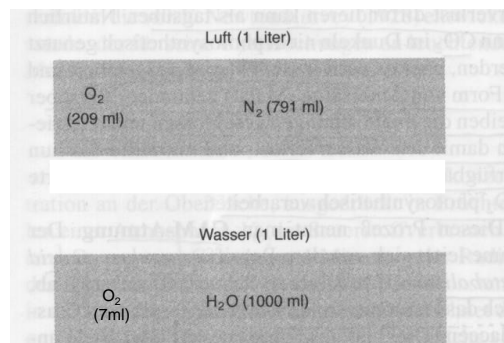
eine soziale Einrichtung der Barmherzigen Schwestern des Hl. Vinzenz von Paul, Zams



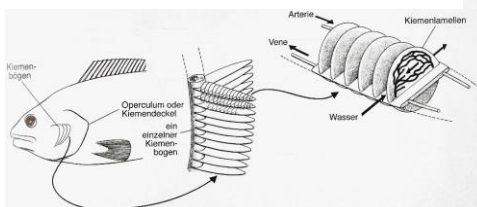
CARITAS CHRISTI  
1861-2022

## VERGLEICH LUFT UND WASSER




- 143 kg  $H_2O$  enthalten 1l  $O_2$  aber bereits 6,2g Luft enthalten einen Liter  $O_2$  !!
- Wasser ist 50 mal visköser als Luft
- Die Diffusionsgeschwindigkeit von  $O_2$  ist ca. 10.000x größer in der Luft als im Wasser



250ml  $O_2$  sind in 36l Wasser enthalten!!



## Druckveränderungen in der Höhe und in der Tiefe

	Distance		Absolute Pressure			
	Feet	Meters	psi	mmHg	kPa	atm
altitude 	18,000	5486	7.34	379.5	50.6	0.5
	10,000	3048	10.11	522.6	69.7	0.7
sea level 	0		14.7	760	101.3	1
under water 	33	10	29.4	1520	202.6	2
	66	20	44.07	2280	303.9	3

Alle 10m nimmt der Umgebungsdruck um 1atm zu!!

### APNOE – Der Respirationstrakt

#### Tauchen über die Elastizitätsgrenze des Thorax:

**FREITAUCHEN:**

Boyle-Mariotte-Gesetz =  $P \times V = \text{konst.}$

**Dogma:**  
Das Thoraxvolumen kann nicht über die „Elastizitätsgrenze“ des Thorax reduziert werden! Ein Tauchen über die Elastizitätsgrenze des Thorax hinaus kann ein akutes Lungenödem induzieren“

**FAUSTREGEL:**

Elastizitätsgrenze in ATM = TLK : RV

Maximale erwartete Freitauchgrenze (Meter) = (EG-1) x 10






## GRENZEN DES FREITAUCHEN – DIE PRAXIS „Blood Shift“ und „Lung Packing“

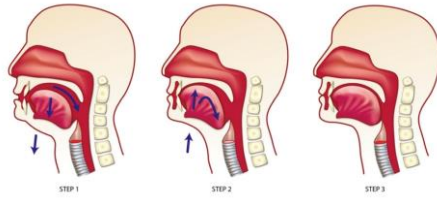
Totale Lungenkapazität = 9,6l  
Residualvolumen = 2,2l

Erwartete Tieftauchgrenze =  $((9,6/2,2)-1) \times 10 = 34\text{m}$

Effekte des BV-Shift von ca. 1,5l Blut auf das RV

$$RV_{\text{neu}} = 2,2 - 1,5 = 0,7\text{l}$$

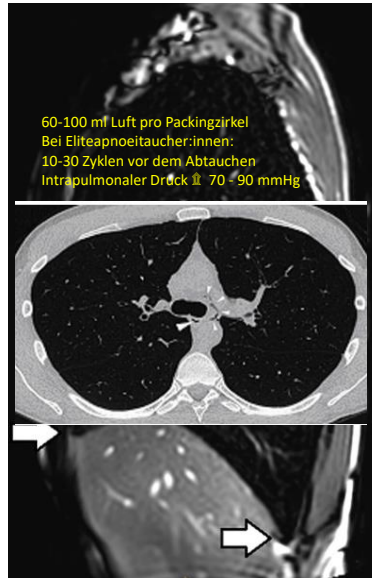
Erwartete Tieftauchgrenze neu =  $((9,6/0,7)-1) \times 10 = 127\text{m}$



Effekte des Lungen-„packings“

Totale Lungenkapazität = 9,6l + 2,8l = 12,4l

Erwartete Tieftauchgrenze neu =  $((12,4/0,7)-1) \times 10 = 167\text{m}$



60-100 ml Luft pro Packingzirkel  
Bei Eliteapnoetaucher:innen:  
10-30 Zyklen vor dem Abtauchen  
Intrapulmonaler Druck  $\approx$  70 - 90 mmHg

Going to extremes of lung physiology-deep breath-hold diving  
Tetzlaff K et al. Frontiers of Physiology 2021; 12: doi: 10.3389/fphys.2021.710429

Children`s Hospital Boston 1938



Hansel Mieth 1906-1998



## Predicting performance in competitive apnoe diving. Part III: depth Schagatay E. Diving and Hyperbaric Medicine 2011; 41: 216 - 228

### „reversed lung packing“

Nach forcierter Expiration saugt der Taucher zusätzliche Luft durch Zwerchfell-Kontraktionen und Einwärtsbewegung der Rippen aus den Lungen und reduziert sein Residualvolumen

Alternativ wird nach maximaler Ausatmung (RV) auf 5m Tiefe abgetaucht

*Mittels „lung packing“ und „reversed lung packing“ kann die totale Lungenkapazität um 2l und mehr erhöht werden. Mit RLP kann die Taucherin in der Tiefe Luft für Druck-Ausgleich der Nasennebenhöhlen rekrutieren!*



## Breath-hold diving performance factors

Fernandez F, Gonzales-Rave JM et al. J of Human Sport and Exercise 2017; 12: 582-592

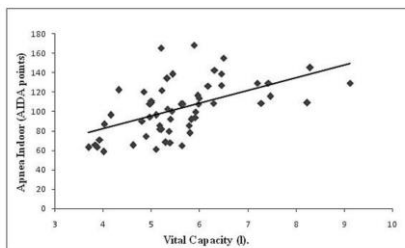


Figure 1. Correlation analysis between Vital Capacity with Apnea Indoor performance.  
 $r = 0.601, p \leq 0.05$ .

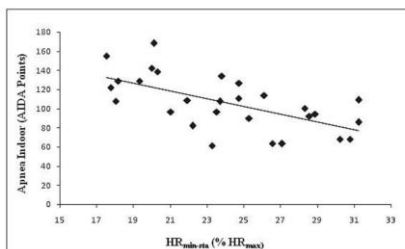


Figure 2. Correlation analysis between minimum heart rate during static apnea in dry conditions with Apnea Indoor performance.  
 $r = -0.624, p \leq 0.05$ .

N=56 male breathhold divers  
STA; DYN; DNF

Measurements: BMI; height; body fat;  
Fat-free mass; bone mineral content; Hb;  
blood volume; VC; VO<sub>2</sub>max; HR<sub>max</sub>; HR<sub>min</sub>;  
RMR; HbO<sub>2</sub>

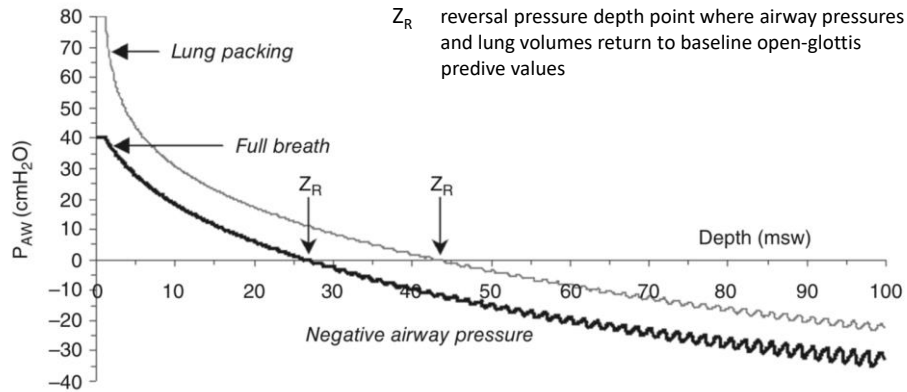
*Apnoe Index (AIDA):*

STA: Apnoe (sec) x 0,2

DYN/DNF: Meter x 0,5

## BREATH-HOLD DIVING

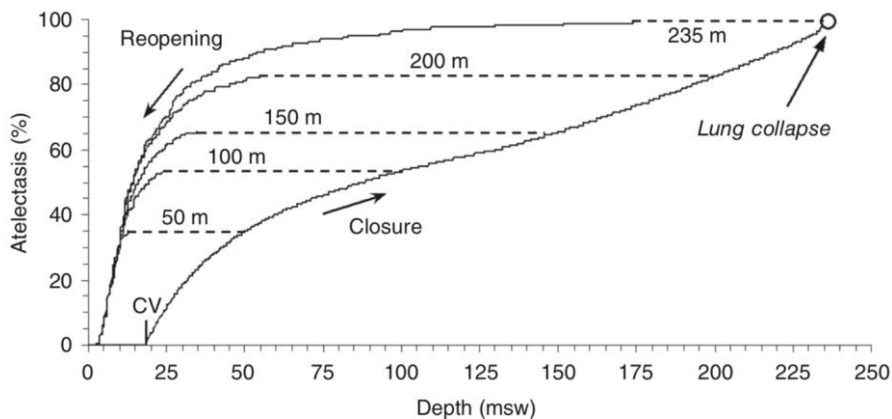
Fitz-Clark JR Comparative Physiol 2018; 8: 585-630



Airway pressure in cmH<sub>2</sub>O versus depth during a breath-hold descent predicted by computer simulation. The model incorporates immersion, air compression, respiratory system compliance, and thoracic blood shift. Lung packing extends the pressure reversal depth  $Z_R$  from 27 to 43 msw. Small ripples are from heart beat volume oscillations.

## Mechanisms of airway and alveolar collapse in human breath-hold diving

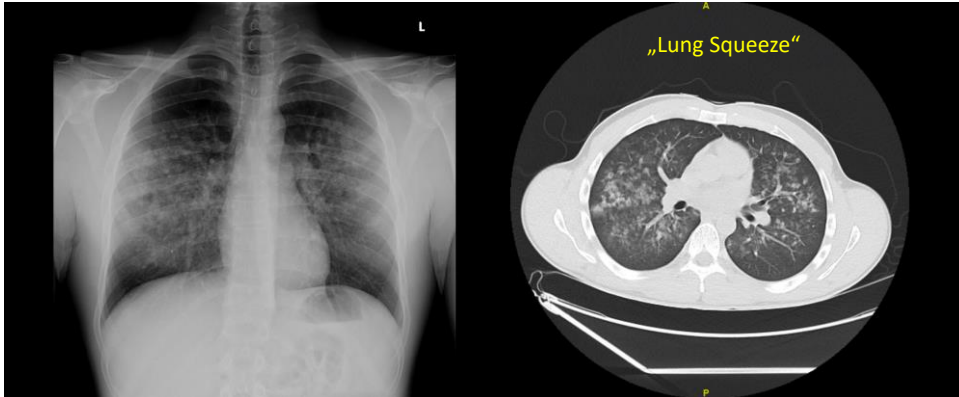
Fitz-Clarke JR. Resp Physiol Neurobiol 2007; 159: 202-210



Computer model estimates of percent alveolar closure and reopening during dives to various depths. First alveolus reaches closing volume CV around 18 m. Lungs reach the fully collapsed state around 235 m assuming an initial lung volume of 9.2 L. Dashed lines indicate ascent to first alveolar reopening.

## Pulmonary barotrauma and related events in divers

Raymond LW. Chest 1995;107:1648-52

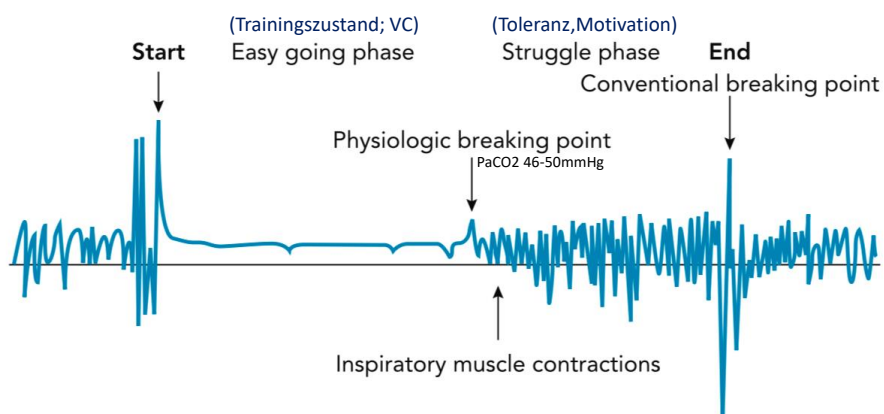


4th AIDA World Free Diving Championship (Vancouver 2006)

4 Freitaucher:innen (7%) aus 57 Teilnehmer:innen entwickelten Hämoptysen, Husten und Thoraxschmerz  
 35 (61%) zeigten Verluste der „Motorkontrolle“ nach dem Auftauchen durch Hypoxie  
 3 (5%) Taucher:innen verloren das Bewusstsein zwischen 38 und 75 Meter Tiefe

## BREATH-HOLD DIVING

Feringo M, Lundgren CE. In Bennett & Eliot's Physiology and Medicine of Diving.  
 Eds. Brubakk A, Neuman T. Philadelphia: Saunders 2003: 153-180

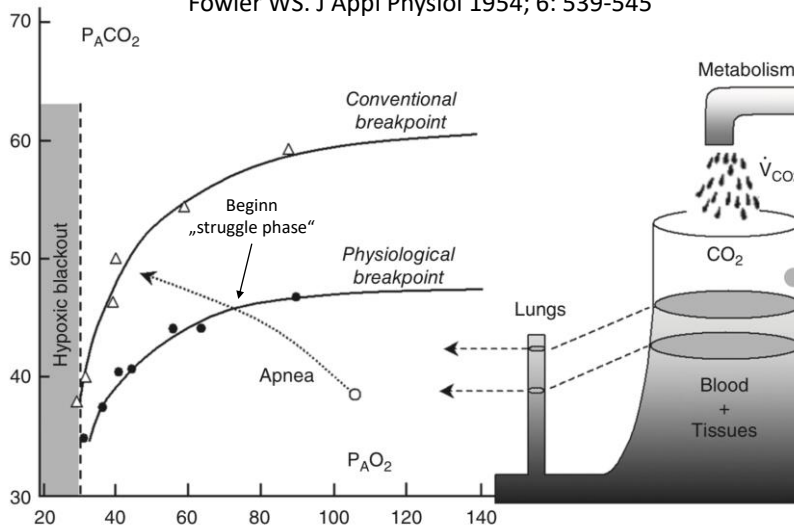


Human thoracic movements measured by electromyography (EMG) during maximal breath-holding in an untrained, non-immersed subject

Diaphragm activity during breath holding. Factors related to its onset  
 Agostini E. J Appl Physiol 1963; 18: 30-36

### Breaking point of breath-hold diving

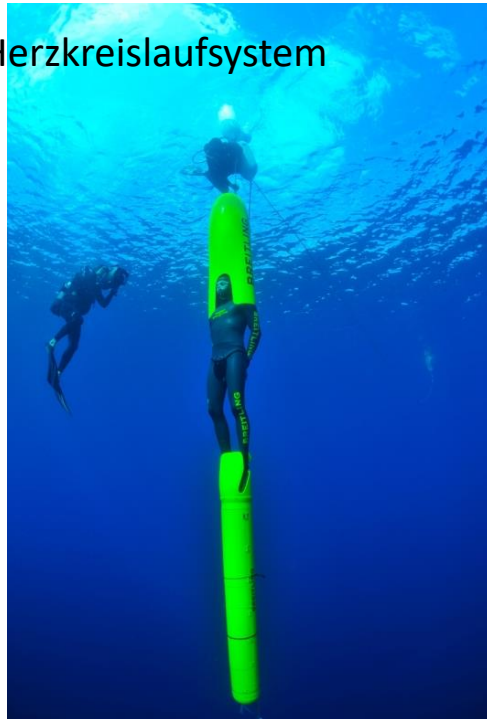
Fowler WS. J Appl Physiol 1954; 6: 539-545



## APNOE – das Herz-Kreislaufsystem

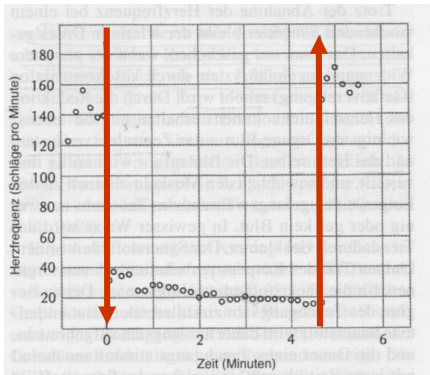
*Herbert Nitsch*  
 Weltrekord Non Limit Tauchen: 214m  
 (Jahr 2007)

*Tanja Streeter*  
 Weltrekord Non Limit Tauchen: 160m  
 (Jahr 2002)

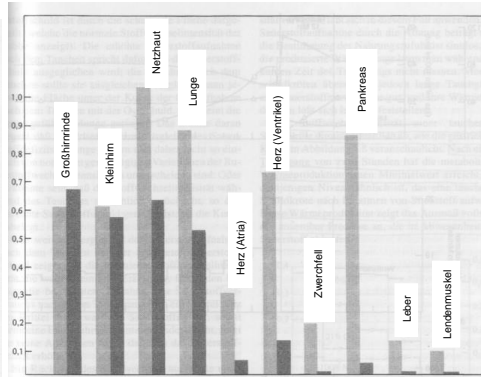


# DER TAUCHREFLEX

HF-Verhalten beim Tauchgang eines Seehundes („Harbour seal“)

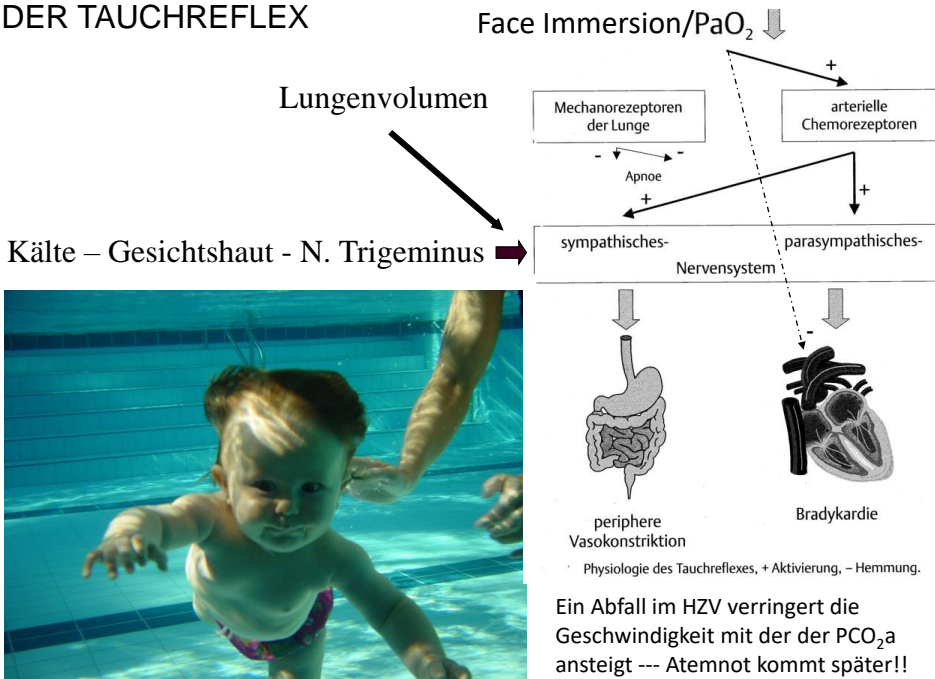


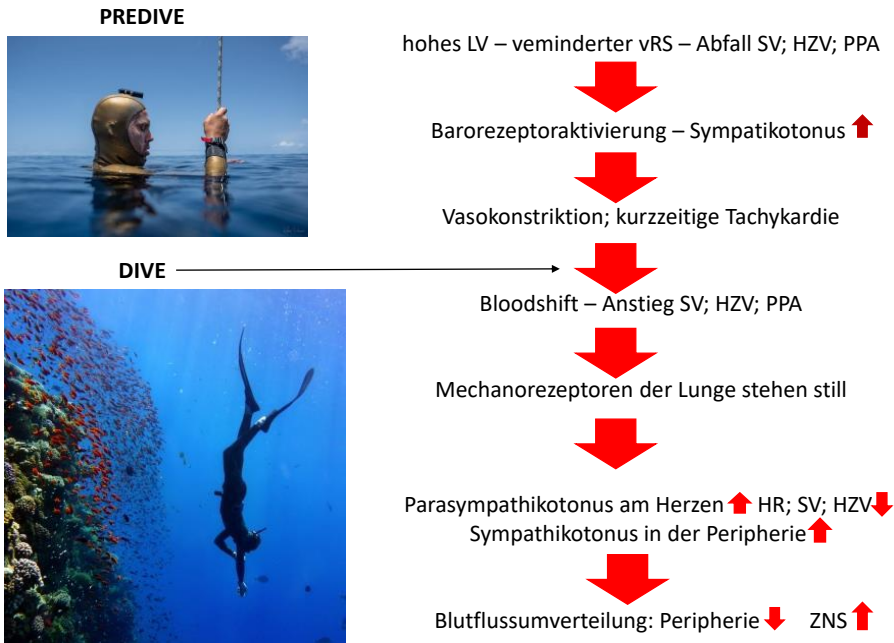
Blutumverteilung beim Tauchen bei einer Weddellrobbe



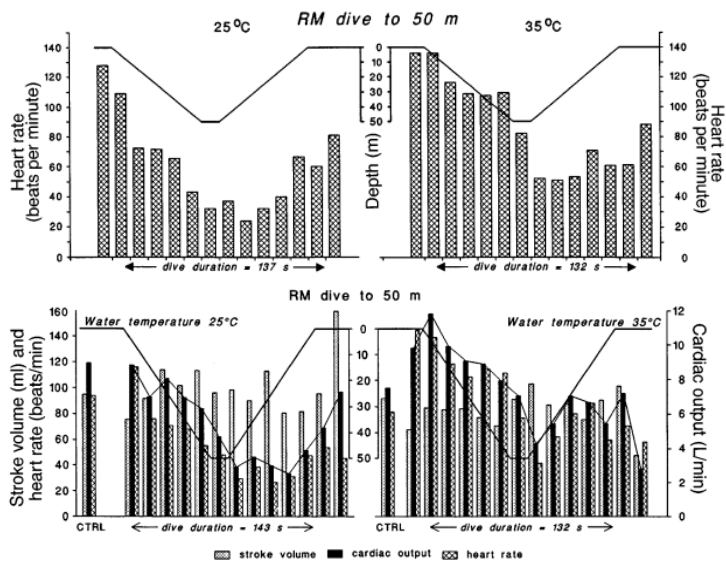
Muskulatur, Gastrointestinaltrakt Zwerchfell werden fast vollständig von der Durchblutung abgeschaltet

## DER TAUCHREFLEX



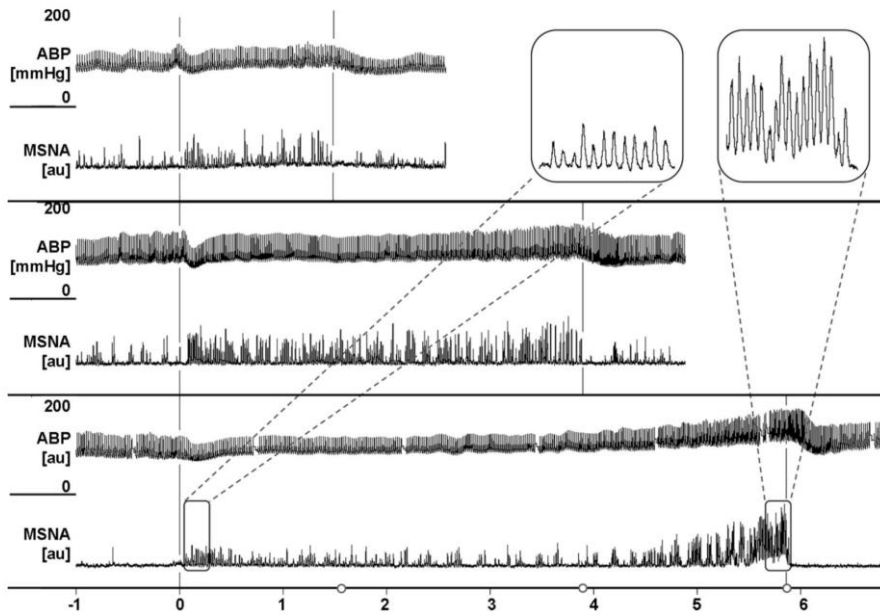


Cardiovascular changes during deep breath-hold dives in a pressure chamber  
 Ferrigno M, et al. J Appl Physiol 1997; 83: 1282-1290



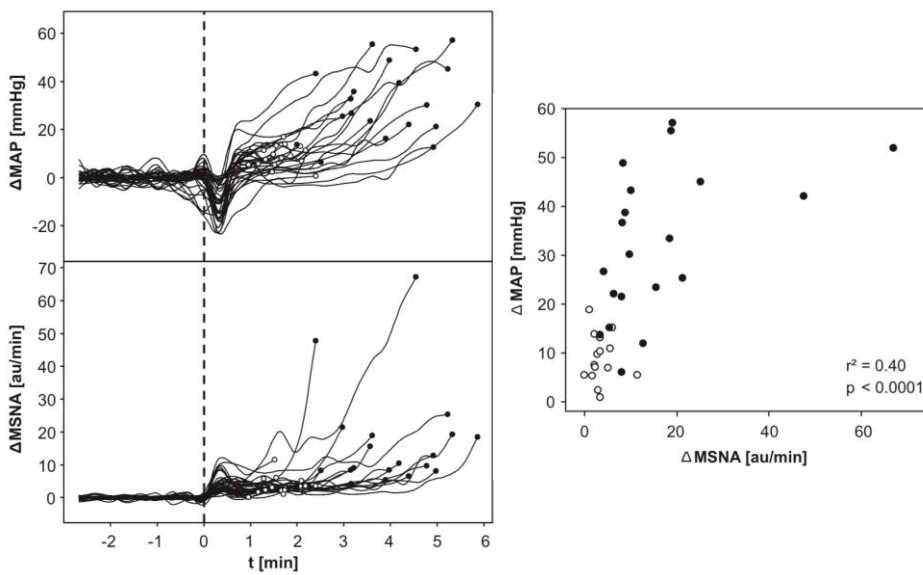
## Cardiovascular regulation during apnea in elite divers

Heusser K et al. Hypertension 2009;53:719-724



## Cardiovascular regulation during apnea in elite divers

Heusser K et al. Hypertension 2009;53:719-724



### $\beta$ 1-blockade increases maximal apnea duration in elite breath-hold divers

Hoiland RL, Ainslie PN, Bain AR, et al.

J Appl Physiol 2017; 122: 899-906

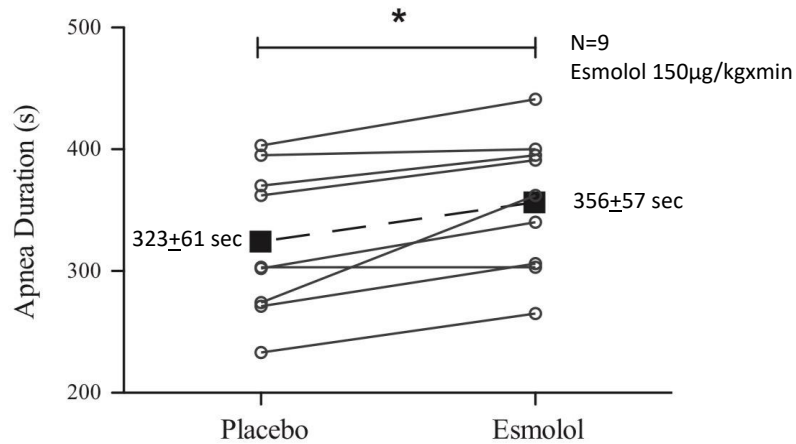


Fig. 1. Maximal apnea duration during placebo and esmolol trials. Individual data are represented by  $\circ$  and solid lines, whereas mean data are represented by  $\blacksquare$  and the dashed line. Overall, there was a  $32 \pm 25$ -s increase in apnea duration with esmolol treatment. \*Significant difference in apnea duration ( $P < 0.01$ ).

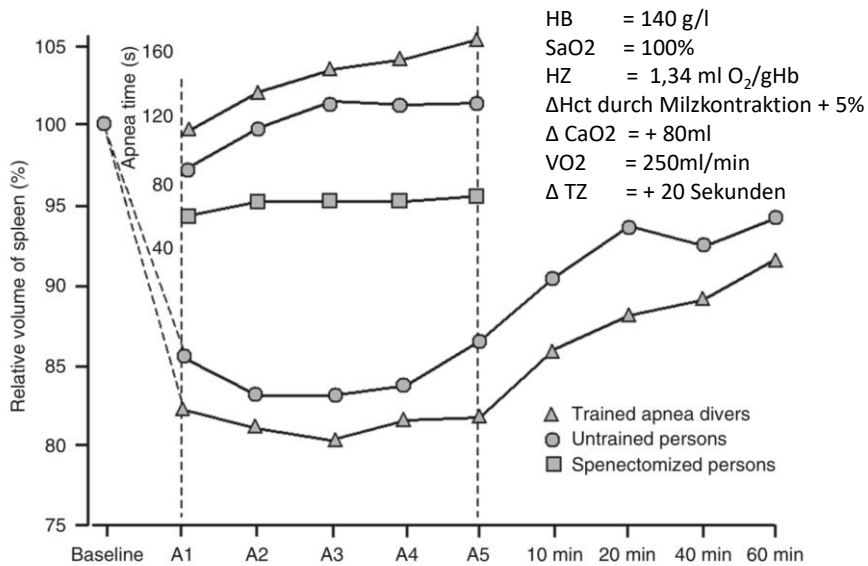
### Cardiovascular changes during deep breath-hold dives in a pressure chamber

Ferrigno M, et al. J Appl Physiol 1997; 83: 1282-1290



## Spleen volume and blood flow reponse to repeated breath hold apneas

Bakovic D, et al. J Appl Physiol 2003; 95: 1460-1466



## APNOE UND DAS GEHIRN

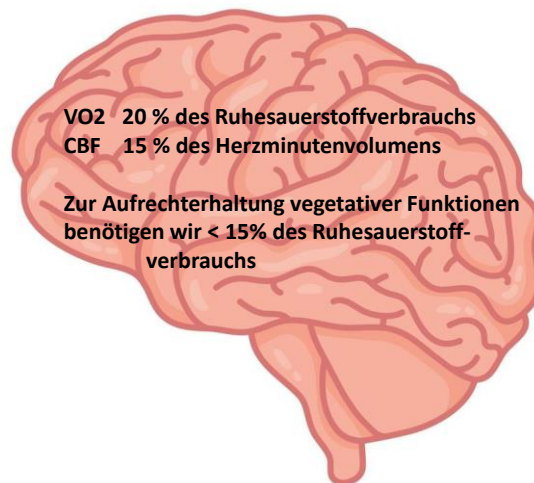
Hypoxie/N<sub>2</sub>



Kognitive  
und  
motorische  
Dysfunktion



Bewusstlosigkeit



## BLACKOUT



MEIST BEIM AUFTAUCHEN:

PaO<sub>2</sub> nimmt in den letzten 10m des Auftauchens um > 50% ab!

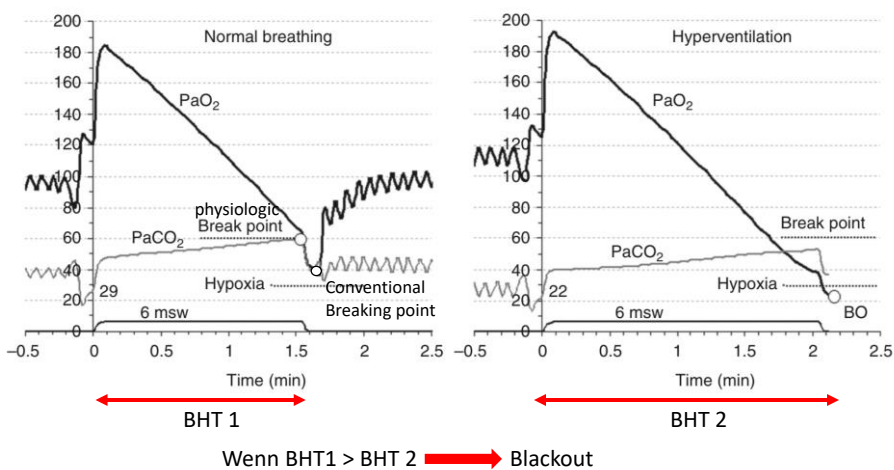
BHT (Air) = Volume of usable Oxygen/ Oxygen uptake

$$\text{BHT} = ((\text{FAO}_2 \times \text{TLC}) + \text{VB} \times (\text{CaO}_2 - \text{C}_\text{H}\text{O}_2)) / \text{VO}_2$$

$$\text{BHT} = ((0,16 \times 12) + 5 \times (0,2 - 0,05)) / 0,25 = 10,7 \text{ min}$$

## Breath-Hold Diving

Fitz-Clarke JR. Comparative Physiology 2018; 8: 585-630



8-10% aller Elite Apnoetaucher:innen zeigen Hypoxiesymptome im Rahmen von Wettbewerben!

**SAMBAS:** Zurückrollen der Augen; Kopfinstabilität nach Auftauchen; Myklonien, Blackout

## Stickstoff und Apnoetauchen

Die Hälfte aller Apnoisten die auf Tiefen > 40m abtauchen erleiden  
wie Schwindel, Konzentrationsprobleme, Koordinationsstörungen, Bewusstseinsstörungen bis Bewusstlosigkeit

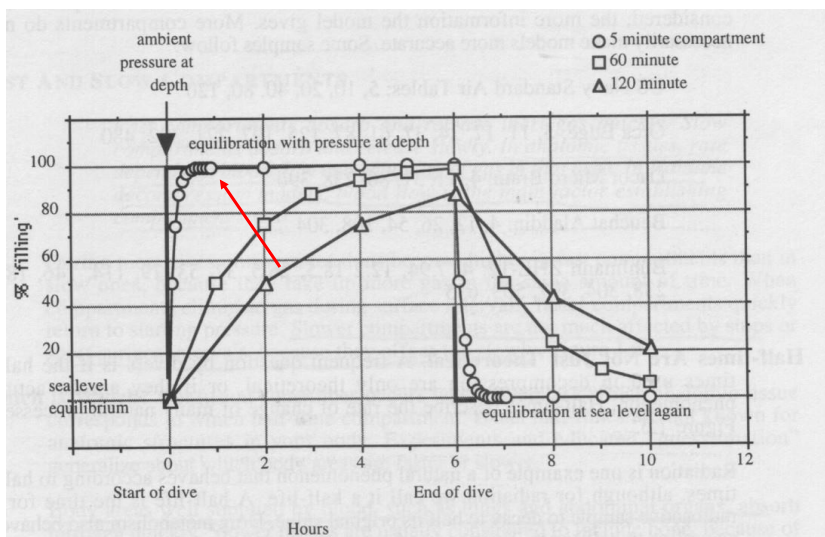
Gas	Narkosepotential
Helium	0,23
Neon	0,28
Stickstoff	1
Argon	2,32
Kohlendioxyd	20
Xenon	25,64
Stickoxyd	31

Table 1 Signs and symptoms of nitrogen narcosis at different depths [2,29]

Depth (msw)	Atmospheric pressure (atm)	pN <sub>2</sub> (atm)	Signs and symptoms of narcosis
0-10	1-2	0.79-1.58	Unnoticeable/minor symptoms such as subtle changes in behaviour
10-30	2-4	1.58-3.16	Mild impairment of unpractised tasks Impaired reasoning
30-50	4-6	3.16-4.74	Delayed response to visual and auditory stimuli Calculation errors and poor choices Mild amnesia Overconfidence, idea fixation and a sense of well-being
50-70	6-8	4.74-6.32	Laughter (chambers) or anxiety (cold water) Impaired judgement and confusion Hallucinations
70-90	8-10	6.32-7.90	Delay in response to signals, instructions and other stimuli Uncontrolled laughter, hysteria (in chamber) Feelings of terror (in some)
90+	10+	7.90+	Mental confusion Loss of memory Stupefaction and loss of judgement Hallucinations, increased intensity of vision and hearing Unconsciousness Death

### The risk of decompression illness in breath-hold divers: a systematic review

Blogg SL, et al. Diving and Hyperbaric Medicine 2023; 53: 31-41



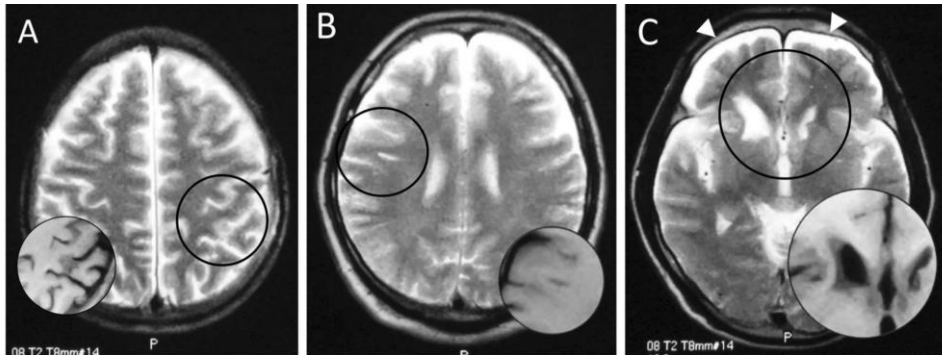
Die Ratio von Oberflächenintervall zu Tauchzeit in einer bestimmten Tiefe ergibt das DCS Risiko!

## Brain damage in commercial breath-hold divers

Kohshi K, Tamaki H, lemaitre F, et al.

PLOS one 2014; 9: e105006. doi:10.1371/journal.pone.0105006

12 AMA; mean age 55 years; 4 history of DCS



**Figure 1. Magnetic resonance images of brains of three Ama divers: hyperintense area on T2-weighted image (circle), corresponding to hypointensity on T1-weighted image (inset).** A patchy shadow in the left parietal cortex (A, No. 2), a linear subcortical lesion in the right frontal lobe (B, No. 5), and deformity of bilateral caudate heads and subdural fluid collection (allow heads) (C, No. 11). doi:10.1371/journal.pone.0105006.g001



**DANKE FÜR IHRE AUFMERKSAMKEIT!**

## Cardiovascular changes during maximal breath-holding in elite divers

Guaraldi P, Serra M, Barletta G, et al.

Clin Auton Res 2009; doi: 10.1007/s10286-009-0025-2

Subject no.	Age (years)	Weight (kg)	Height (cm)	BMI	Apneic time (s)	Static apnea record (s)	Individual delay (s)
1	27	72	182	21.7	240	285 <sup>a</sup>	17 <sup>a</sup>
2	38	74	176	23.9	208	285 <sup>a</sup>	23 <sup>a</sup>
3	34	70	168	24.8	223	246 <sup>a</sup>	20 <sup>a</sup>
4	32	60	173	20	207	330 <sup>a</sup>	17 <sup>a</sup>
5	48	83	177	26.5	237	345 <sup>a</sup>	19 <sup>a</sup>
6	44	75	183	22.4	267	326 <sup>a</sup>	12 <sup>a</sup>
Mean ± SD	37 ± 8	72 ± 8	177 ± 6	22 ± 3	230 ± 23	303 ± 37 <sup>a</sup>	18 ± 4 <sup>a</sup>

*BMI* body mass index; *static apnea record* individual static apnea record; *individual delay* individual time delay from the end of apnea to the minimum of sO<sub>2</sub> and pO<sub>2</sub> and to the maximum of pCO<sub>2</sub>

**Table 2** Cardiovascular and blood gases changes during baseline, end of "easy-going" and end of "struggle" phases of breath-holding with face immersion in cold water

	Basal period	End of "easy-going" phase	End of "struggle" phase
Length (s)	NA	108 ± 59	122 ± 48
SBP (mmHg)	142 ± 9	173 ± 10	275 ± 48 <sup>a§</sup>
DBP (mmHg)	89 ± 8	102 ± 9	131 ± 22 <sup>a§</sup>
HR (b/m)	77 ± 13	65 ± 12	54 ± 8 <sup>§</sup>
CO (L/min)	5.86 ± 1.05	5.06 ± 1.63	5.02 ± 1.83
TPR (mmHg s/ml)	1.19 ± 0.32	1.71 ± 0.58	2.35 ± 0.76 <sup>§</sup>
pO <sub>2</sub> (mmHg)	86 ± 16	61 ± 26	20 ± 8 <sup>a§</sup>
pCO <sub>2</sub> (mmHg)	33 ± 6	36 ± 7	47 ± 7 <sup>a§</sup>
sO <sub>2</sub> (%)	100 ± 1	93 ± 11	72 ± 13 <sup>a§</sup>

Data are presented as means ± SD in the three phases of the maneuver

*SBP* systolic blood pressure; *HR* heart rate; *CO* cardiac output; *TPR* total peripheral resistance; *sO<sub>2</sub>* oxygen saturation; *pO<sub>2</sub>* partial tension of oxygen; *pCO<sub>2</sub>* partial tension of carbon dioxide

<sup>§</sup> End of "struggle" phase versus basal: *P* < 0.05

<sup>a</sup> End of "struggle" phase versus end of "easy-going" phase: *P* < 0.05