

Physiology of apnea

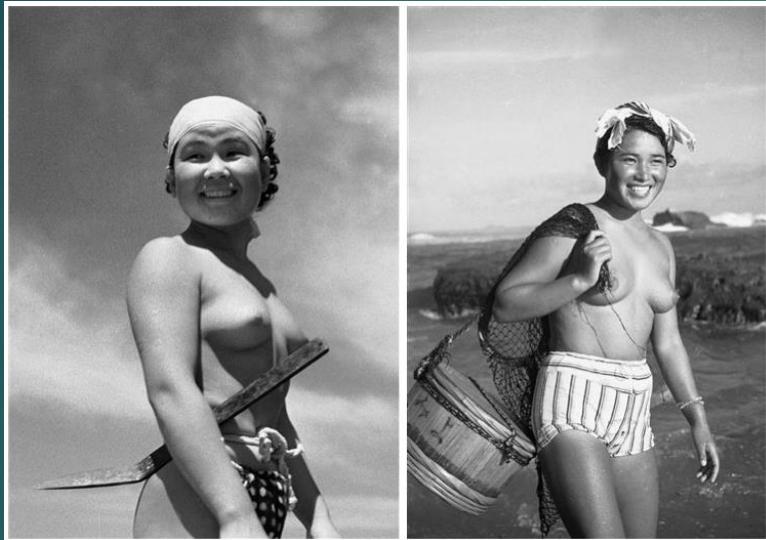
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apnea history

- Older proofs between 5 - 8 000 BC (mésolithic)
- 2500 BC Mésopotamie (Irak actuel), proofs of free dives (pearls from deep-sea pearl oysters)
- Salomon Islands (wooden glasses with tortoiseshell porthole)
- 500 BC first feat of apnea divers described by Herodotus. Scyllias de Scione and her daughter Cyana
- 415 BC Aristotle describes the action of Greek divers sawing the anti-landing piles
- Heraclitus called man-boat snorkelers in Greek "SKAPHE ANDROS" which originated the term scuba for scuba diving.
- Alexander the Great had regiments of swimmers divers from the 4th century BC (ultricularis) ancestors of combat swimmers and mine clearance divers

apnea history

The Ama in Japan and the Haenyo of Korea are mentioned as early as 268 BC



apnea history



Bajau nomads of Indonesia



Moken of Birmania



Urak Lawoi (Orang Laut) of Thailand

Main apnea disciplines

- Static apnea.
- Dynamic apnea (with or without fins) in swimming pool
- Free immersion
- Constant weight apnea
- Variable weight apnea
- No limit
- Apnea under ice



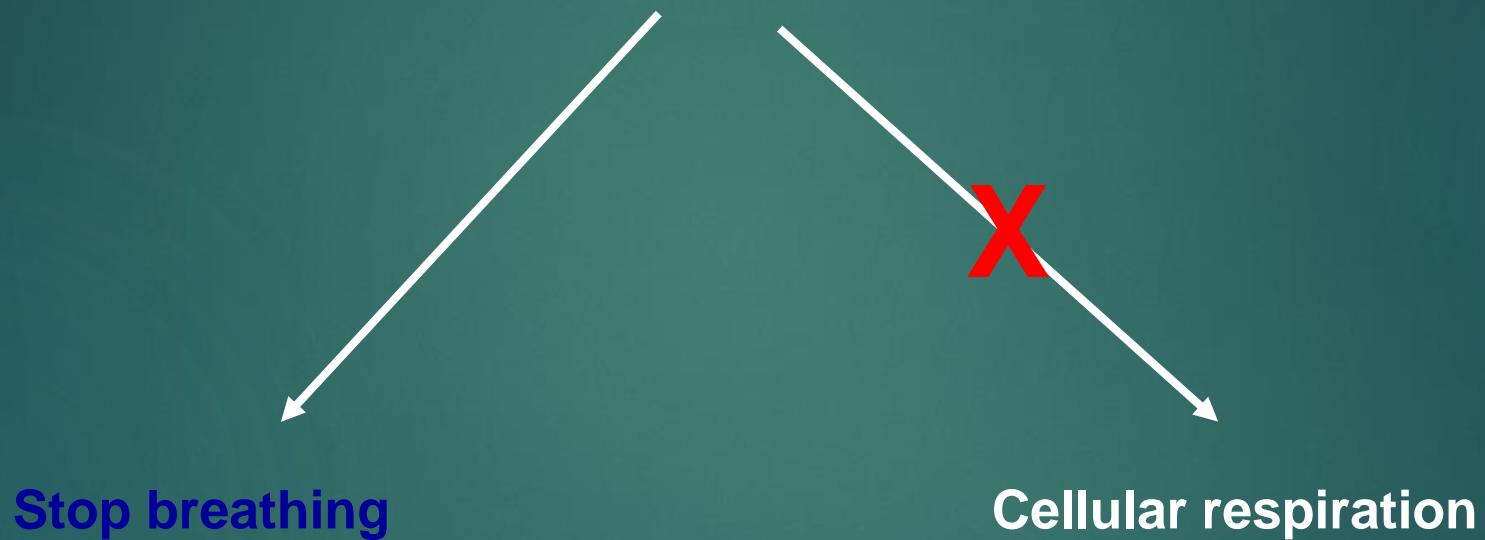
Disciplines	Sexe	Nom	Nationalité	Performance	Année du record
Poids constant	F	Alenka ARTNIK	Slovénie	122m	2021
Avec Mono palmes	M	Alexei Molchanov	Russie	131m	2021
Poids constant	F	Alessia ZECCHINI	Italie	74m	2021
Sans palme	M	William Trubridge	Nlle Zélande	102m	2017
Poids variable	F	Nanja VAN DEN BROEK	Pays bas	130m	2015
	M	Walid Boudhiaf	Tunisie	150m	2021
No Limit	F	Streeter	USA	160m	2002
	M	Nitsch	Autriche	214m	2007
Apnée Statique	F	Molchanova	Russie	9min02s	2013
	M	Mifsud	France	11min35s	2009

Dynamique	F	Zecchini	Italie	250m	2016
Avec Mono palme	M	Mateusz Malina	Pologne	316m	2022
Dynamique	F	Julia Kozerka	Pologne	209m	2022
sans palme	M	Mateusz	Pologne	250m	2022
Poids constant	F	Alenka ARTNIK	Slovénie	106m	2021
Bi palmes	M	Arnaud Jerald	France	120m	2022
Immersion	F	Grasmeijer	Pays Bas	92m	2016
Libre	M	Trubridge	Nlle Zélande	124m	2016

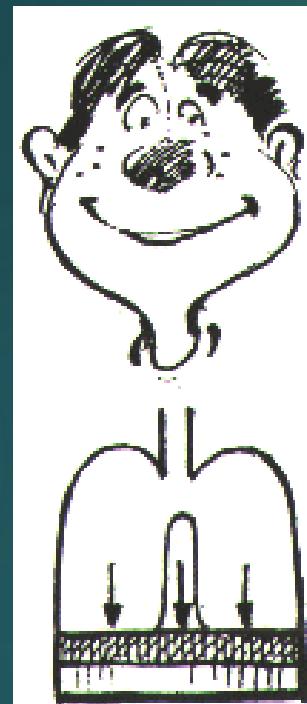
- Apneas are caused by the effect of thoracic plating against the bodywork or the steering wheel and by the driver's concentration in certain Race Phases (qualifying lap, start)
- These episodes are brief but repetitive, and represent up to 1/4 of the total time of the race increasing the hypoventilation.



Breath-hold



breathing

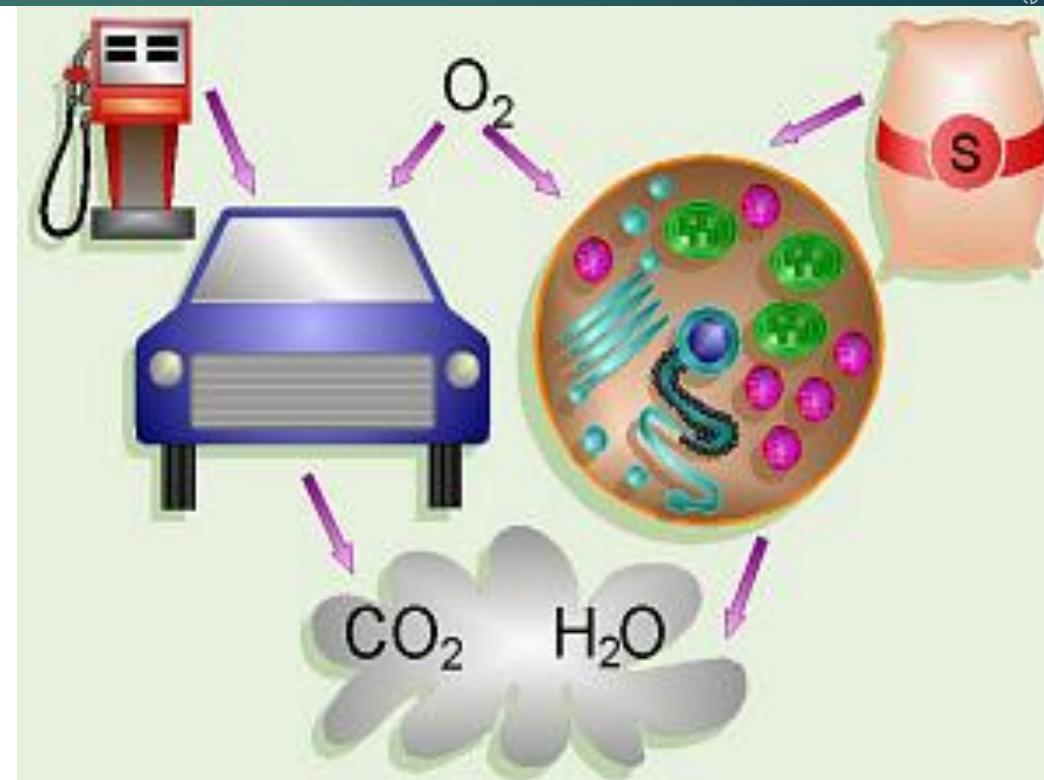


INSPIRATION



EXPIRATION

Cellular respiration



factors determining the duration of apnea

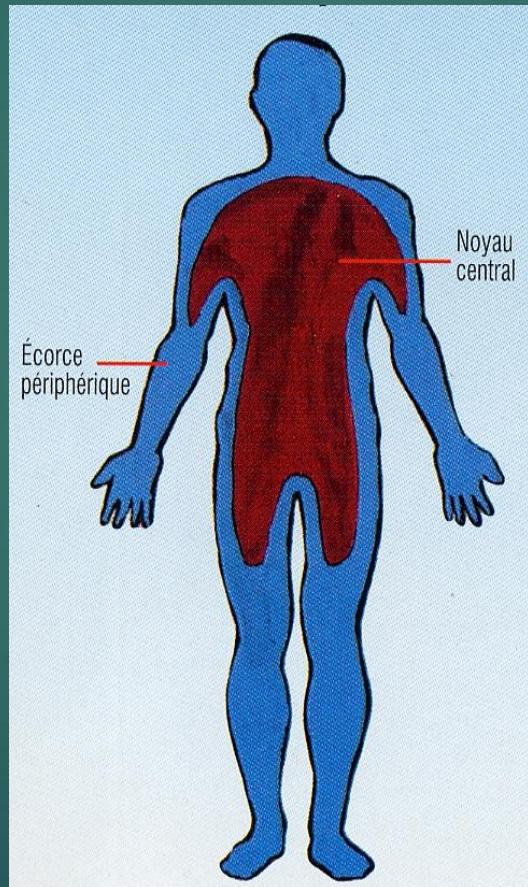
- O₂ reserves
 - Lungs
 - Blood (hemoglobin)
 - Cells (myoglobin, cytoglobin...)
 - Spleen
- O₂ uptake
- CO₂ production
- Chemo-sensitivity
- buffer system efficacy

- Lack of rib cage movement
- Ability to deal with unpleasant feelings
- Intensity of physical activity
- Environmental conditions (pressure, temperature,...)
- Training
- Genetic

Core and peel

core

- brain eyes, ears)
- thoracic and abdominal organs
- 8 % body weight



peel

- skin
- Adipose tissue
- Skeletal muscles
- Buffer zone between the core and the environment

The diving reflex

- The diving reflex is a protective, multifaceted physiologic reaction that occurs in mammals including humans in response to water submersion. Aspects of the dive reflex were first described in 1786 by Edmund Goodwyn
- Edmund Goodwyn, a British physician who studied medicine at the University of Edinburgh, had described this reflex in his doctoral thesis, which was originally published in Latin in 1786 and in English in 1788.
- It would take until an 1870 publication by Paul Bert for the physiologic adaptations to be recognized.
- The diving response exists in all mammals including humans, and it helps in the preservation of oxygen stores for key organ systems during times of asphyxia.

The diving reflex

- The reflex was described in human infants as well. it is believed to be a protective response to avoid drowning. When the dive reflex activates in infants, the cardio-respiratory response is more intense than compared to adults. (Goksör E, Rosengren L, Wennergren G. Bradycardic response during submersion in infant swimming. *Acta Paediatr.* 2002;91(3):307-12)
- During the first year of life, the dive response can be fully elicited by merely immersing the infant's face in water without having them hold their breath (Pedroso FS, Riesgo RS, Gatiboni T, Rotta NT. The diving reflex in healthy infants in the first year of life. *J Child Neurol.* 2012 Feb;27(2):168-71)
- Diving reflex was observed in 95.3% of newborns and in 100% of infants between 2 and 6 months of age. At 6 months, it started to decrease but persisted in 90% of the infants up to 12 months. The diving reflex is highly prevalent in the first year of life.

Diving reflex

- Its main mechanisms involve peripheral receptors, neuronal pathways, and chemoreceptors. Once a mammal holds its breath and submerges under water two things occur: the face gets wet and the oxygen content in the lungs becomes fixed.
- When mammals dive under water, sensory information from the nasal region is relayed to the brainstem, making up the afferent tract of the diving reflex neural pathway. (McCulloch PF. Animal models for investigating the central control of the Mammalian diving response. *Front Physiol.* 2012;3:169)
- Specifically, the afferent neuronal pathway involved is the trigeminal nerve relaying sensory information back to the brainstem. The brainstem then sends efferent signals via the vagus nerve to specific target organs. The vagus nerve primarily associates with the parasympathetic nervous system, and the result of this neuronal pathway is **bradycardia**. The brainstem also sends out efferent signals to the peripheral vascular musculature which **increases peripheral vascular resistance** and results in **blood shunting toward more vital organs**.

Apnea response and hypoxia response

- diving reflex
 - bradycardia
 - Peripheral vasoconstriction
 - Apnea
- apnea effects
- Spleen contraction

(Schagatay E, Andersson JP, Hallen M, Palsson B. Selected contribution: role of spleen emptying in prolonging apneas in humans. *J Appl Physiol* 2001;90:1623–9.

Bakovic D, Valic Z, Eterovic D, Vukovic I, Obad A, Marinovic-Terzic I, et al. Spleen volume and blood flow response to repeated breath-hold apneas. *J Appl Physiol* 2003;95:1460–6.)

- Blood adenosin increase
- pH decrease
- Coronary perfusion increase
- Brain perfusion increase
- La increase
- Decrease cardiac output

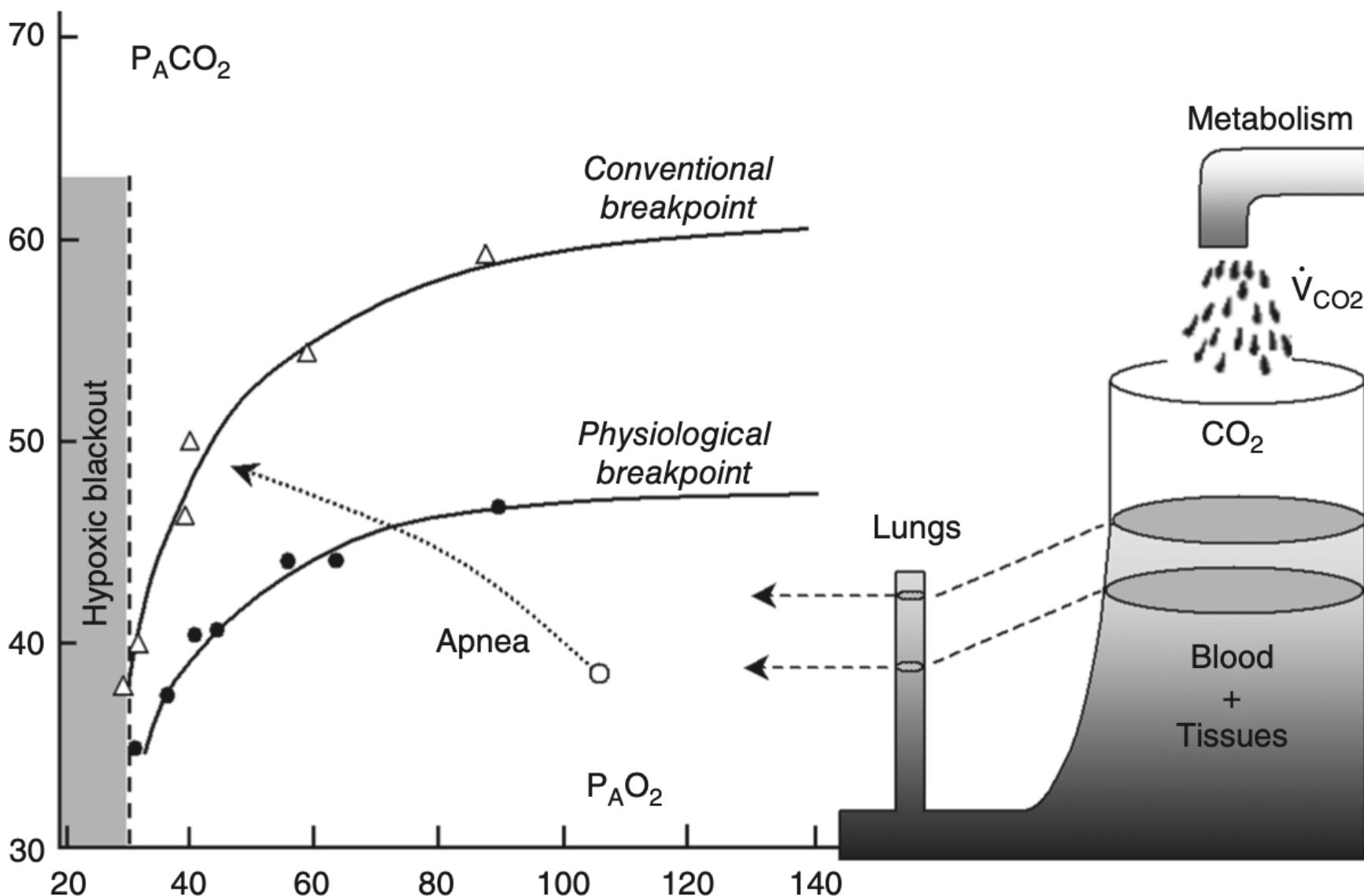


Figure 14 Alveolar CO_2 rises and O_2 falls during a breath-hold on air (dashed curve). Involuntary diaphragmatic contractions begin at the physiological breakpoint. Apnea becomes intolerable at the conventional breakpoint. Hypoxic blackout occurs if oxygen level falls below about 20 to 30 mmHg. Modified, with permission, from Agostoni (1).

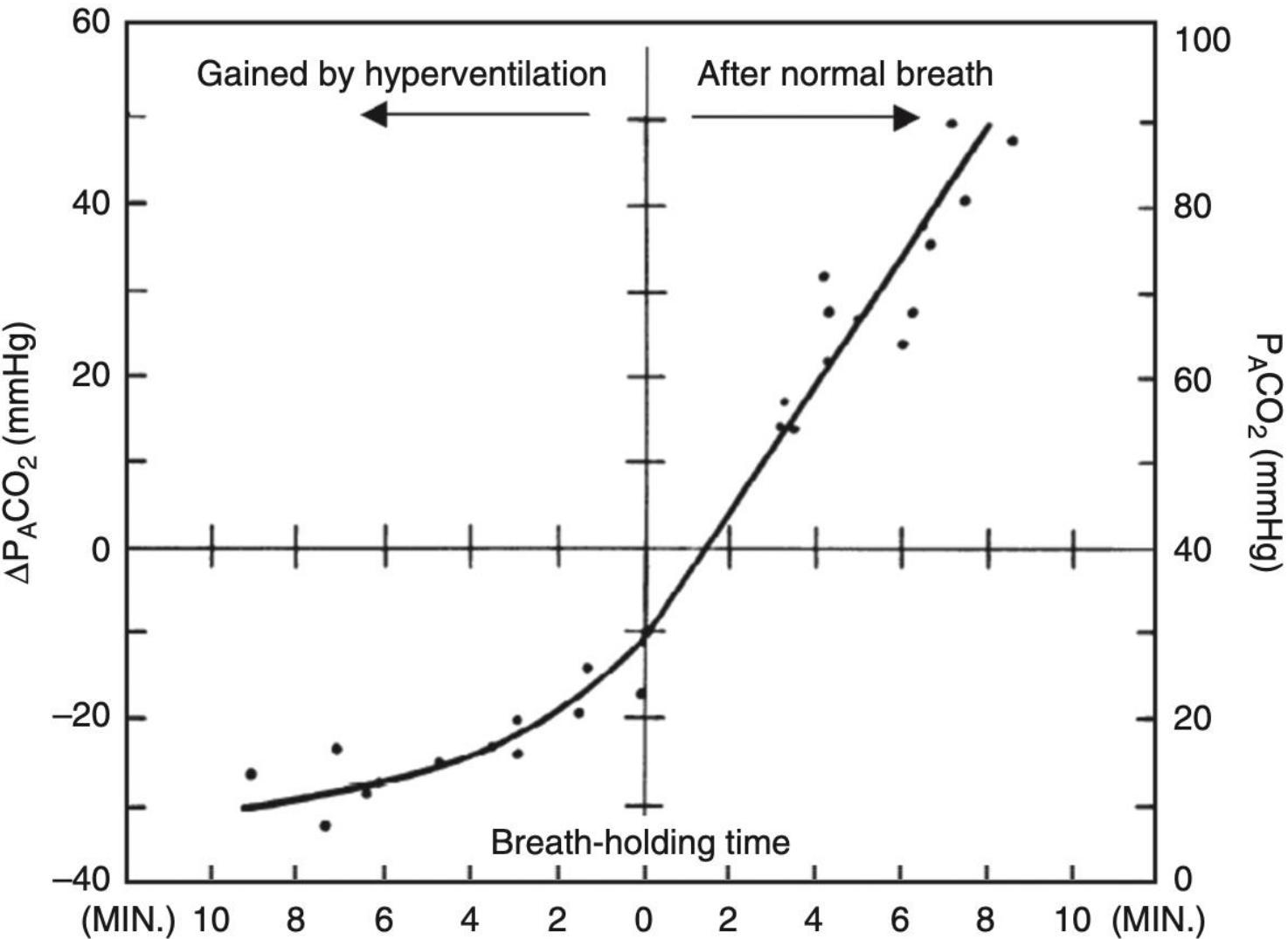


Figure 13 Apnea time on a breath of pure oxygen is limited by intolerable carbon dioxide accumulation. The right-hand side of the curve tracks alveolar $P_{\text{A}}\text{CO}_2$ rise with apnea time to the breakpoint. Preceding hyperventilation adds the time shown on the left-hand side by having lower initial $P_{\text{A}}\text{CO}_2$. Total apnea time is the sum of both sides. Reproduced, with permission, from Klocke and Rahn (204).

Face immersion

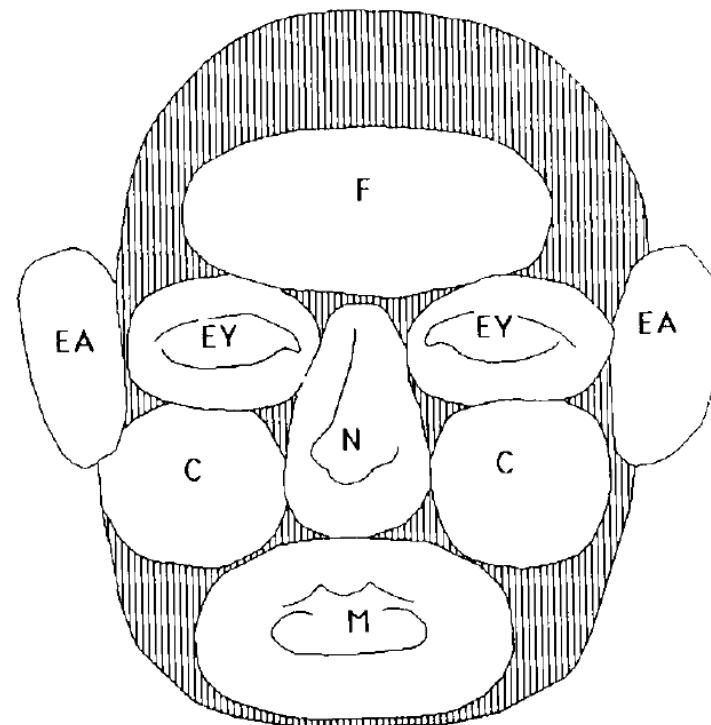
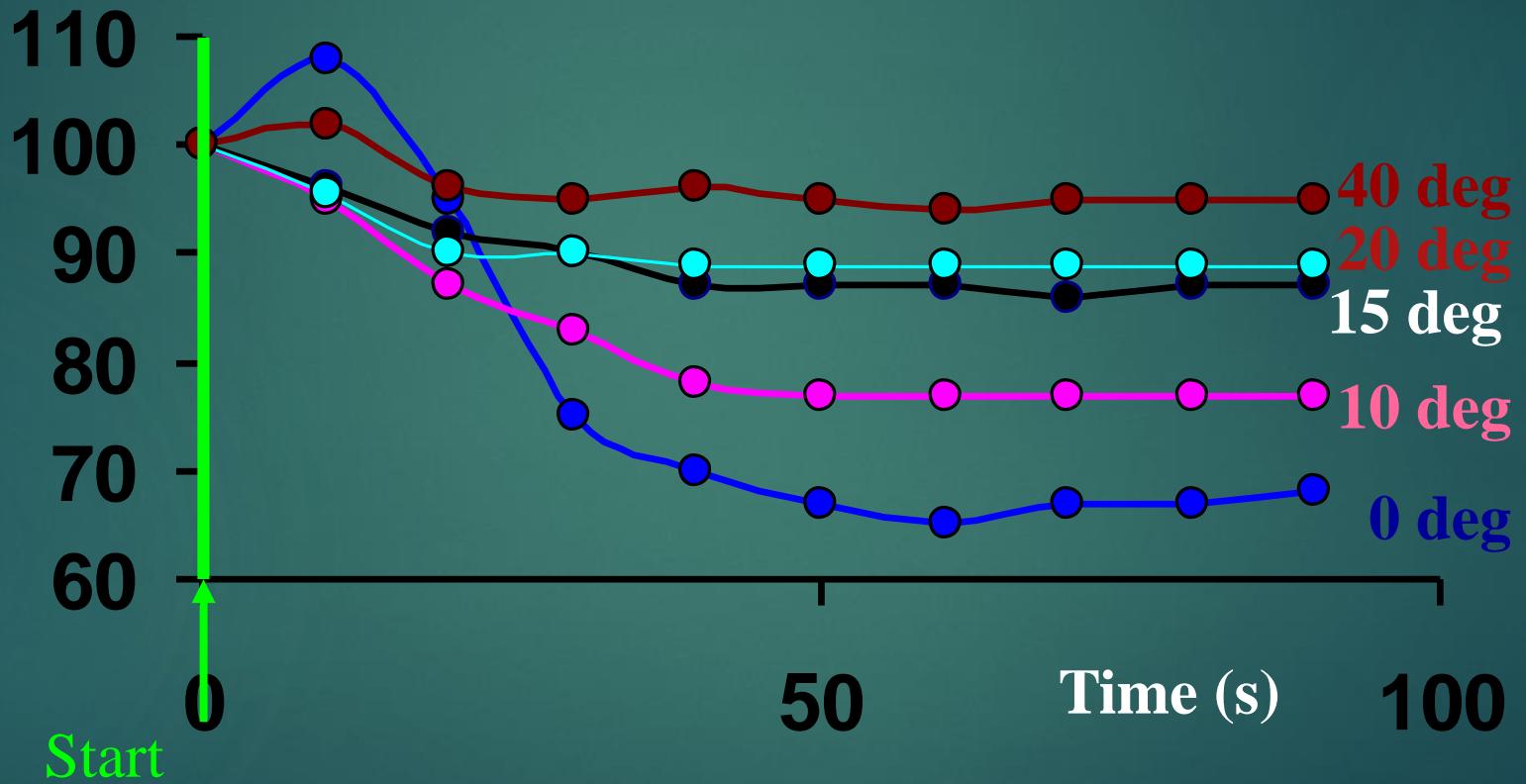


Fig. 1. The facial areas chilled with ice-water bags in six of the tests, the other two being only breath-holding (BH) and face immersion (FI) including all areas except the ears (EA).

- ✓ *The diving response is obtained in man when the face is immersed in cold water and the breath is held (Furedy 1983). Cold stimulation without wetting gives a similar bradycardia as face immersion (Kawakami et al. 1967) indicating that cold receptors are involved.*

Schuitema KE, Holm B. The role of different facial areas in eliciting human diving bradycardia. *Acta Physiol Scand* 132: 119-120, 1988.

Heart rate variations



EKG during a 100 m apnea dive

(doi:10.1152/japplphysiol.00877.2020)

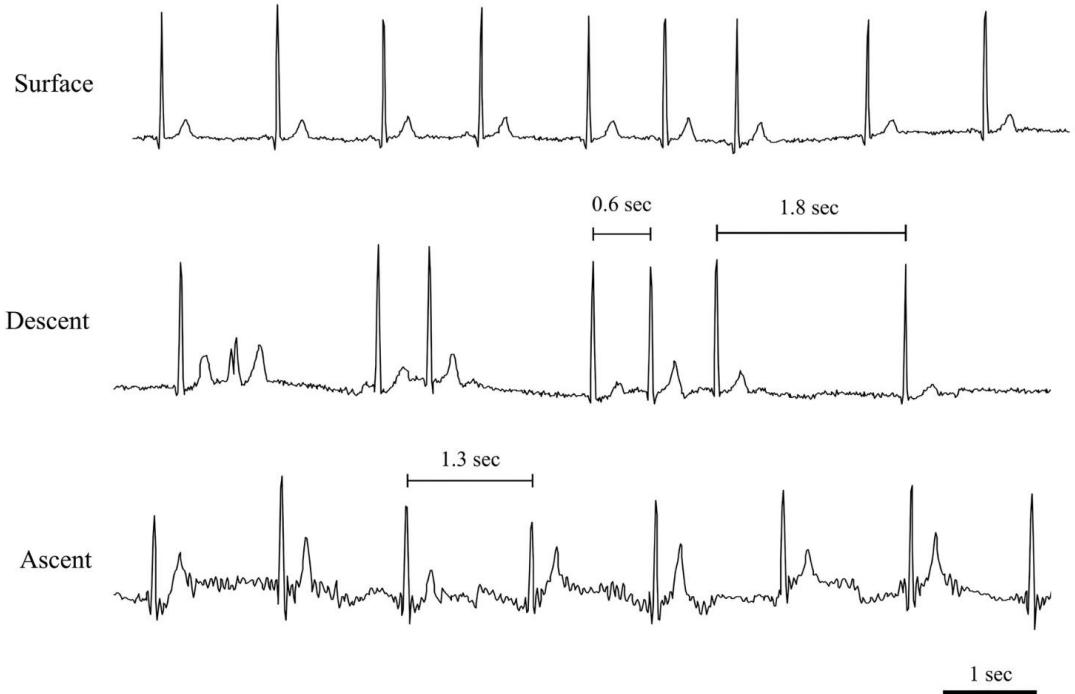


Figure 2. Electrocardiographic signals in diver 1 (lead V5). Surface—sinus rhythm with respiratory fluctuations during the relaxed breathing preparation phase (3 min before dive). Descent—sinus bradycardia with regular supraventricular premature beats and six premature ventricular contractions occurring from 10 m on descent, continuing for ~2:16 min to 77 m on ascent. Ascent—sinus bradycardia, occurring during the last 77 m of ascent. Mean R-R interval durations during descent and ascent are included.

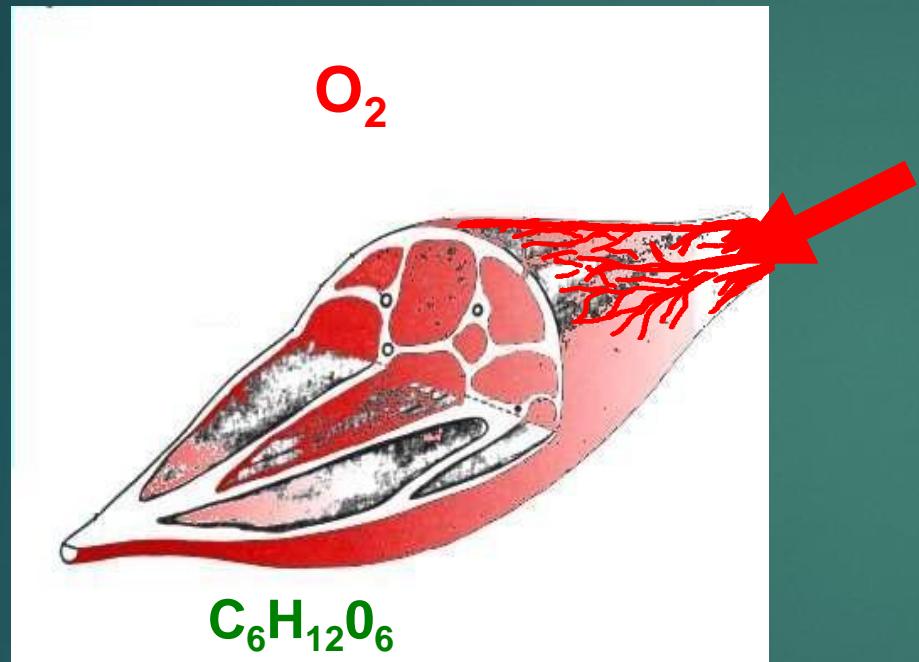
Peripheral vasoconstriction



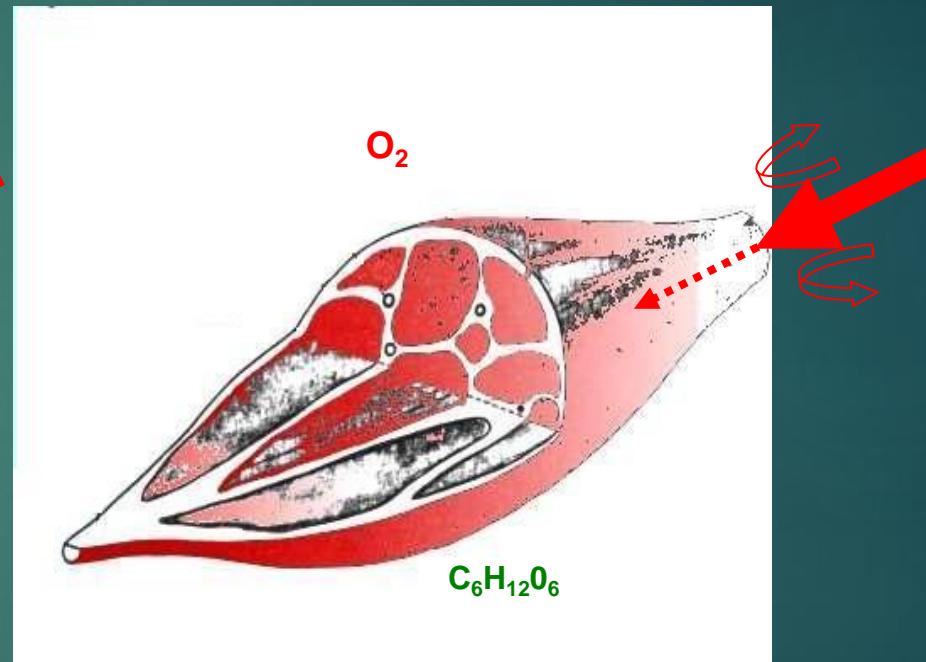
Hypoxie M1
Scatá 2010

Muscular perfusion

Exercice



Exercice + Apnée



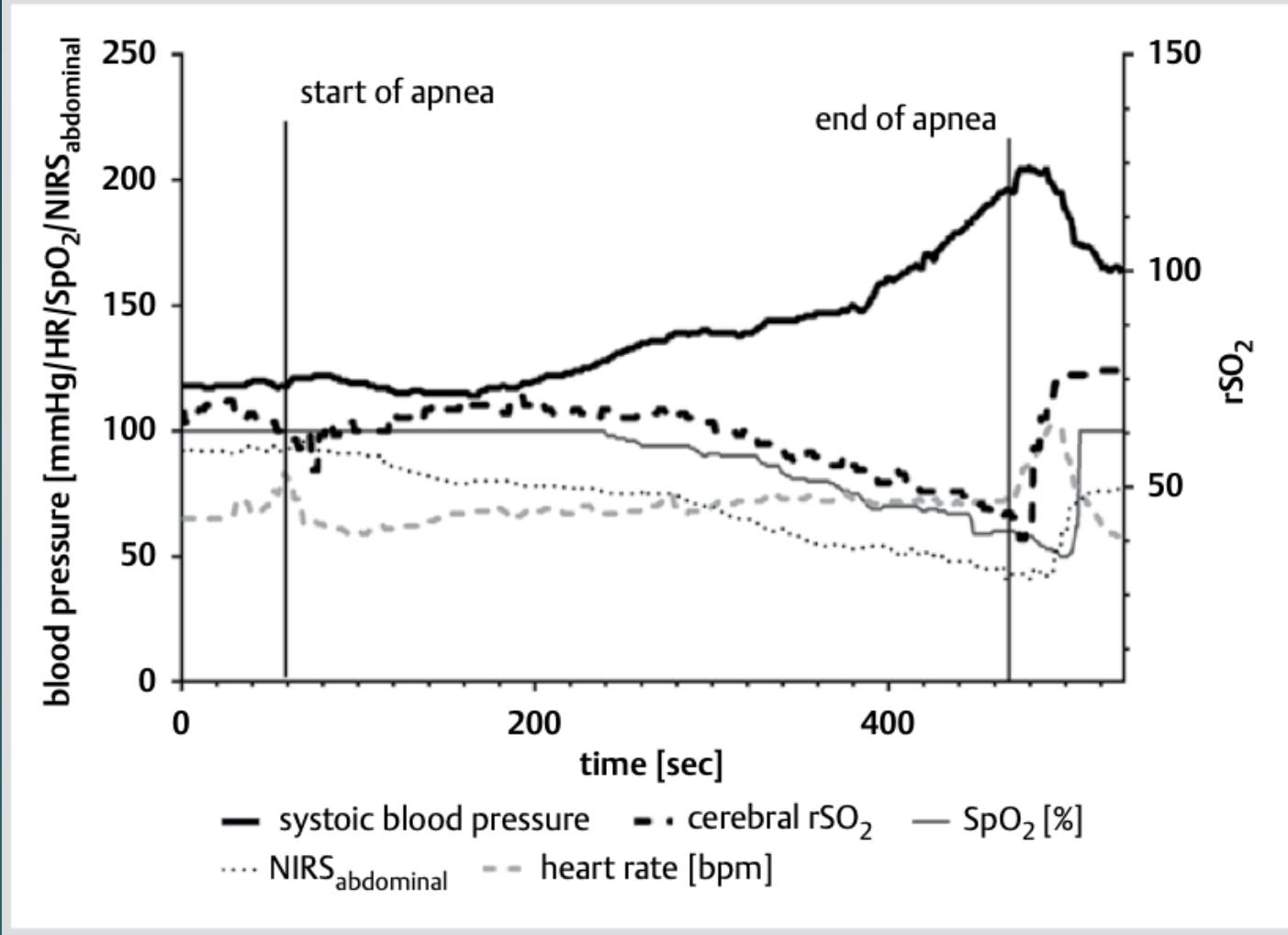
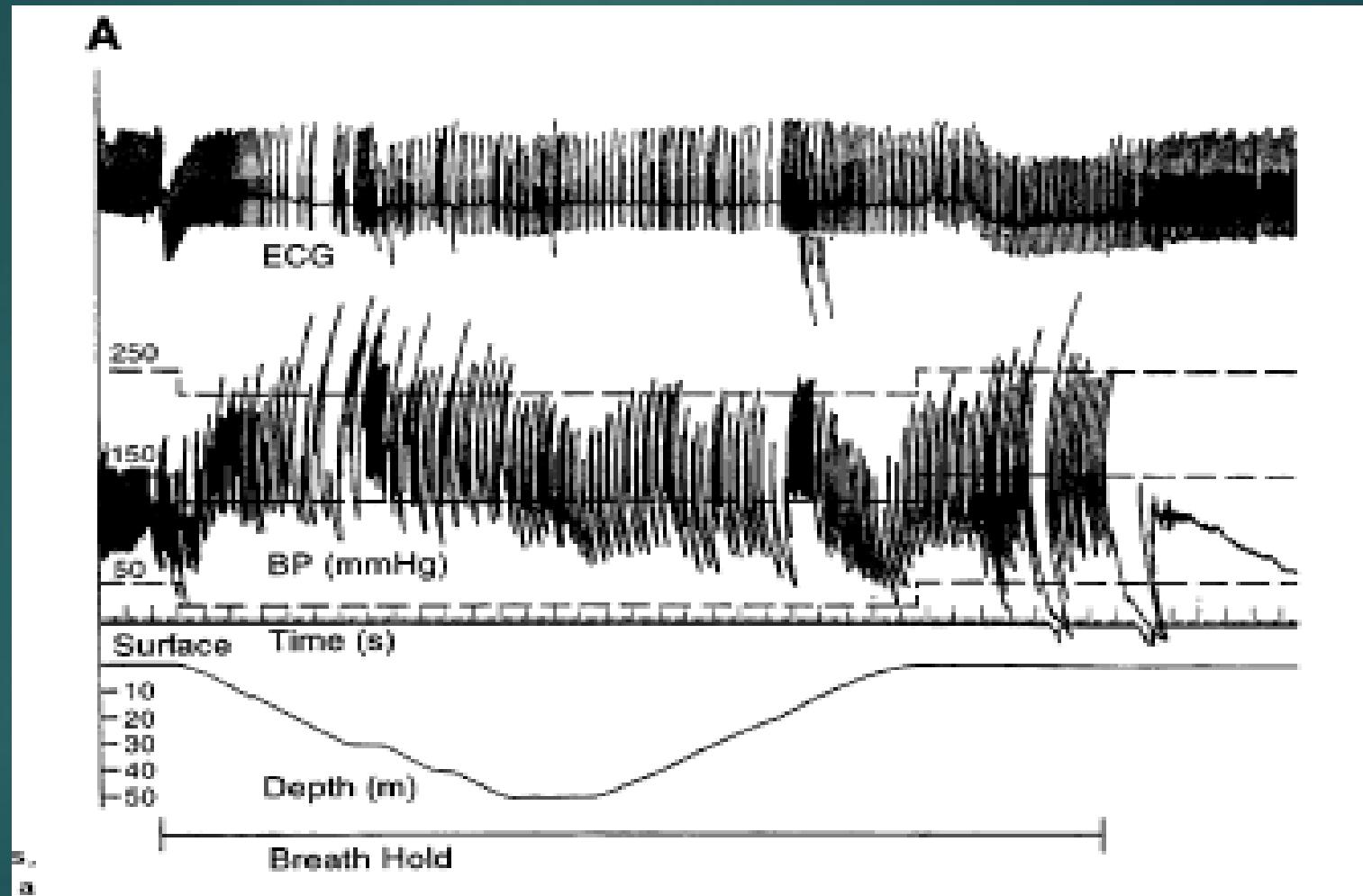


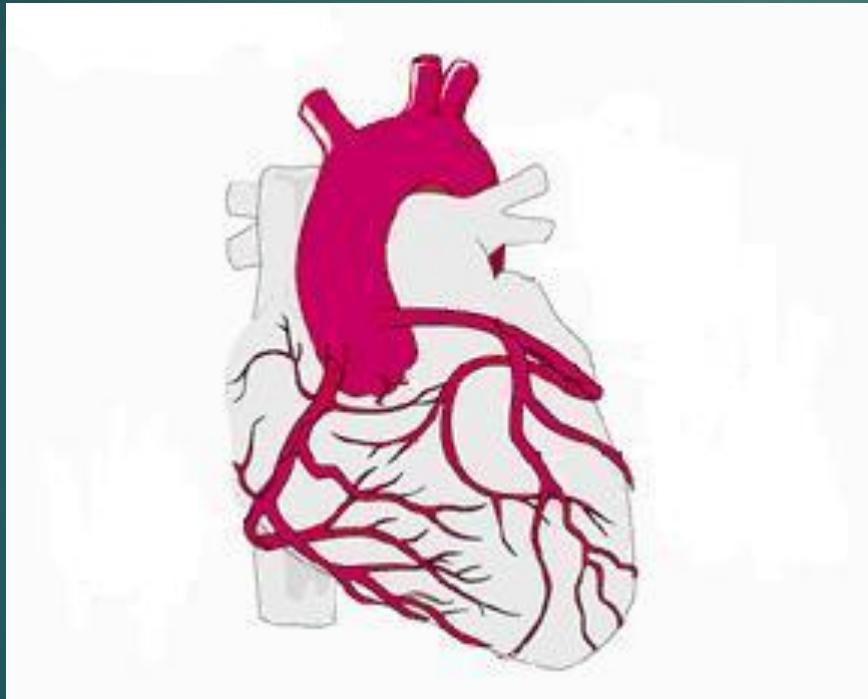
Fig. 1 Raw data of one subject. Total apnea time was 411 s. Subject exhibited an earlier decrease in NIRS_{abdominal} and SpO₂ than in cerebral rSO₂. This subject desaturated steadily (defined as fall > 2 % of baseline-level) in SpO₂ after 181 s and in rSO₂ after 240 s. Desaturation of NIRS_{abdominal} started after 21 s. Re-saturation was observed in NIRS_{abdominal} after 19 s, in rSO₂ after 5 s and in SpO₂ after 29 s.

Blood pressure

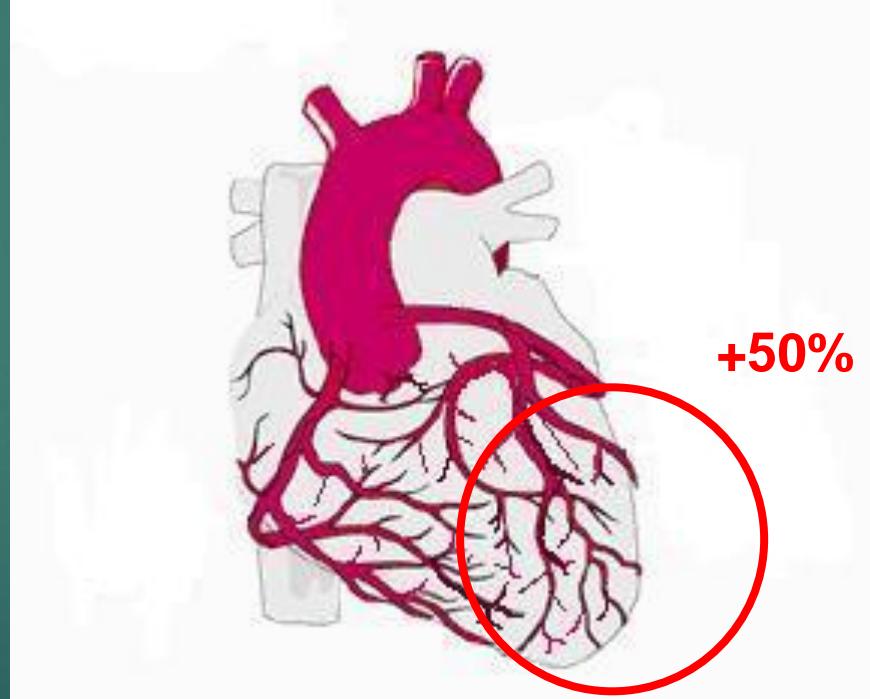


Coronary perfusion

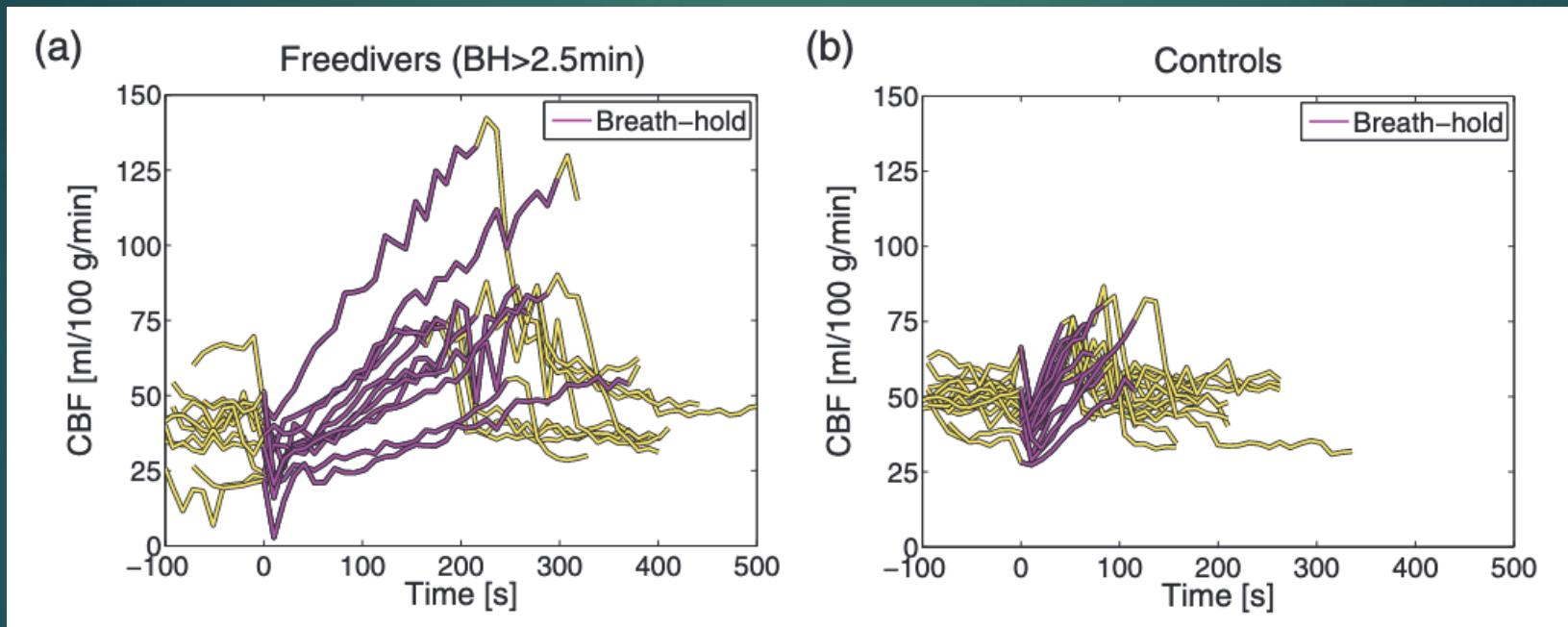
Rest



SA



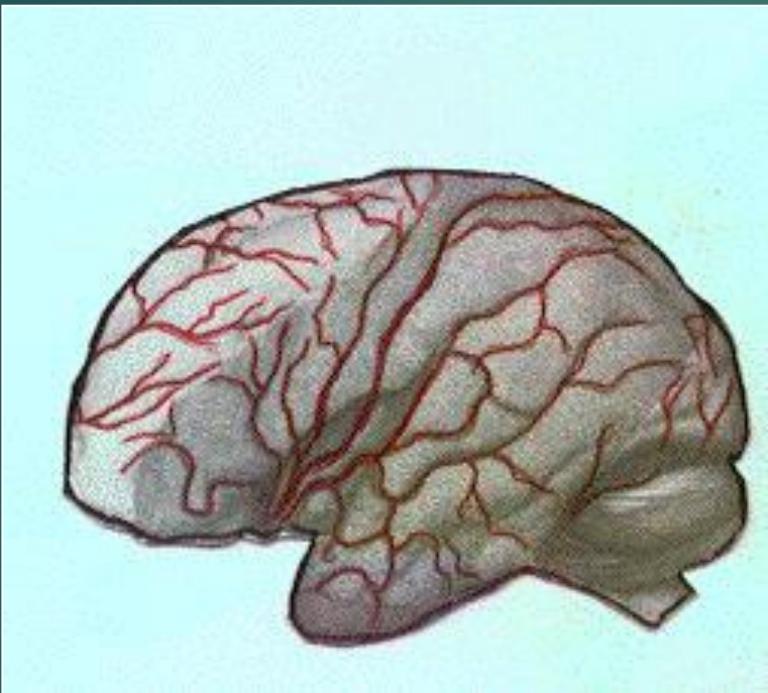
CBF during apnea



DOI: 10.1177/0271678X17737909

Brain perfusion

Static apnea 2 min



Before



End of apnea

Surface

-10 m

-20 m

-30 m

1 bar

2 bars

3 bars

4 bars

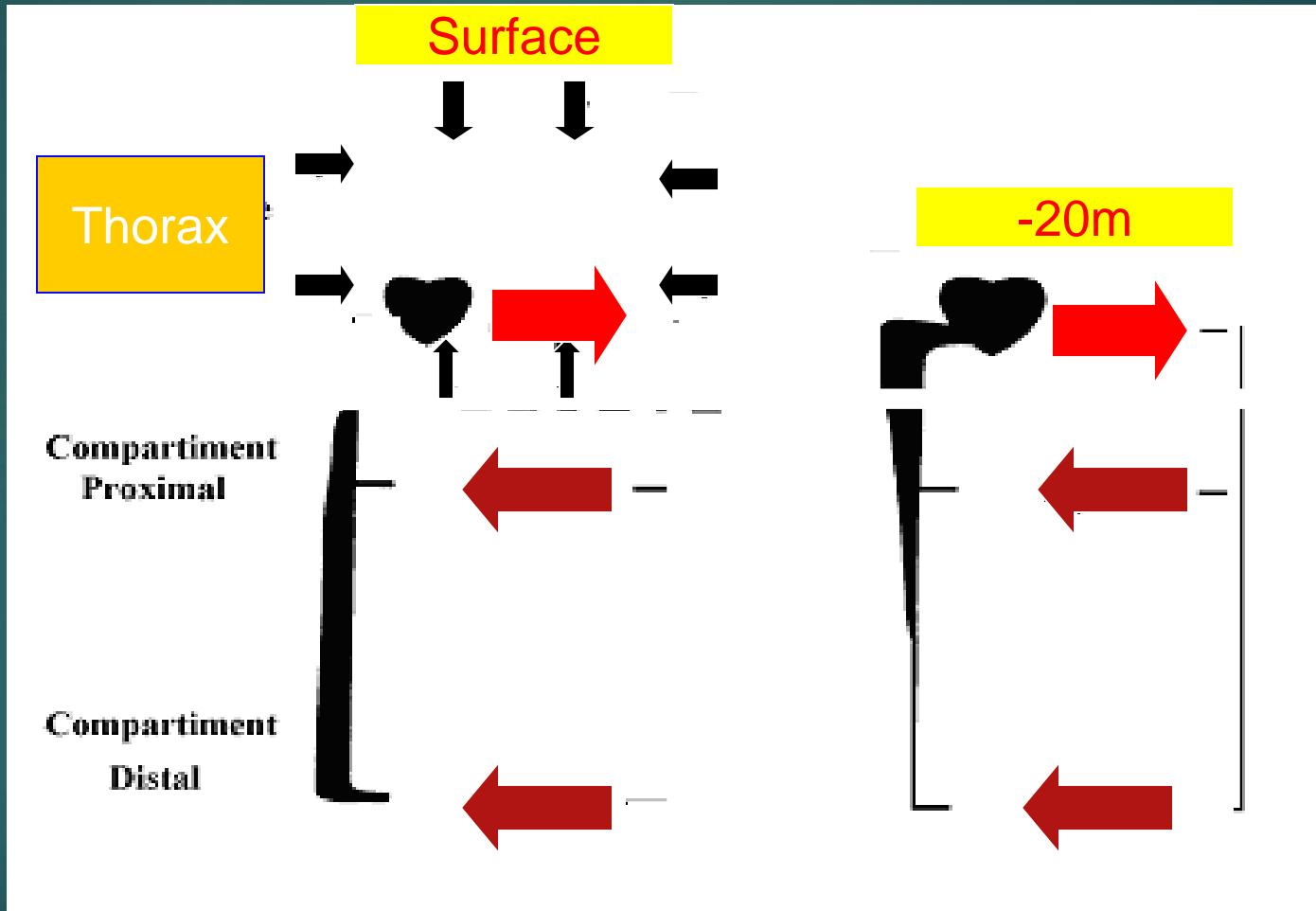


blood shift



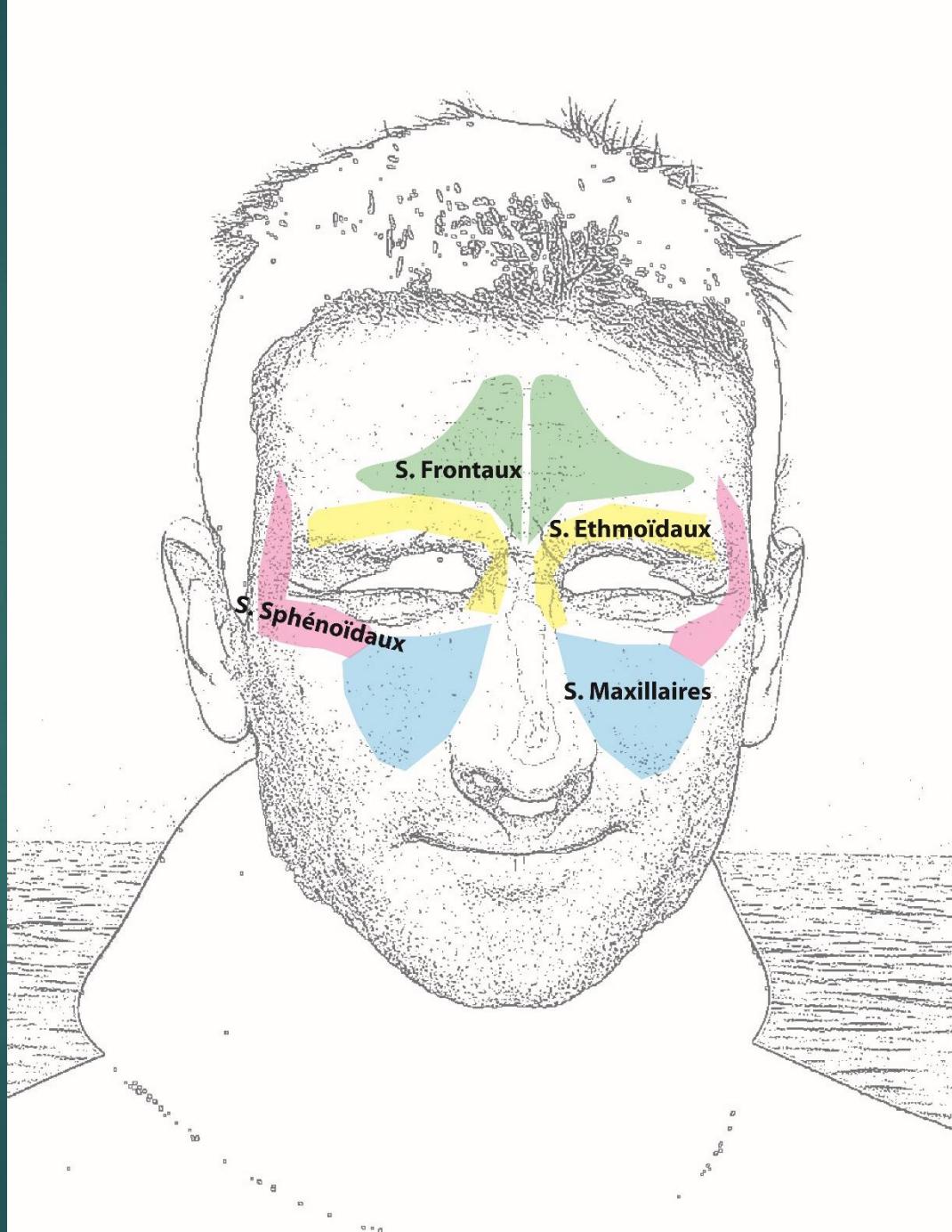
Hypoxie M1
Santé 2018

blood shift

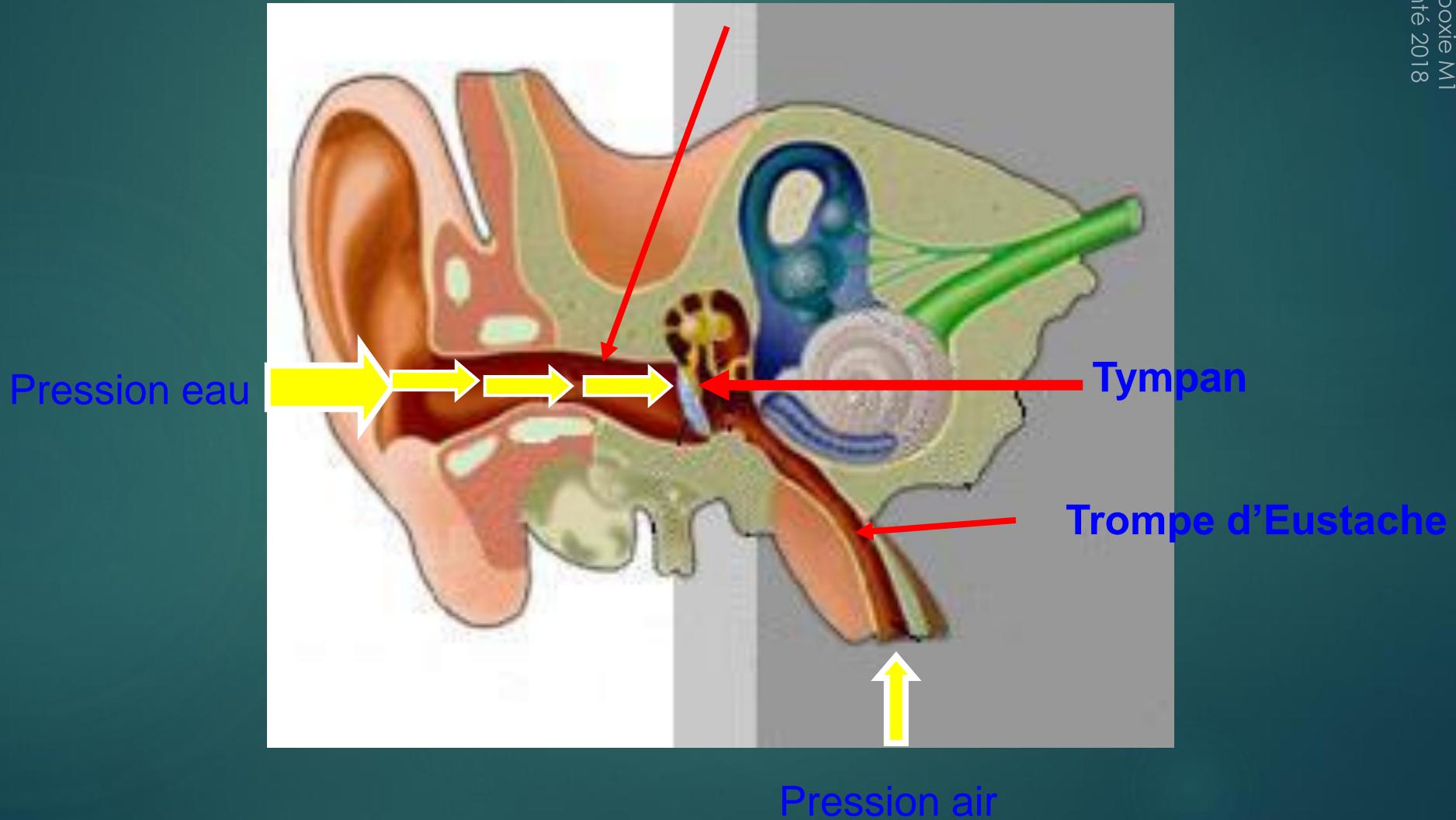


(Liner, 1994)

Sinus



Conduit auditif



Sea mammals

- The diving physiology of aquatic animals at sea began 50 years ago with studies of the Weddell seal. Even today with the advancements in marine recording and tracking technology, only a few species are suitable for investigation. The first experiments were in McMurdo Sound, Antarctica.
- Some dives were longer than an hour and as deep as 600 m

Antarctic Weddell seals (Zapol, Sci Am 1987;256:100)

Hypoxie M1
Santé 2018



Performances

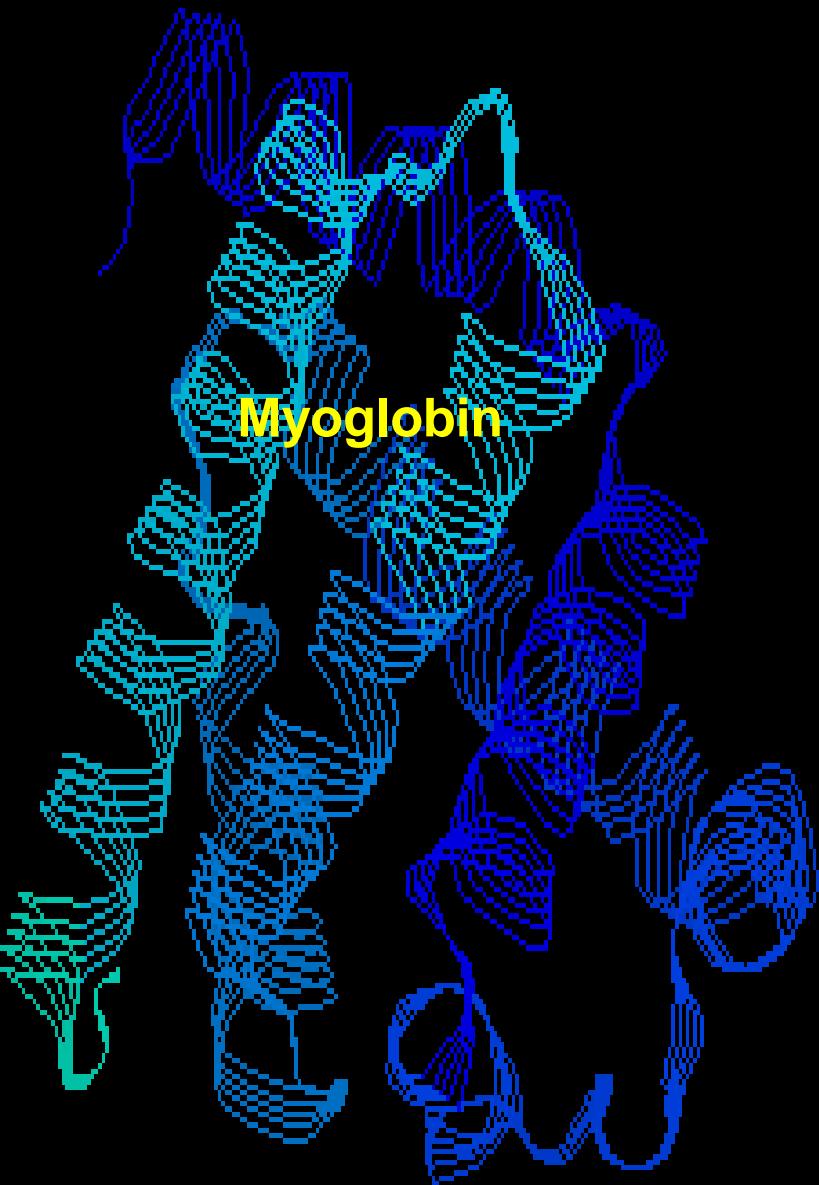
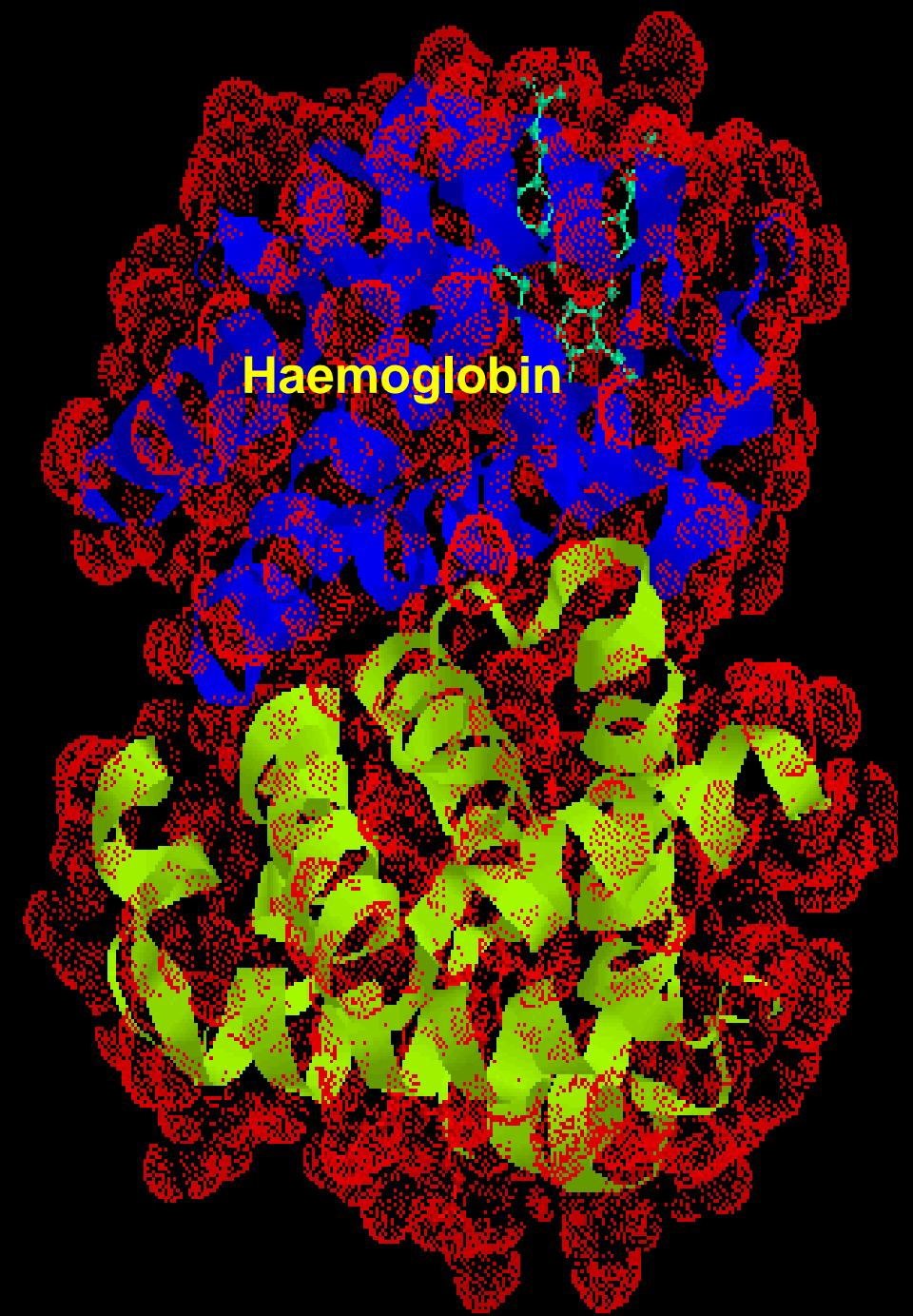
Nom commun	Profondeur (m)	Temps apnée (minutes)
Phoque de Wedell	600	73
Baleine bleue	355	20
Cachalot	2250	90
Dauphin commun	215	60
Homme	200	3'30

Capacités et volumes pulmonaires

	Dauphin	Homme
CPT	10 l	6l
VR	0,5l	1,5l
CV	9,5l	4,5l
VT	9l	0,5
Coeff de ventilation	90%	18%

Oxygen storage

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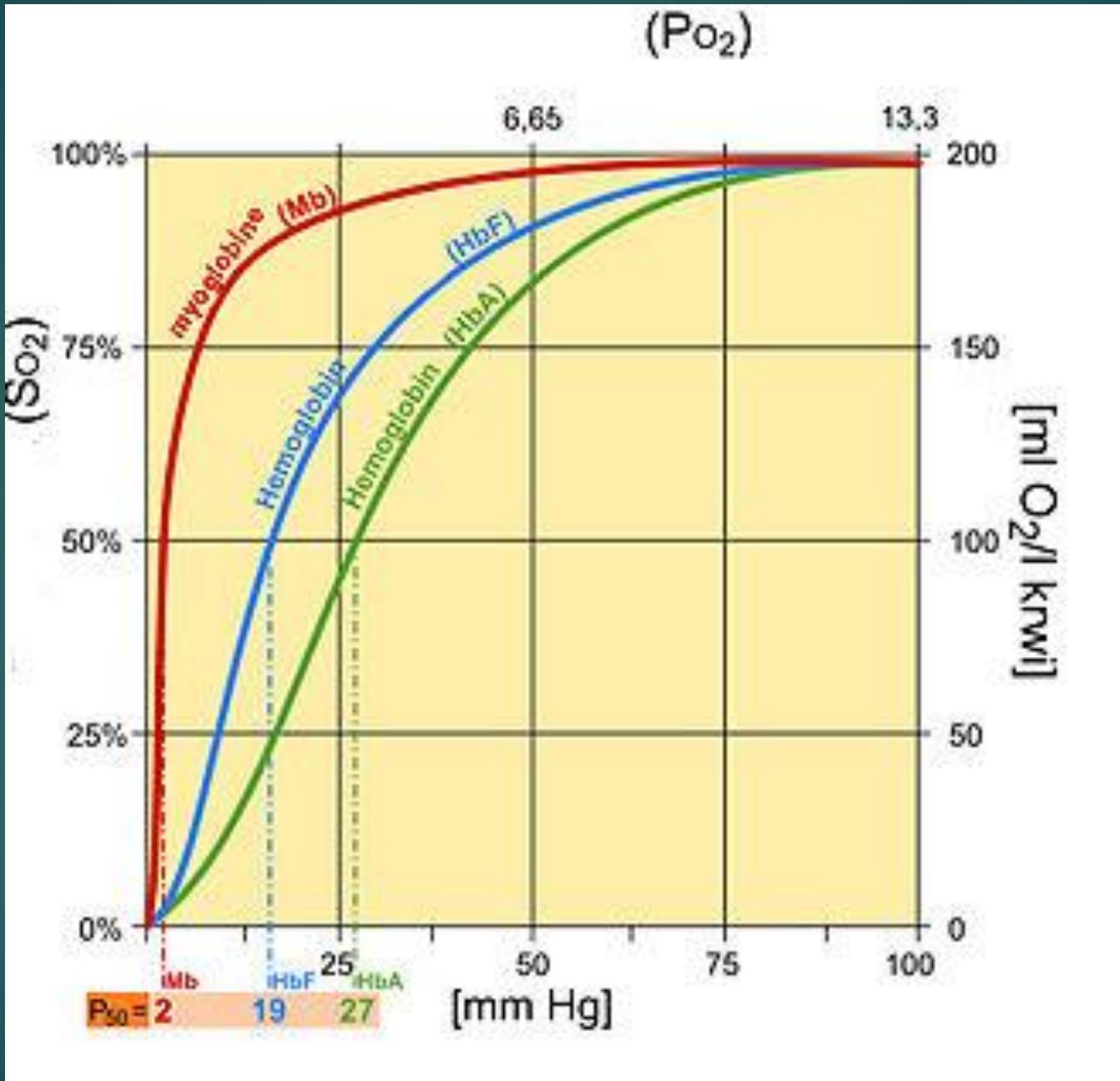


Oxygen transport and storage

- Hemoglobin and myoglobin are widely responsible for oxygen transport and storage
- The ability of diving mammals to obtain enough oxygen to support extended dives and foraging is largely dependent on muscle myoglobin (Mb) content

L'hémoglobine est une métalloprotéine contenant du fer, présente essentiellement dans le sang des vertébrés au sein de leurs globules rouges. Elle a pour fonction de transporter l'oxygène O₂ depuis les poumons vers le reste de l'organisme. Elle libère l'oxygène dans les tissus afin d'y permettre la respiration cellulaire aérobie, laquelle, à travers le métabolisme, fournit l'ATP des processus biologiques essentiels à la vie

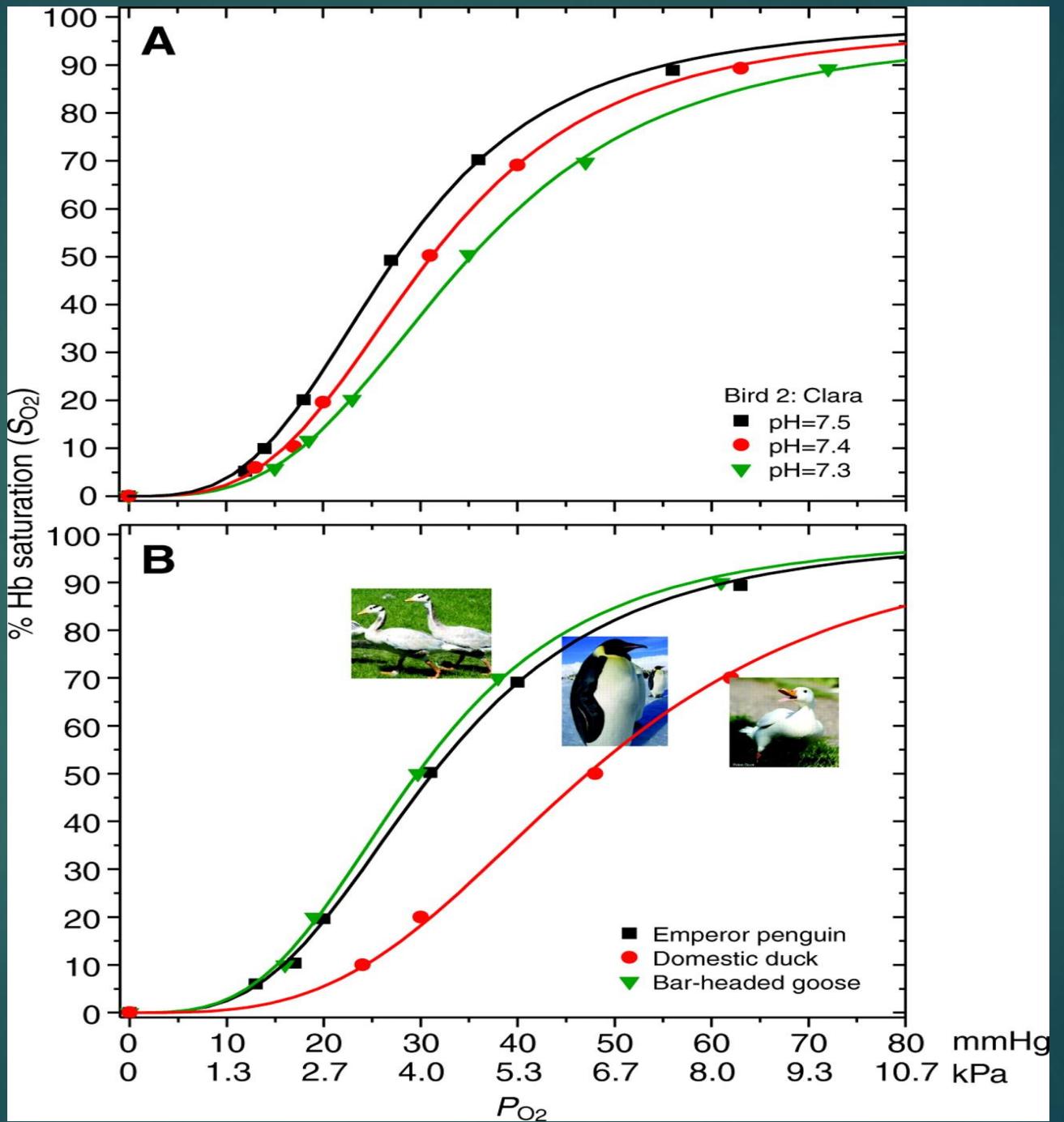
Toute l'hémoglobine n'est pas concentrée dans les globules rouges. On en trouve ainsi par exemple dans des neurones dopaminergiques dans les macrophages, dans les cellules alvéolaires et au niveau des reins. Dans ces tissus, l'hémoglobine joue un rôle d'antioxydant et de régulateur du métabolisme du fer



Plusieurs facteurs augmentent la *p*50 et font donc glisser cette courbe vers la droite :

- une baisse du pH, qui devient acide : c'est l'effet Bohr ;
- une augmentation du taux de dioxyde de carbone CO₂ : c'est l'effet Haldane ;
- une augmentation du taux de 2,3-bisphosphoglycérate (2,3-BPG) (plus élevé chez les Mm marins)
- une élévation de la température, avec cependant un effet relativement faible.

Ces effets sont réversibles, et l'inversion du sens de variation de ces facteurs fait glisser la courbe vers la gauche.



	Ht (%)	Hb (g/100ml)	Blood volume(ml/ kg)
Phoque de Weddell	60	20	160
Otarie	45	16	120
Dauphin	45	15	71
Homme	45	15	70

Arenicola marina vs Human Hb

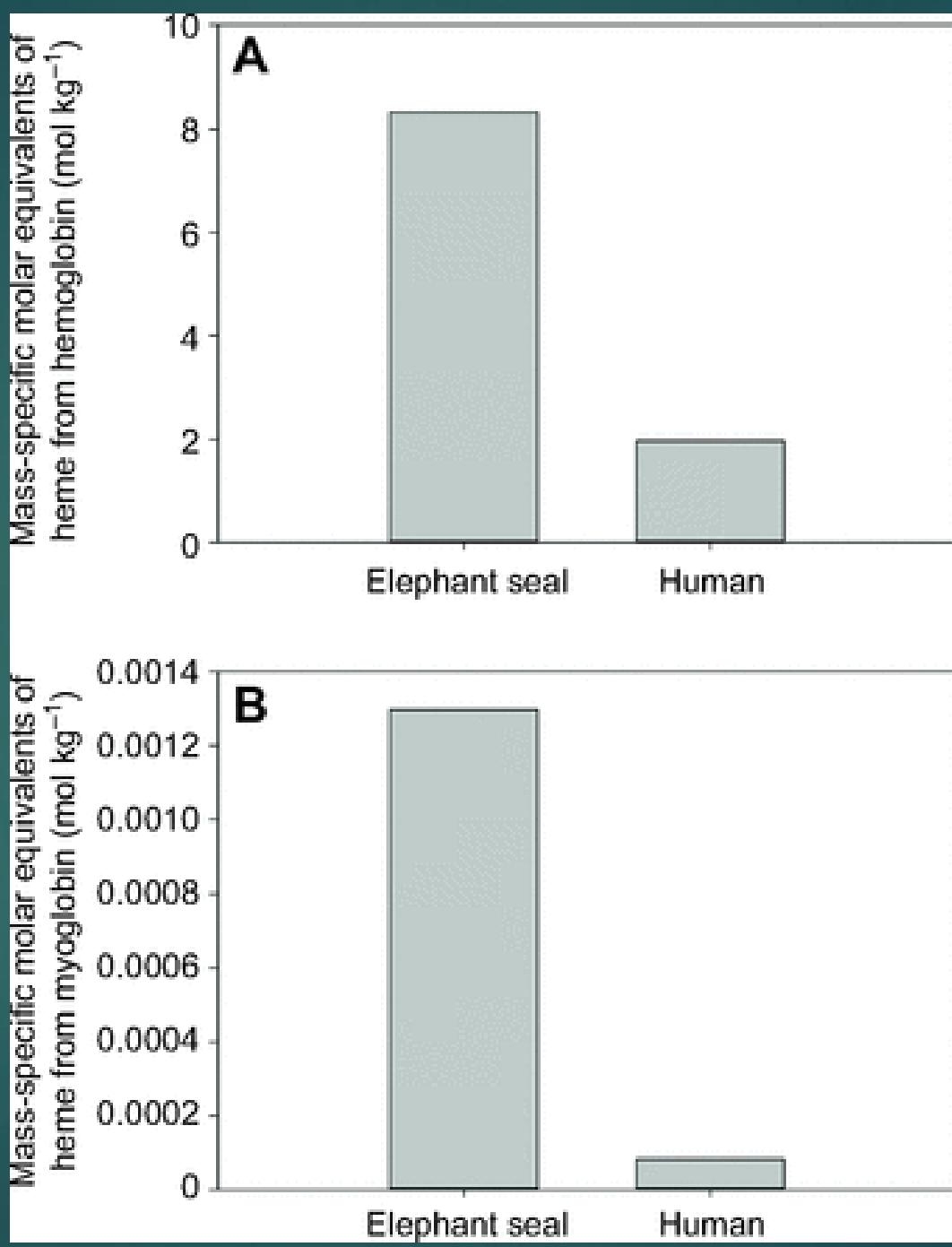
<i>Arenicola marina</i>	Homme
156 globin	4 globin
No co-factors	Effects of pH, T°, 2,3 PG
molecule capable of storing 40 times more oxygen than human hemoglobin	
molecule 250 times smaller than human hemoglobin	

Myoglobin

- High myoglobin net surface charge in mammalian divers increases intermolecular electrostatic repulsion, permitting higher muscle oxygen storage capacities

Myoglobin

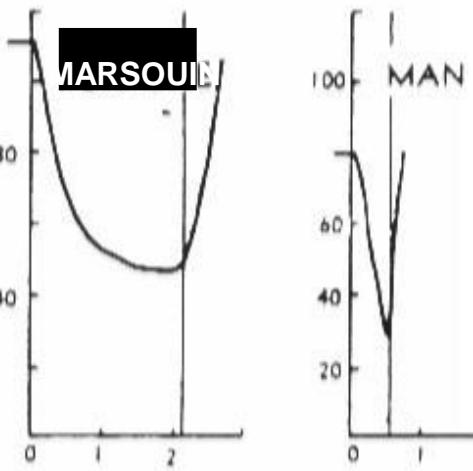
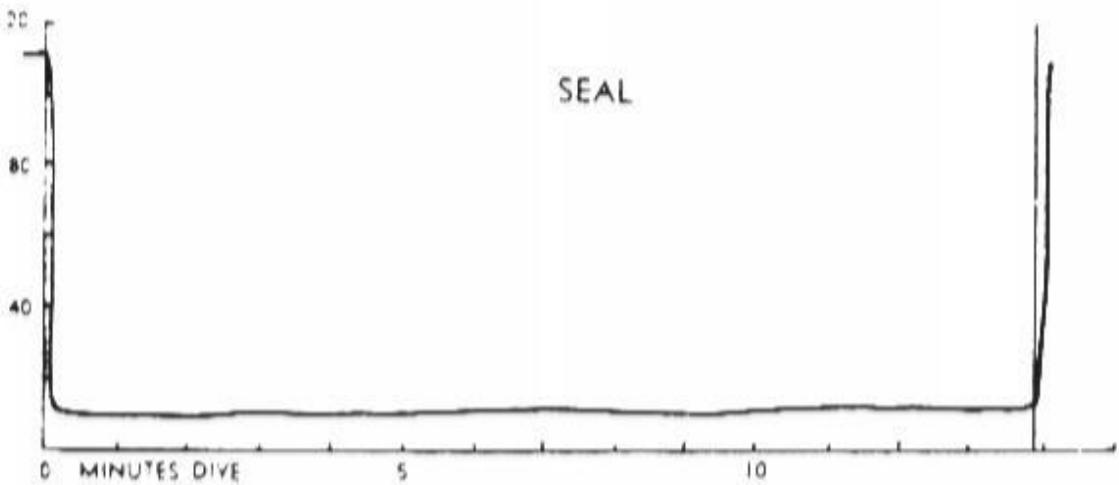
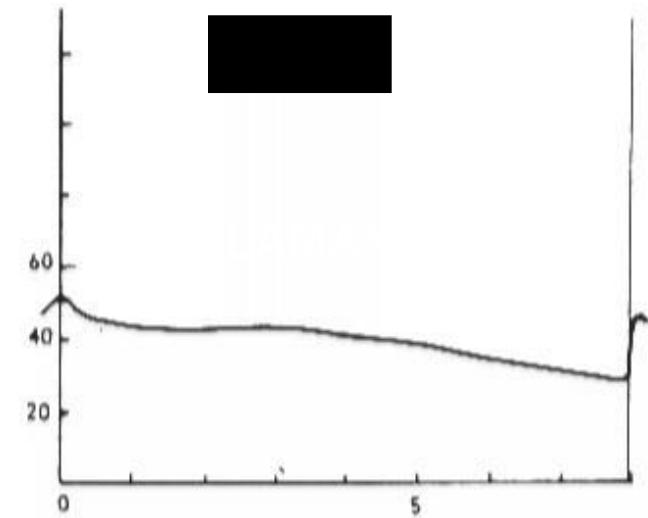
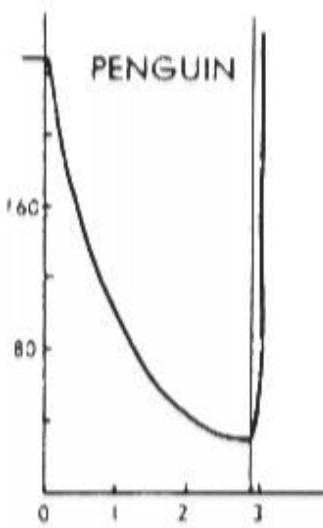
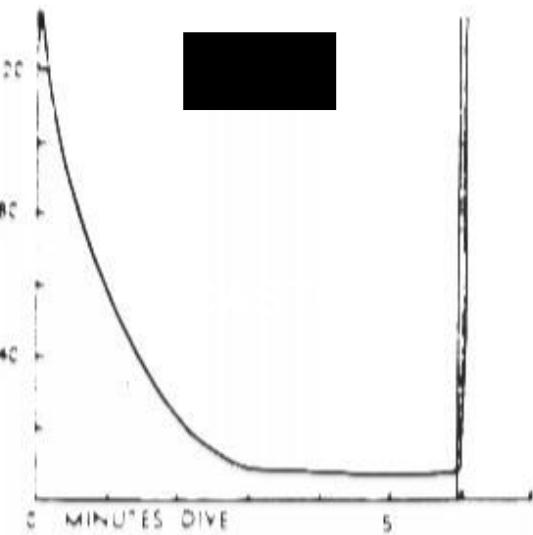
	Myoglobin (g/100g de muscle)
Phoque de Weddell	4,5
Otarie	3,2
Dauphin	3,3
Homme	0,5



Heart rate

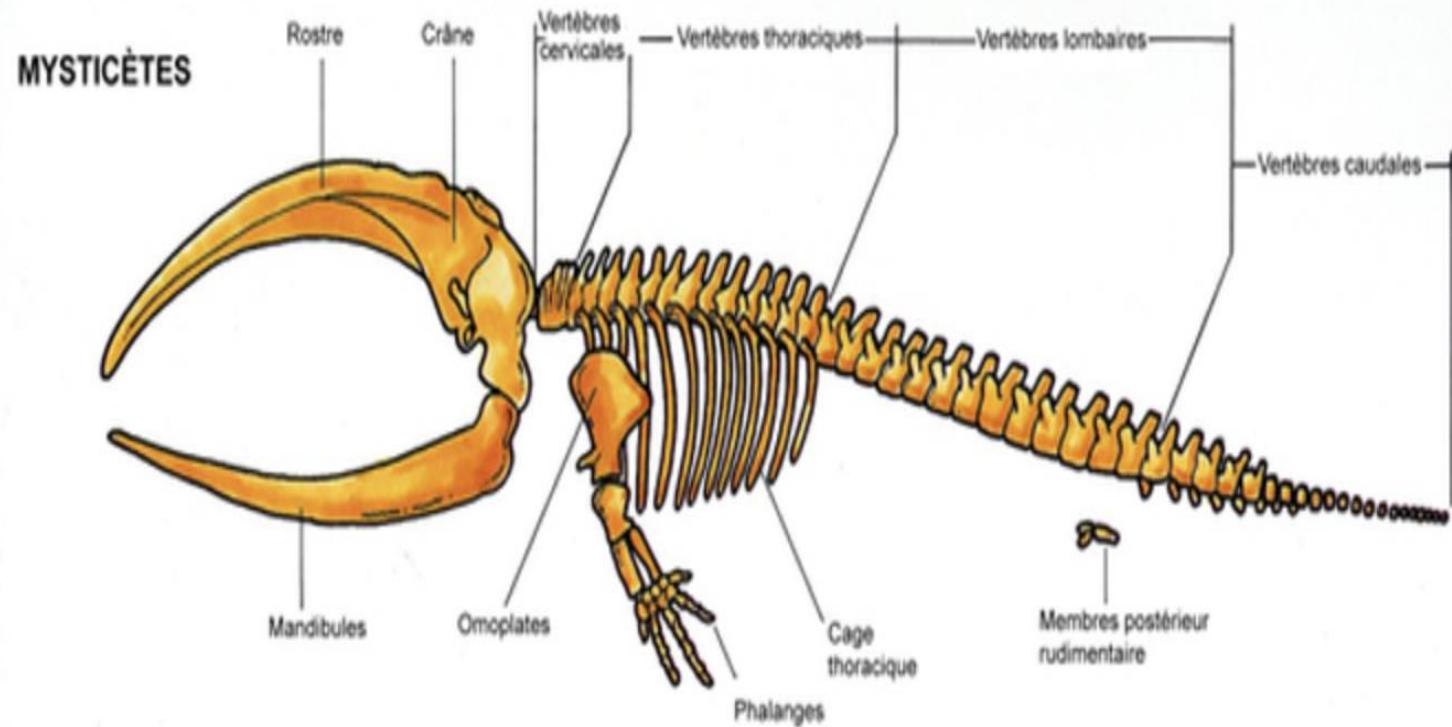
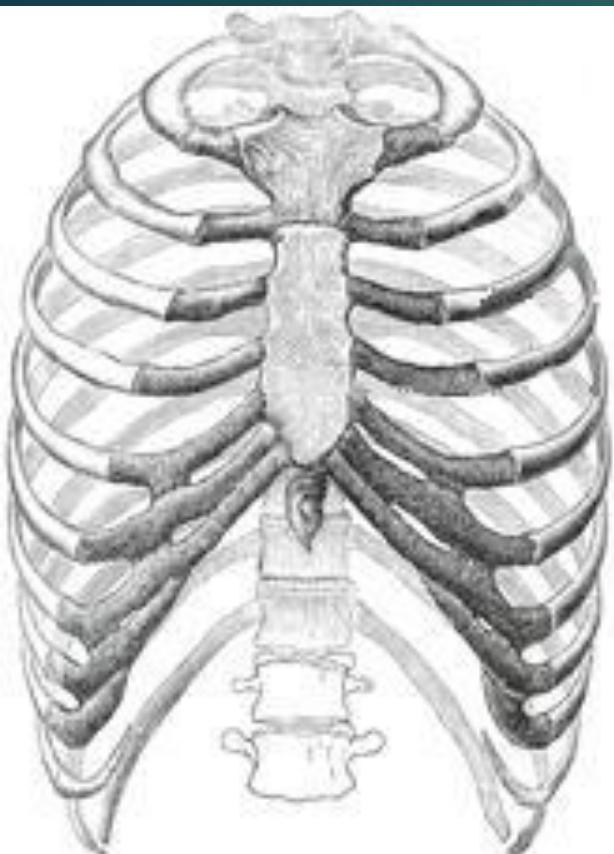
	FC surface (bpm)	FC immersion (bpm)
Phoque gris	120	10
Otarie	95	20
Dauphin	90	20
Homme	70	45

Heart rate



Rib cage

Hypoxi
santé



Comparaison Homme vs Mammifères marins

Hypoxie marine
Séptembre 2011

- Cage thoracique peu déformable : peu de cotes flottantes
 - 2 ou 3 paires de cotes seulement rattachées au sternum
 - Voies aériennes renforcées (anneaux cartilagineux jusqu'aux bronchioles empêchant les collapsus)
 - Réseaux admirables
 - Double extraction alvéolaire de l'oxygène (10% Oxygène extrait)
- Poumons non compressibles
 - Poumons compressibles par la présence de sphincters alvéolaires (pas de collapsus)
 - Effet Bohr plus important
 - Taux de myoglobine jusqu'à 10 fois supérieur
 - Sang = 10% du poids du corps

training

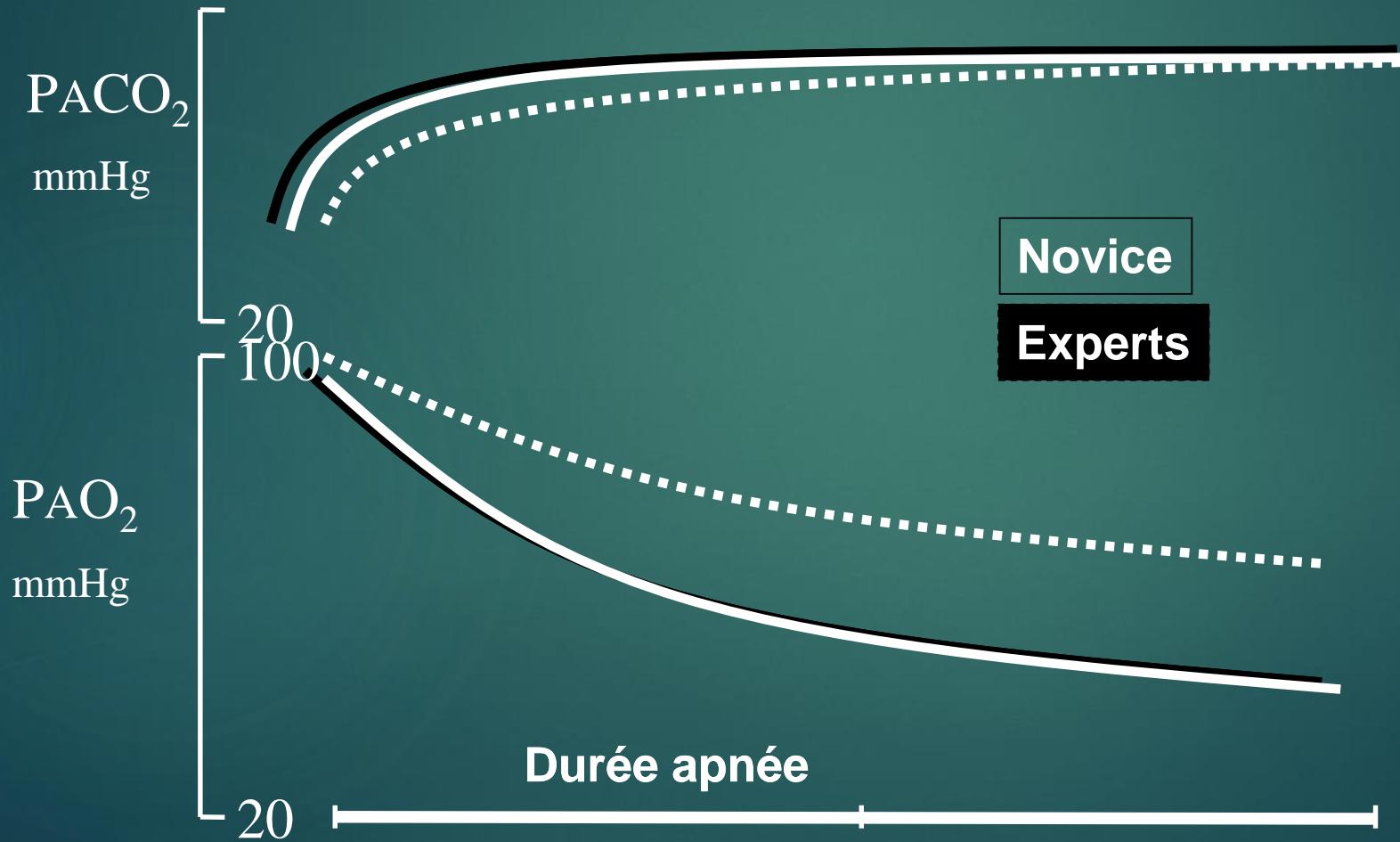


Hypoxie M1
Santé 2018

Prédisposition ou entraînement

- ▶ Bajau ont une rate plus grosse (*Ilardo et al. 2019*)
- ▶ Les Amas y compris les non plongeurs présentent un diving reflex plus marqué que les autres ethnies vivant à proximité
- ▶ Les meilleurs apnéistes mondiaux sont issus de tous les continents suggérant qu'il y a un effet de l'entraînement.

Evolutions des PACO_2 et des PAO_2



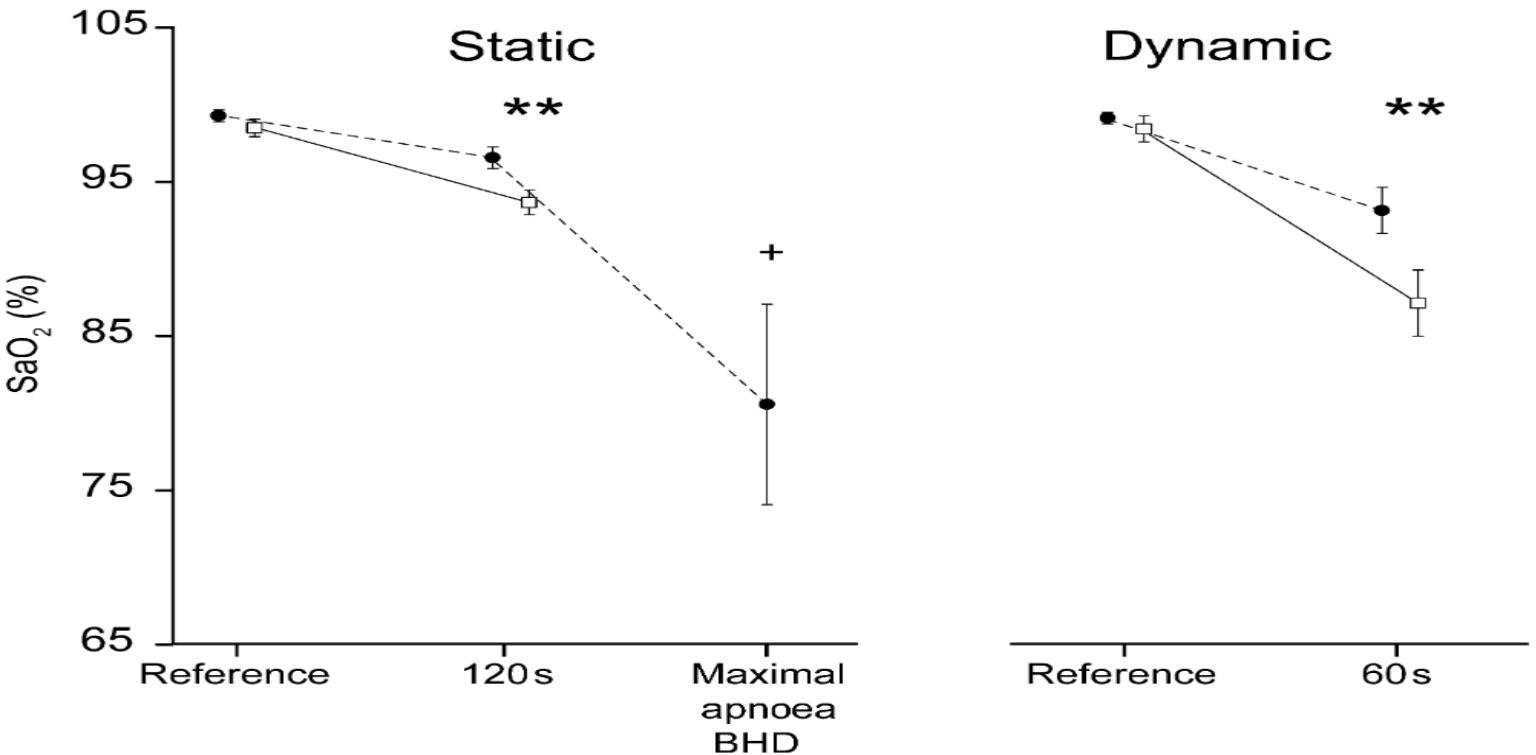
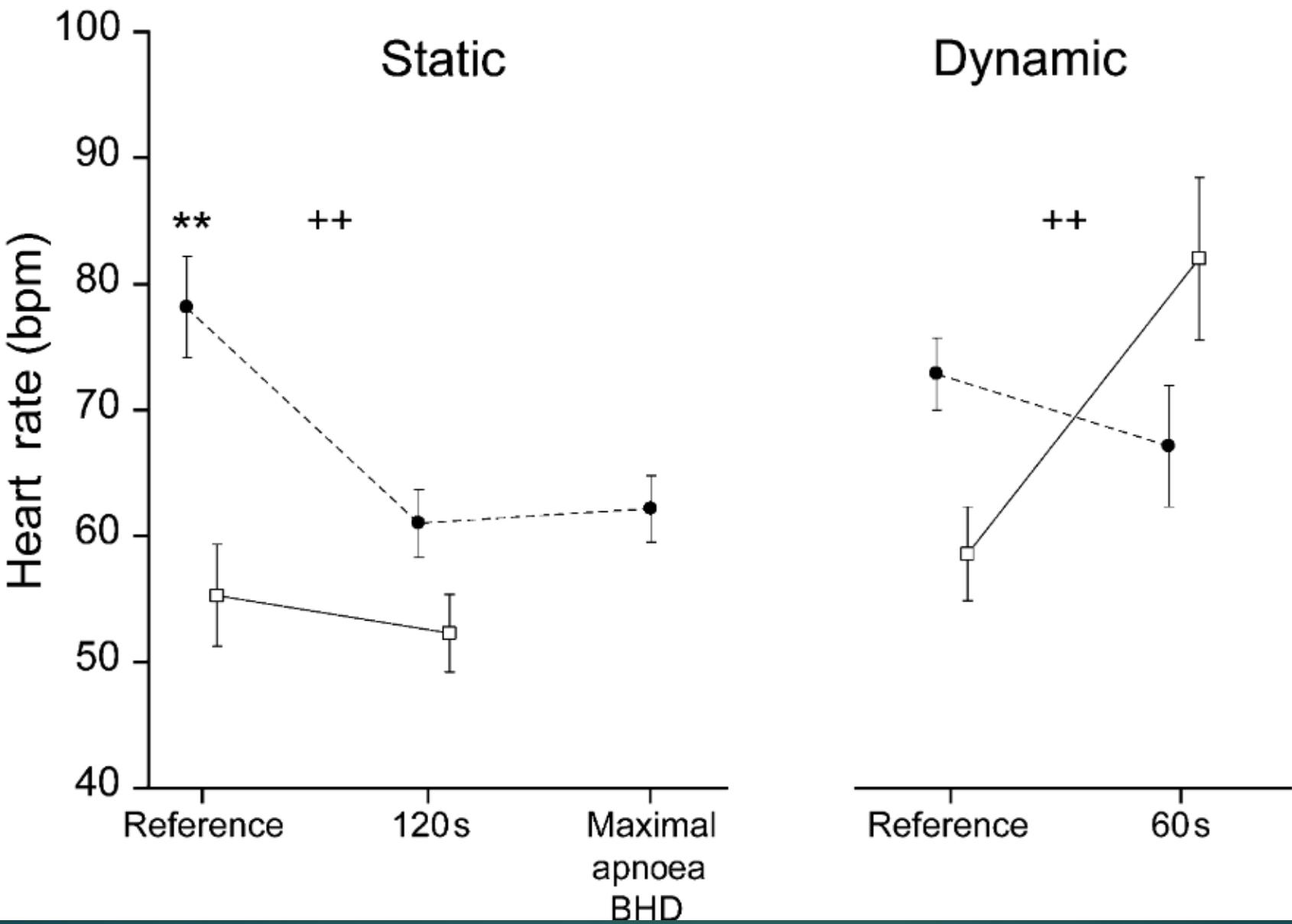
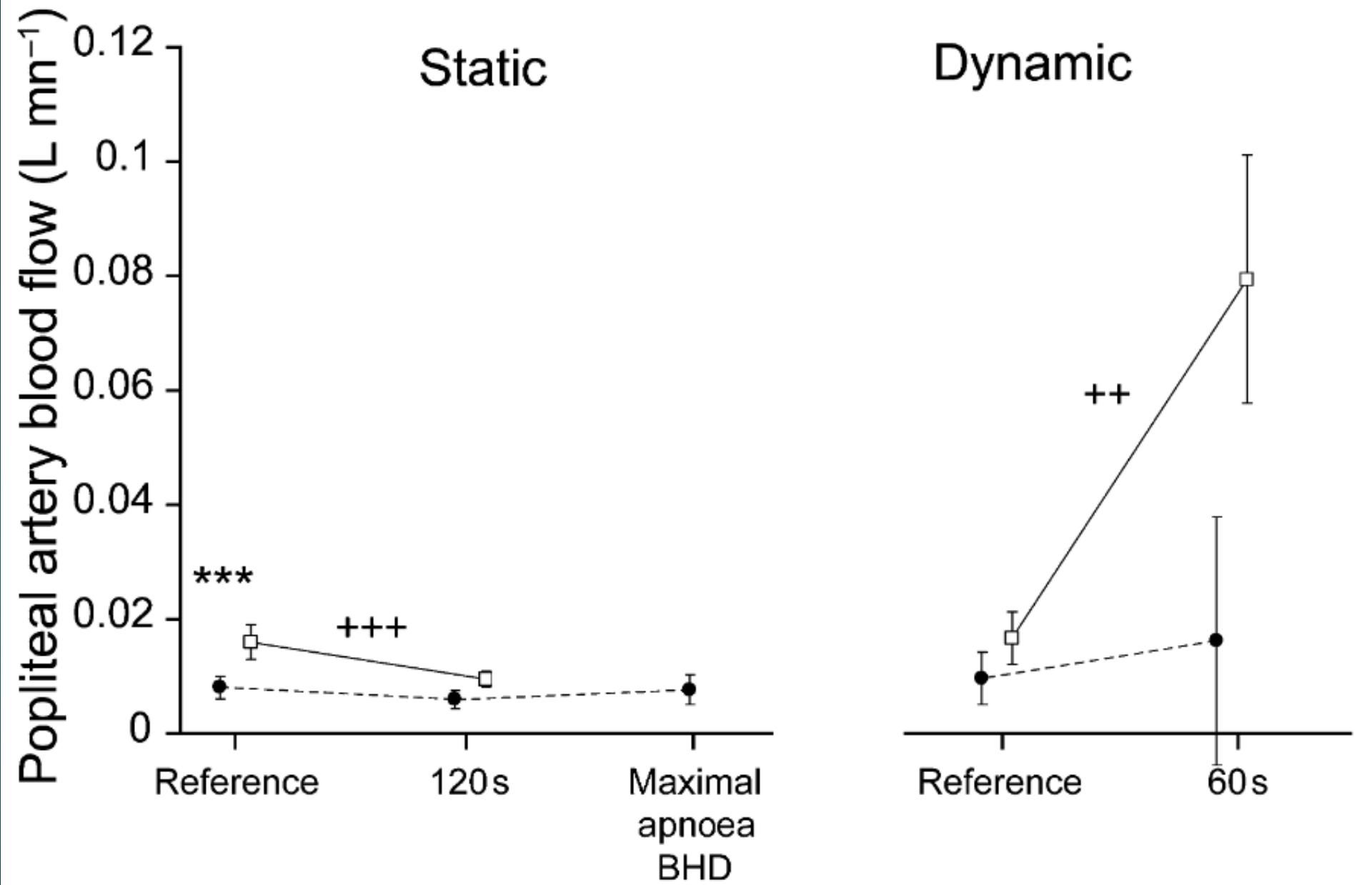
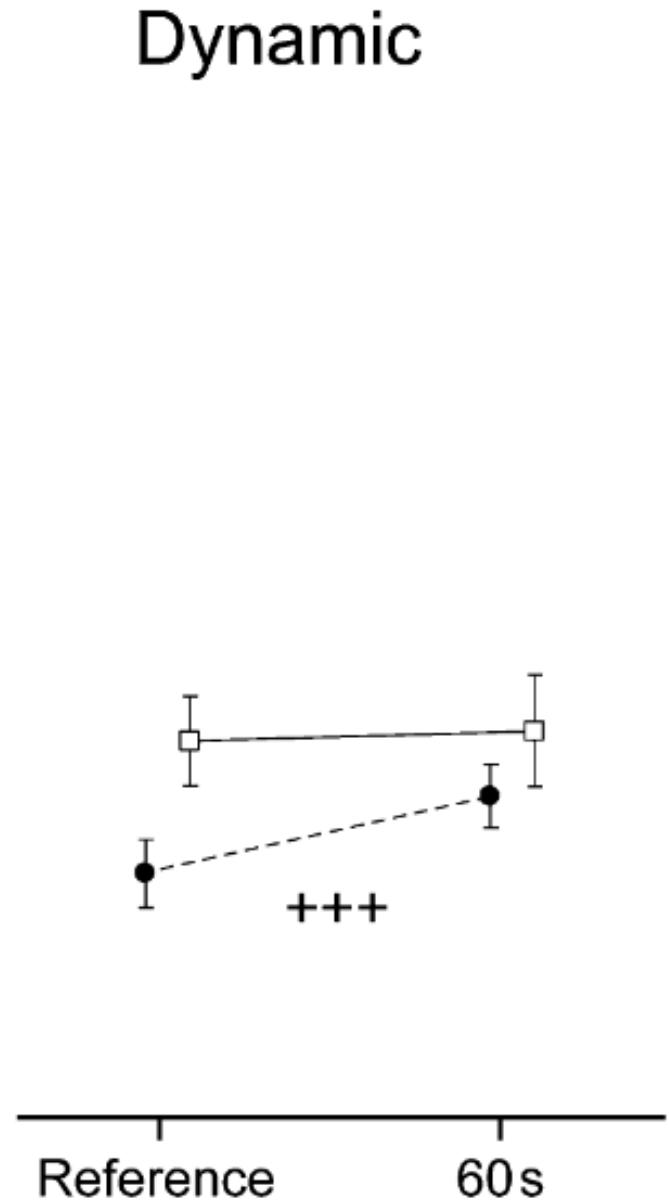
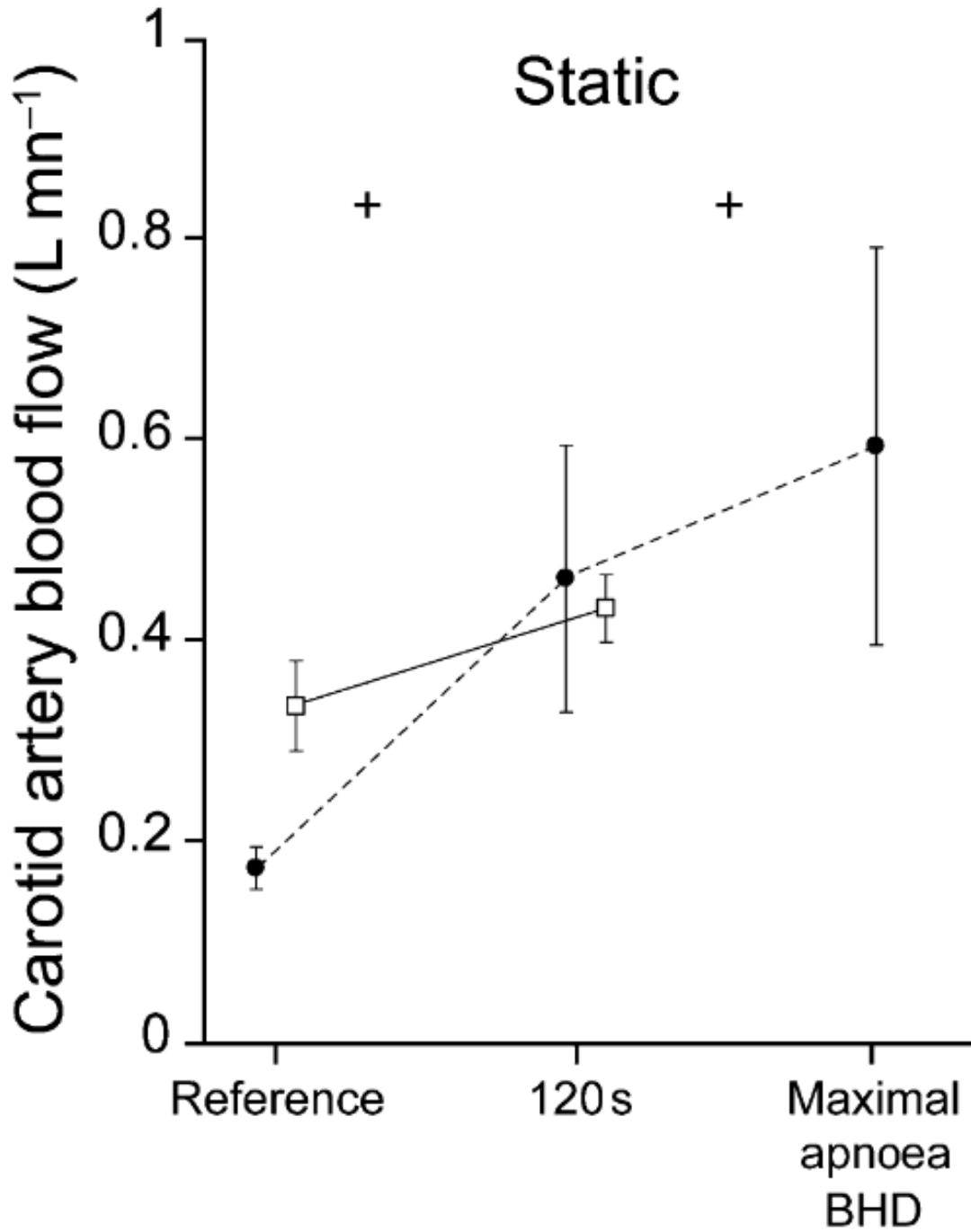


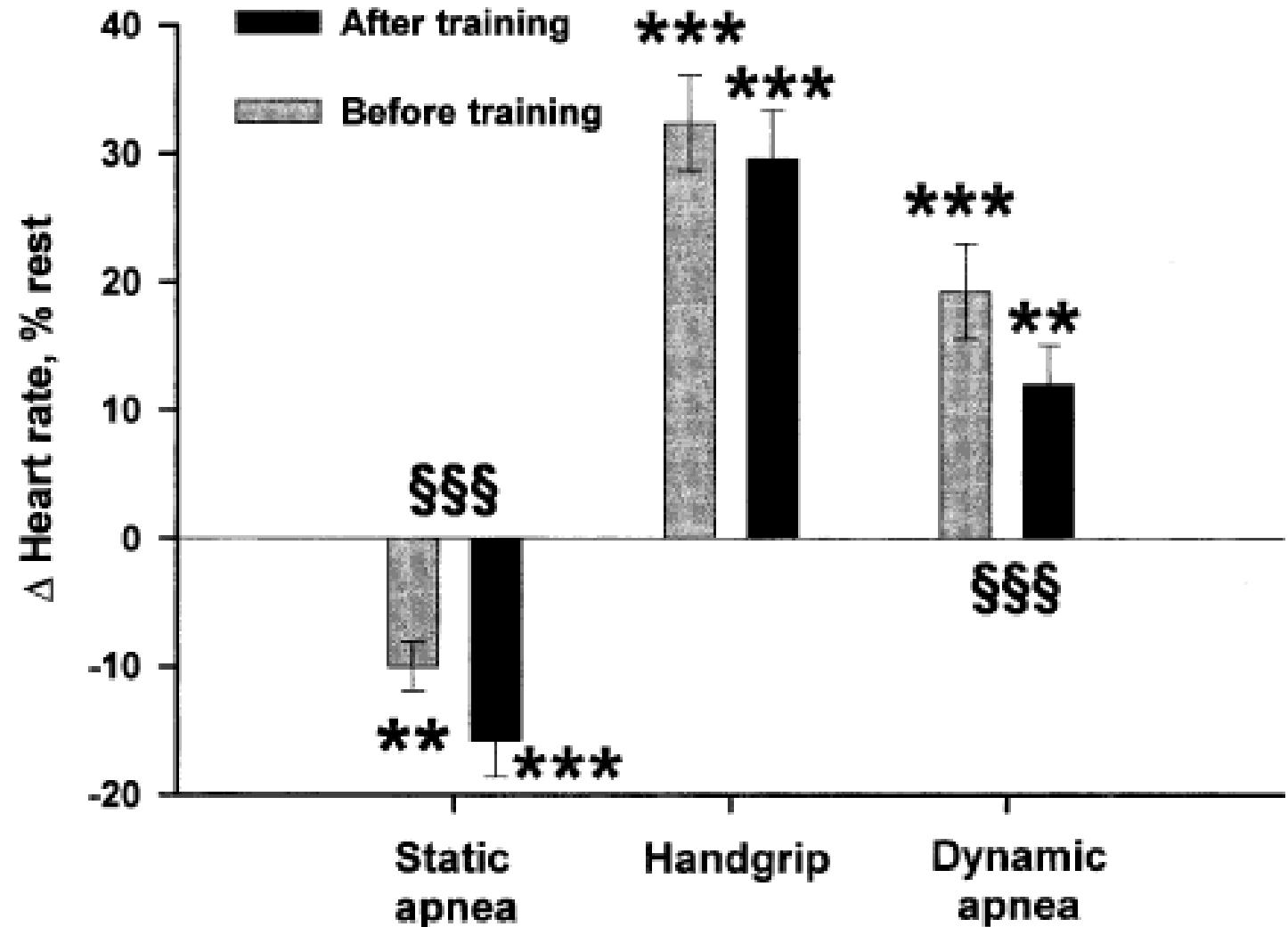
Figure 1 Mean (+SEM) SaO₂ values for breath-hold divers (BHD, black circles) and non-divers (ND, white squares). Left: values recorded at rest (reference), after 2 min (120 s) of static apnoea and at the end of maximal static apnoea for BHD. ** indicates a difference between BHD and ND after 2 min of static apnoea ($P < 0.01$). + indicates a difference between values at 120 s and at maximal static apnoea in BHDs ($P < 0.05$). Right: values recorded at rest and after 60 s of exercise in apnoea. ** indicates a difference between BHD and ND after dynamic apnoea ($P < 0.01$).



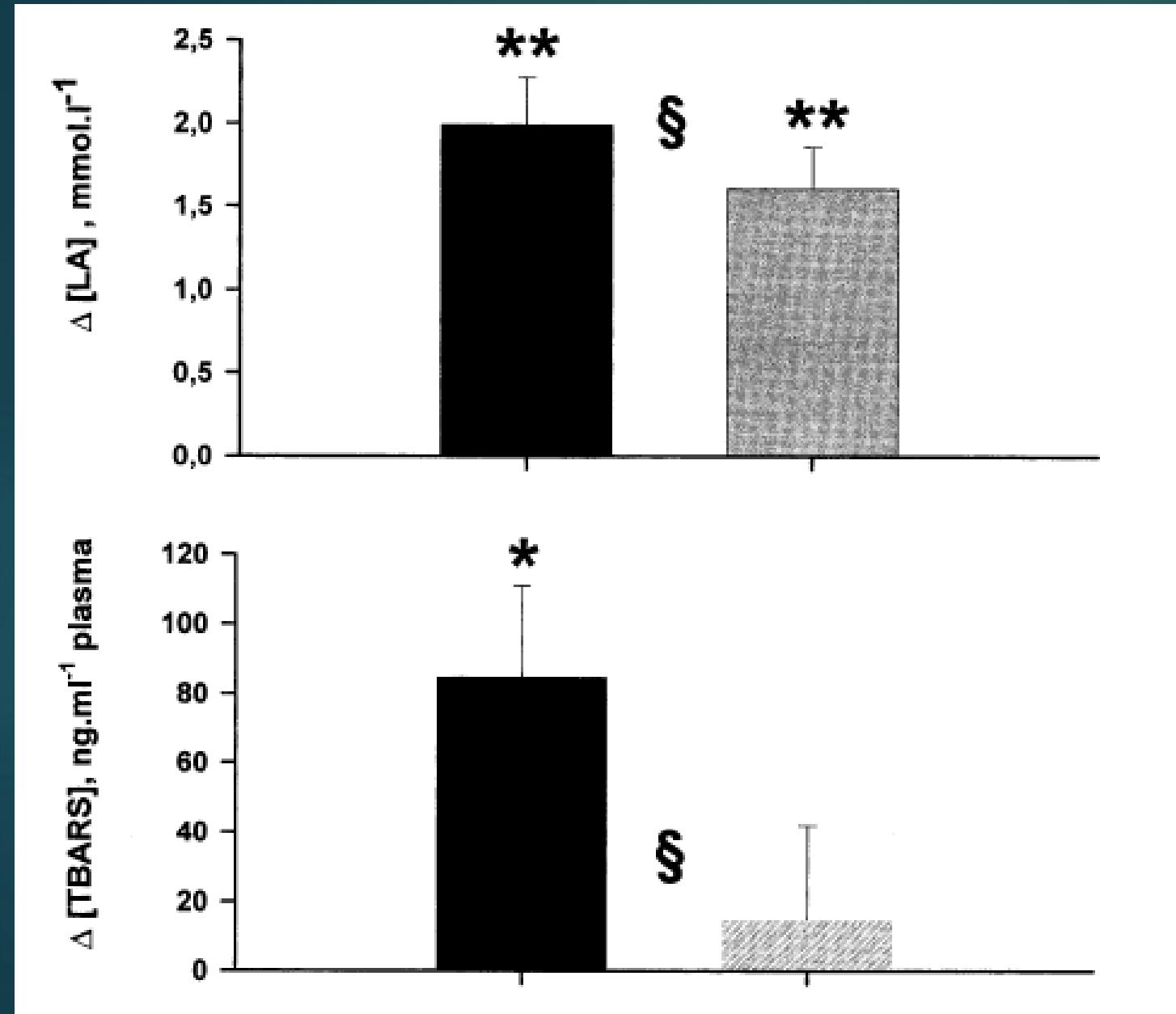




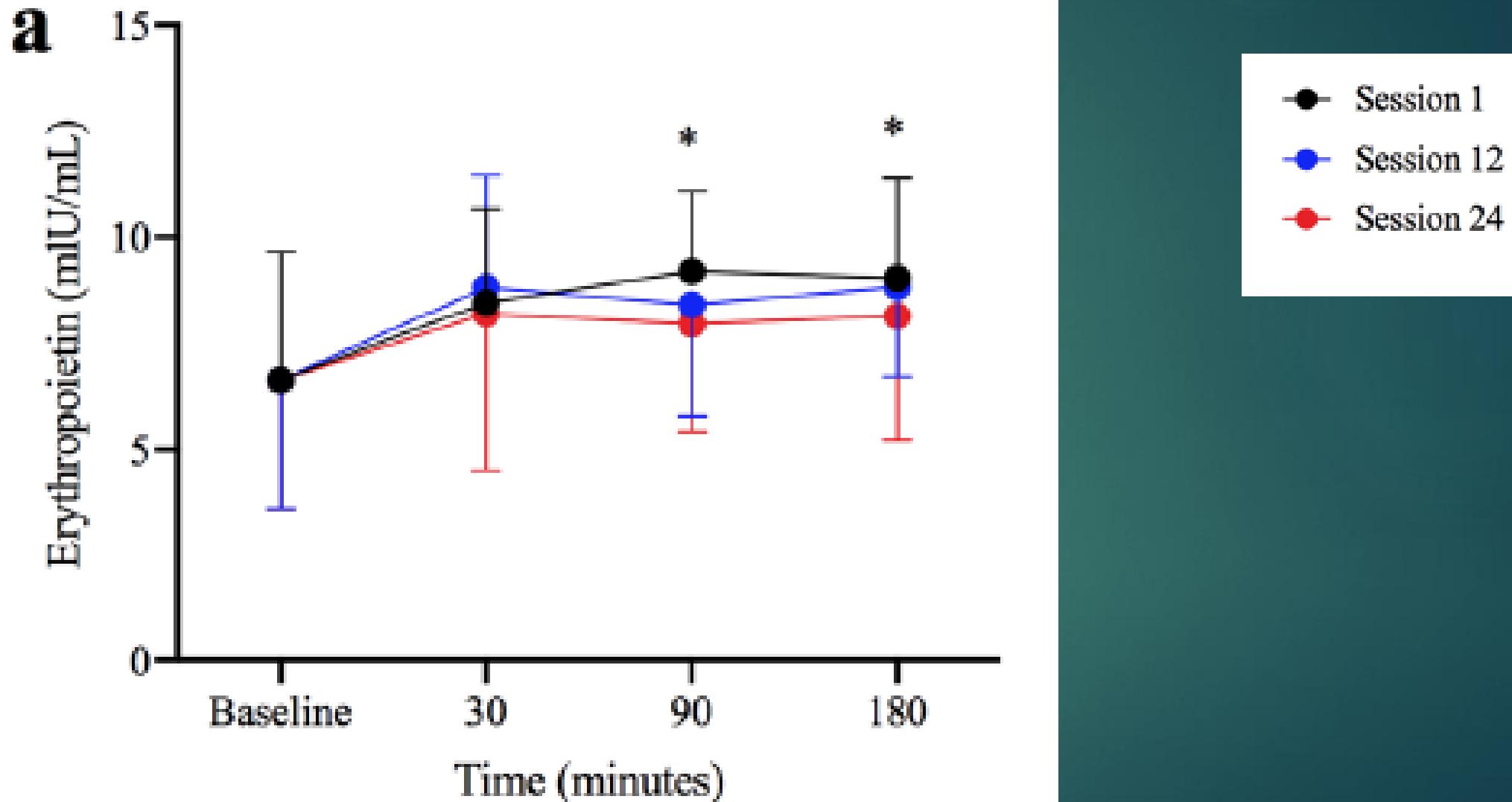
Bradycardic apnea and training



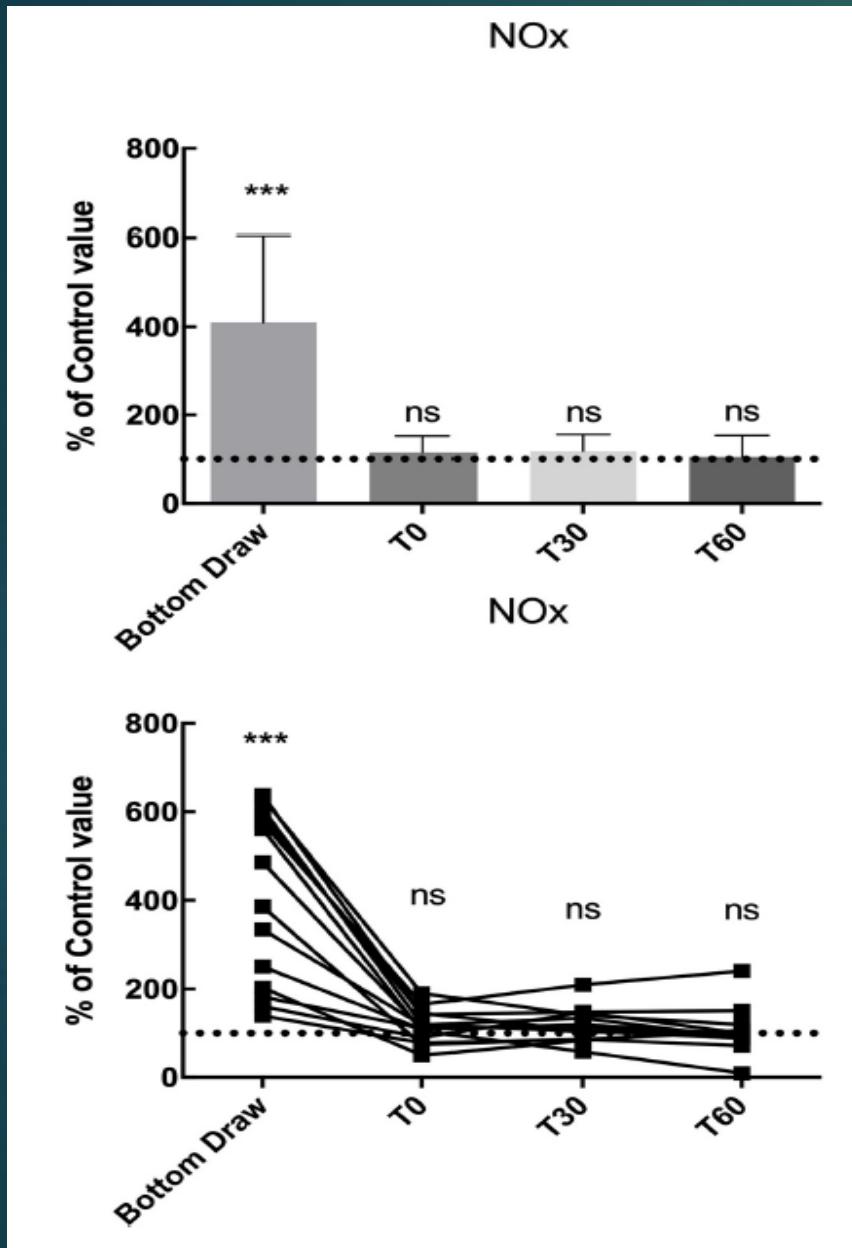
Effects of training on blood lactate concentration and free radicals



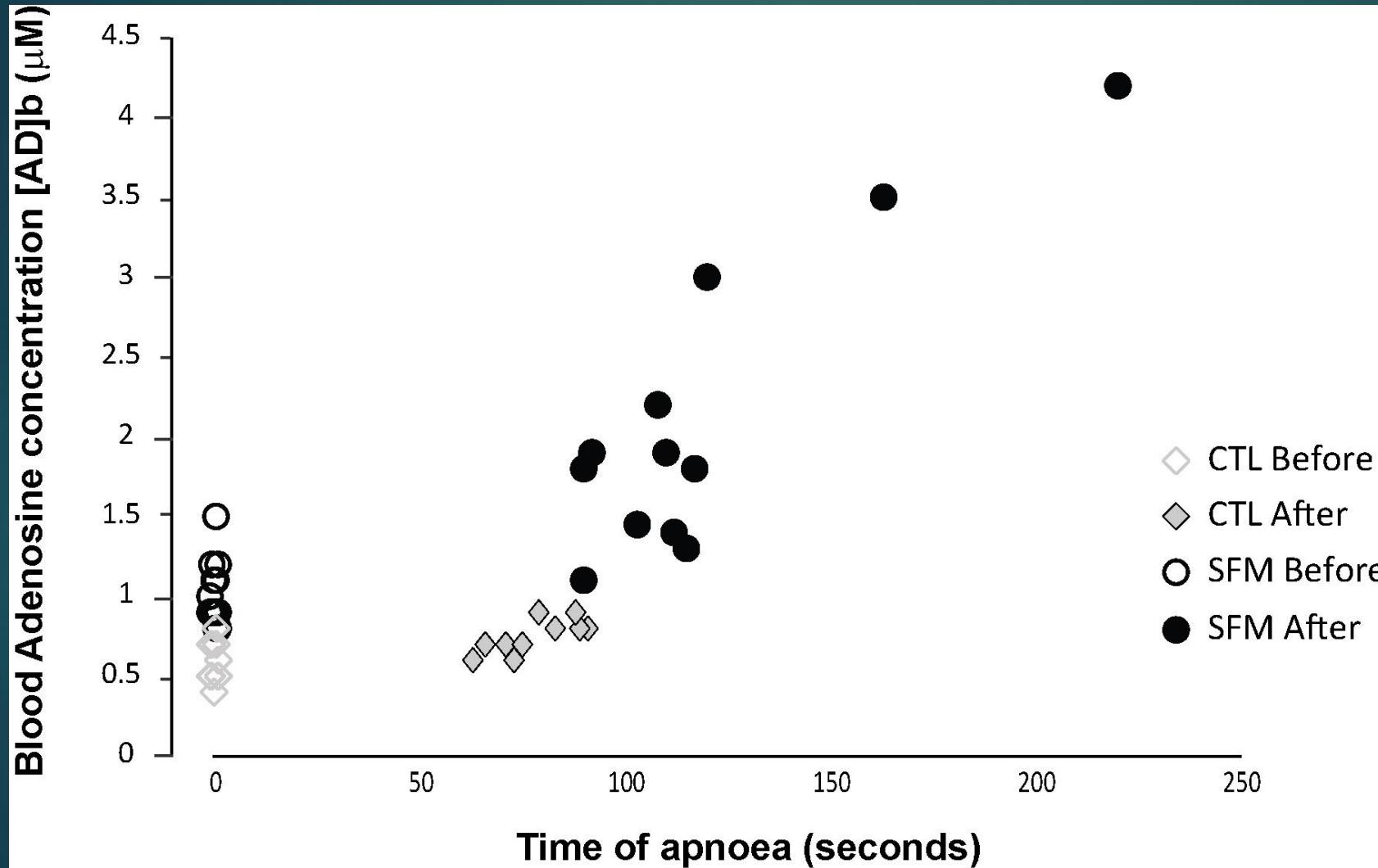
Apnea training and Erythropoietin



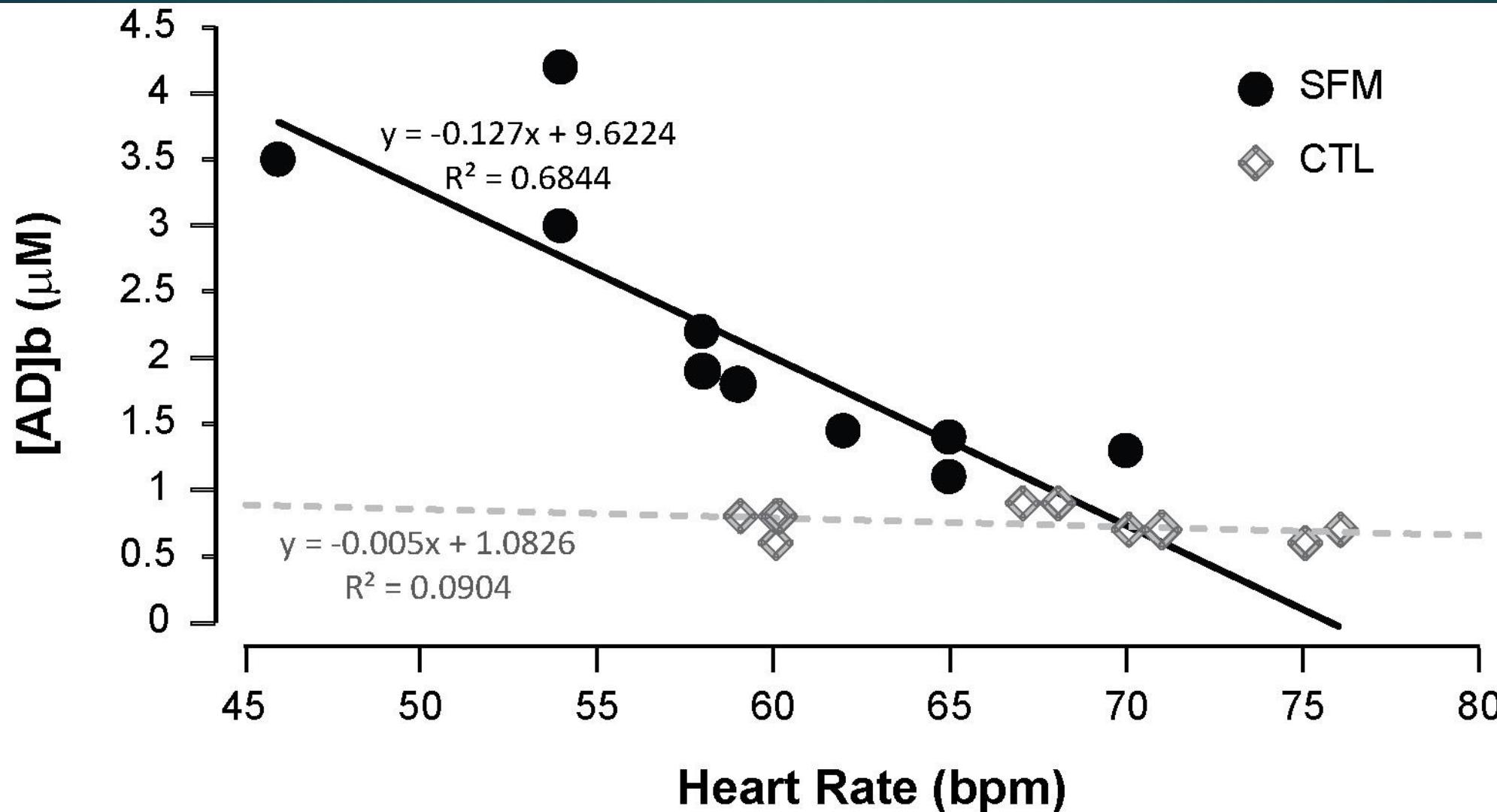
Free radicals and free dive



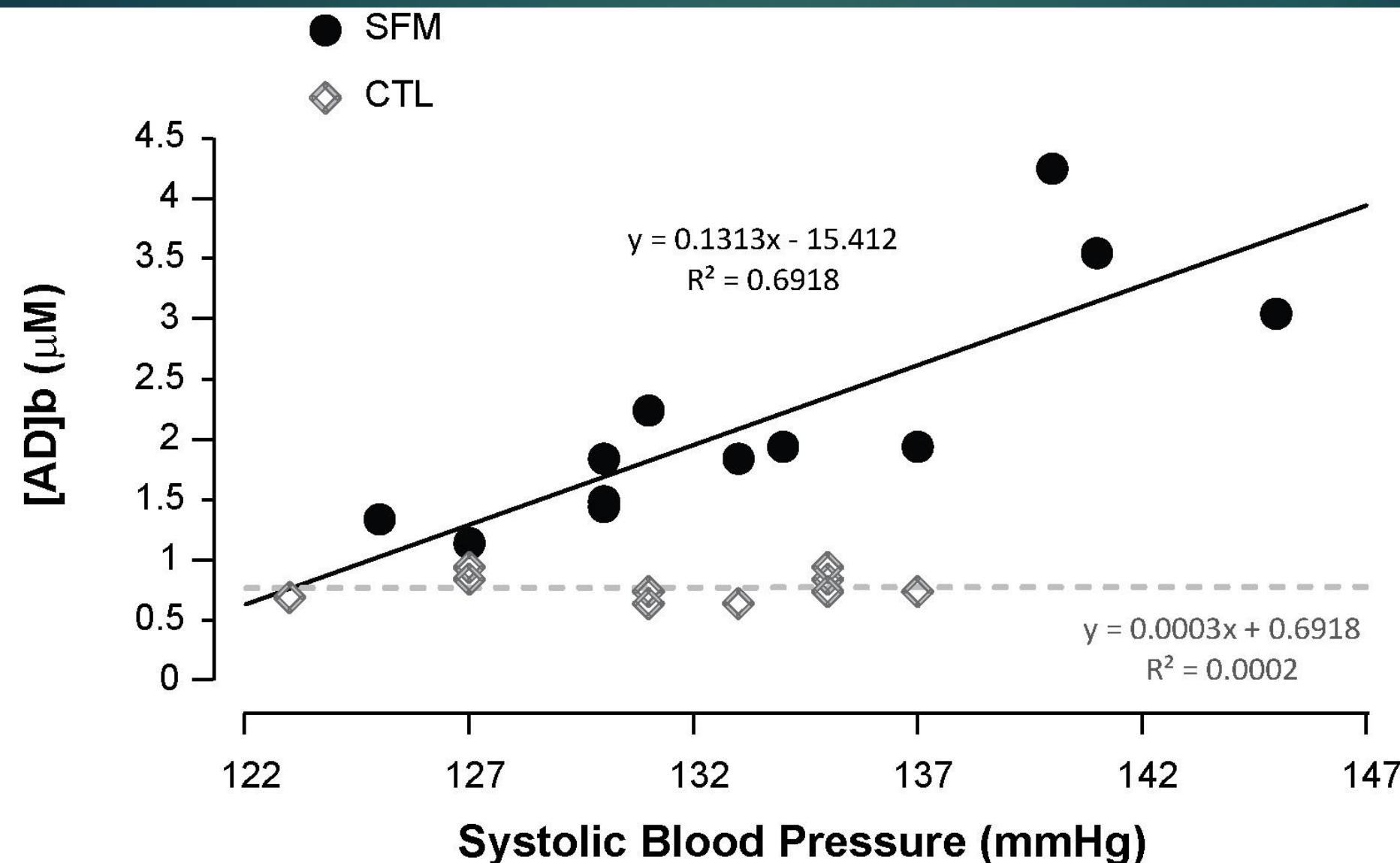
Adenosin and apnea



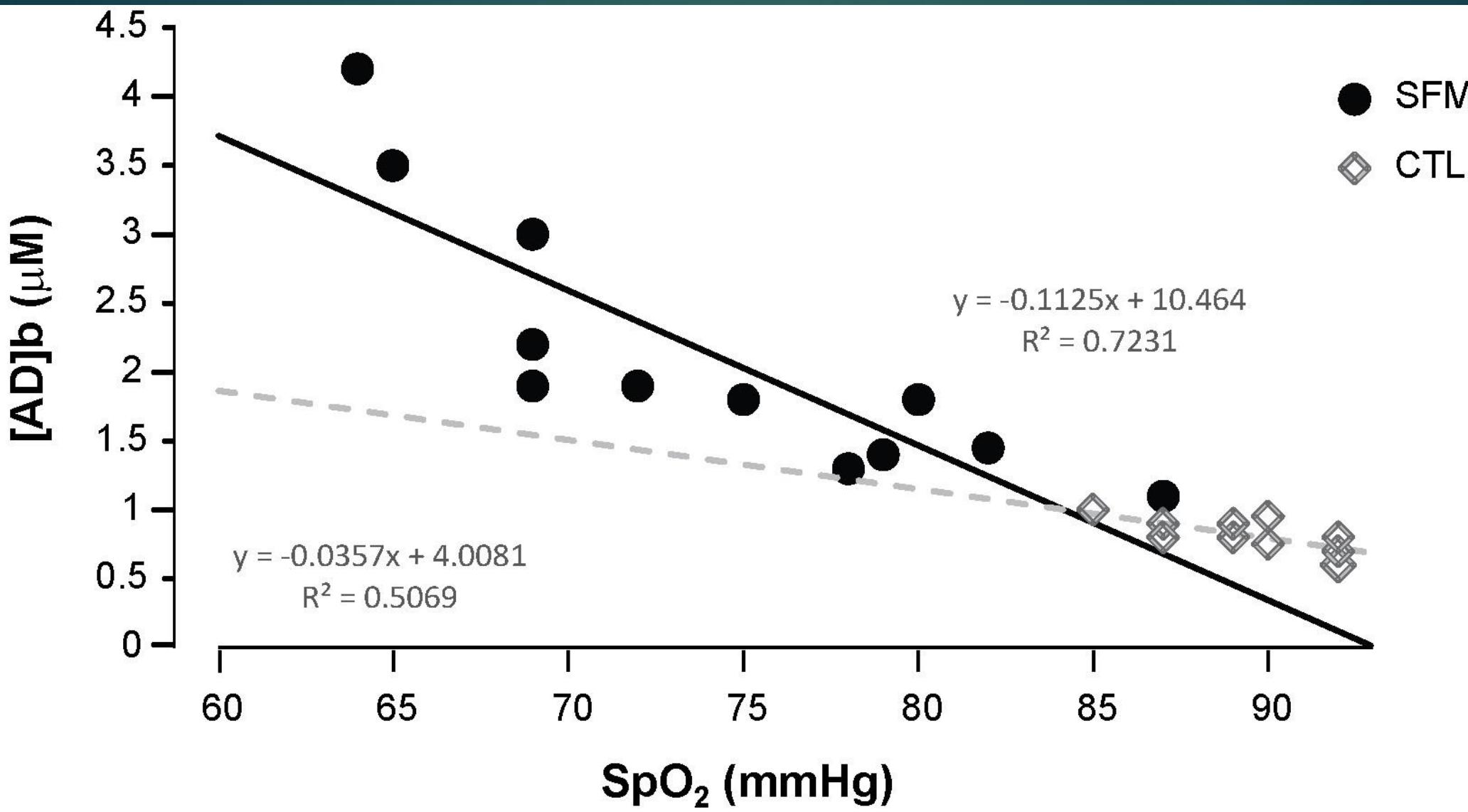
Adenosin AND heart rate



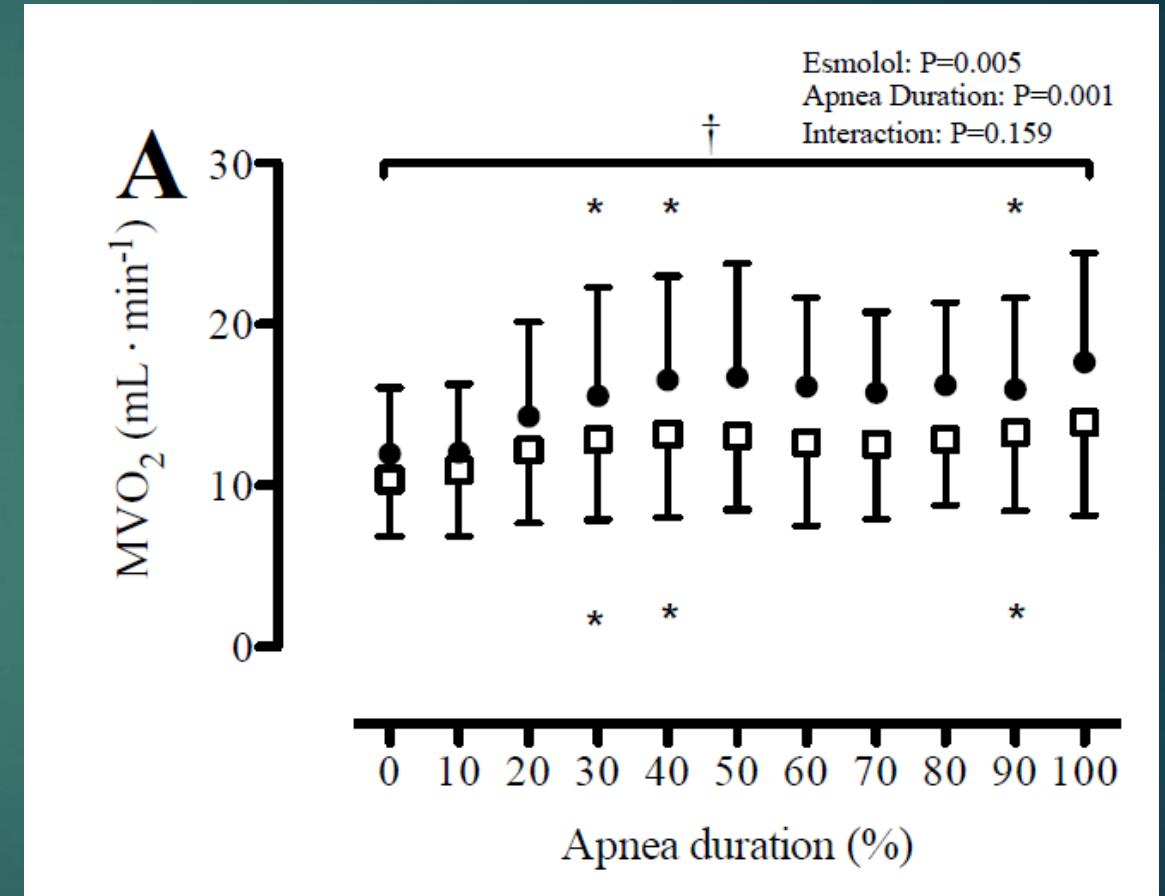
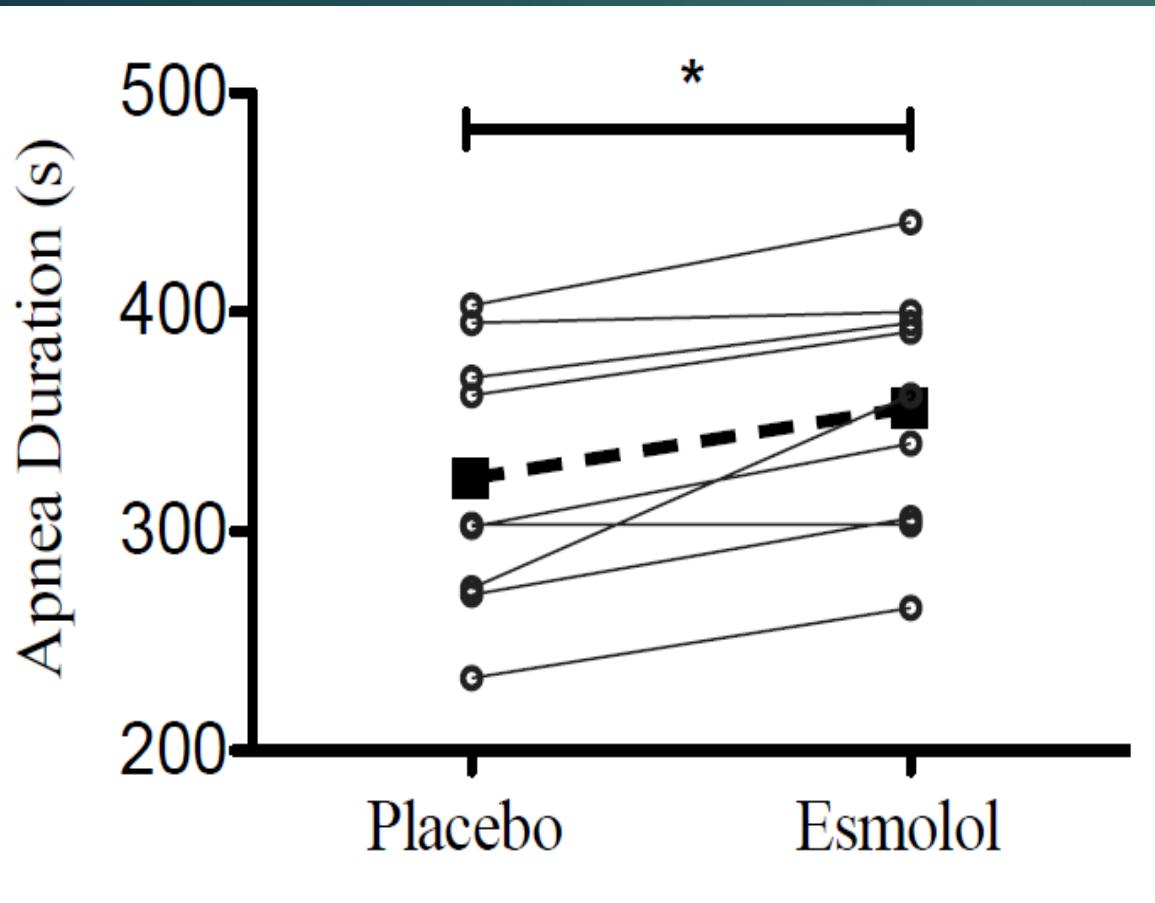
Adenosin AND systolic blood pressure



SpO_2 and adenosin



Effets des β bloquants sur la performance en apnée



D'après Hoiland et al. J. Appl. Physiol 2016

Entrainement en apnée : ascension Himalaya

D'après Shah et al. 2020

- ▶ Entrainement de grimpeurs (3 à 10 apnées par jour pendant 6 semaines)
- ▶ Aucun effet significatif sur le risque de survenue de MAM
- ▶ Nombre d'apnées trop faible pour engendrer un effet chronique donc logique de ne pas avoir d'effets