Cardiovascular effects of breath hold diving

Zeljko Dujic, MD, PhD

Department of Integrative Physiology, University of Split School of Medicine, Split, Croatia

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Croatia
Area: 56 542 km$^2$
Population: 4.3 million
Number of islands: 1185 (66 inhabited)

City of Split
Population: 200 000
Presentation outline

Breath hold diving

a) Historical overview  
b) Challenging the traditional concepts  
c) Physiological diving response  
d) Cardiovascular impacts  
e) Similarities to OSA
Historical overview of breath-hold diving

- Reaches long ago in the past (fishing, collection of sponges and pearls)
- Ama divers – 2000 years ago
- After World War II became an international sport
Apnea disciplines and current records

- Static apnea (SA)
  World record: 11 min 35 sec

- Dynamic apnea (DA)
  World record: 265 m

- Constant weight (CW)
  World record: 123 m

- No limit
  World record: 214 m
Stretching the limits

- Diver begins with the largest volume of the air in the lungs
- Air packing (squeezes out the blood and increases TLC for up to 40 %) – dry apnea model of cardiac compression via pulmonary hyperinflation
- Lung compression in deep diving
- Extreme chemostress (hypoxia/hypercapnia)
Magnetic resonance images of the heart and upper abdomen in one breath-hold diver at rest (left) and during air packing (right).
Physiological challenges during apnea diving

- Physiological/psychological response to hypoxia and hypercapnia
  - $\text{PaO}_2 - 19$ mmHg, $\text{SaO}_2 - 30-40\%$, $\text{PaCO}_2 - 55$ mmHg

- Extreme ambient hydrostatic pressure
  - Barotrauma at descent and ascent (pneumomediastinum)
  - Pulmonary edema and alveolar hemorrhage (capillary stress failure)

- Increased gas uptake and nitrogen supersaturation
  - $\text{N}_2$ narcosis
  - Decompression sickness (Deco stops)

Human Diving response – *lab vs field physiological data*

1. Changes of cardiac rhythm (bradycardia)
2. Peripheral vasoconstriction and redistribution of blood to the central blood reservoir
3. Arterial pressure increase
4. Reduction of cardiac output
5. Contraction of the spleen?
1. Changes in cardiac rhythm

- Initial anticipatory tachycardia (stimulation of the lung mechanoreceptors; hyperventilation; excitement?)
- Increased parasympathetic input to SA node
  - immersion of the face in the cold water
  - enlargement of venous inflow and distention of heart cavities
- Arrhythmisas (bradyarrhythmia and extra beats)
2. Peripheral vasoconstriction and blood redistribution

- Increased sympathetic outflow to the periphery – reduced blood flow to the peripheral tissues and skin
- Anaerobic metabolism on the periphery (lactate increase)
- Blood centralization to the brain and heart
- 100% increase of cerebral flow through middle cerebral artery (MCA)
Figure 1. Original recordings of beat-to-beat arterial blood pressure (ABP; Finom) from Heusser et al., Hypertension. 2009 Apr;53(4):719-24
Figure 2. Individual courses of mean arterial pressure (Finometer) and MSNA during apnea (starting at 0 minutes).

From Heusser et al., Hypertension. 2009 Apr;53(4):719-24
Figure 3. Relationship between changes in mean arterial pressure (MAP) and MSNA at the end of apnea.

○, control subjects; •, divers.

From Heusser et al., Hypertension. 2009 Apr;53(4):719-24

$r^2 = 0.40$
$p < 0.0001$
Recruitment of large sympathetic postganglionic neurons – Henneman’s principle described in sympathetic nervous system

Identification of single APs using continuous wavelet transform algorithm in single diver during end-inspiratory breath-hold (total of 2 min 34 s in duration). It can be seen that towards the end of the breath-hold the burst size (i.e. burst content) increases and the number of clusters are increased.
Increase of cerebral flow through middle cerebral artery (MCA)

From Palada et al., Respir Physiol Neurobiol. 2007 Aug 1;157(2-3):374-81

MCAV = mid cerebral artery flow
BHD = breath-hold divers
ND – controls (non divers)
Anatomy of the cerebral arterial circulation

Frontal view of the carotid arteries, vertebral arteries and intracranial vessels and their communication with each other via the Circle of Willis.

The cerebral metabolic rate of oxygen (CMRO$_2$) (measured from arterial and internal jugular vein samples) was reduced from baseline for about 30%. Hypercapnia has a major effect.
3. Increase in arterial pressure

- Significant pressure rise - invasively measured to 290/150 mmHg; a few systolic values to 345 mmHg
- We found only moderate BP increase during dives (2m)
- Caused by peripheral vasoconstriction
Biomedical Engineering Partner: SEABEAR Diving Technology

SME based in Graz, Austria

Research focus:
- Biomedical engineering
- Diving physiology
- Diving computers and head up displays
- Re-breather gas monitoring
- Apnea diving computer – improved diving safety?
ECG device

SpO₂ and HR

ECG device
Underwater BP device
BP measurements at the end of DA
Two phases of apnea

Fig. 5.2  Recording of thoracic movements, in a human volunteer subject, during a maximal duration breath-hold. (Modified with permission from Schagatay 1996)
Methodologies:

- **FingerAP, MAP, SV, CO** - Finometer (Modelflow technique); invasive BP
- Brain/tissue hemoglobin oxygenation; oxygenation index - NIRS
- MCAv and PCAv – TCD and ICA and VA - echo
- Microneurography - muscle sympathetic neural activity (MSNA)
- Respiratory mechanics – esophageal and gastric balloons
- Cardiac MRI, echocardiography

Breath-hold divers as models for studying OSA

- Cerebrovascular reactivity and sympathetic central chemoreflex sensitivity are unchanged in elite breath-hold divers during hypercapnia.

Cerebral and peripheral hemodynamics and oxygenation during maximal dry breath-holds

- Despite large increases in cerebral perfusion, regional cerebral desaturation may become a factor limiting the maximal breath-hold duration

From Palada et al., Respir Physiol Neurobiol. 2007 Aug 1;157(2-3):374-81
4. Changes of the cardiac output

- increased / reduced / unchanged
- surface apneas vs breath hold diving
- influence of bradycardia > changes of stroke volume
Restoration of hemodynamics in apnea struggle phase in association with involuntary breathing movements

- Contribution of diaphragm contractions to the enlargement of the venous inflow throughout struggle phase of the apnea

Involuntary breathing movements improve cerebral oxygenation during apnea struggle phase

Involuntary breathing movements improve cerebral oxygenation during apnea struggle phase

Conclusion

Increased sympathetic activity, restoration of hemodynamic parameters through the IBM and CO₂-mediated central vasodilatation act synergistically to improve cerebral oxygenation and enable prolongation of maximal apnea time.
5. The role of spleen in diving response?

- Significant reservoir of blood to many land and water mammals (RBC, WBC, platelets)
- Exercise and diving cause the contraction of the spleen
- Increased adrenergic activity (α1-stimulation)
- Constitutive part of SNS?

- rapid decrease in spleen volume was mainly completed throughout the first apnea

- in 2 min. periods between repeated apneas, spleen not did not recover

- the increase in number of circulating erythrocytes would put the second and subsequent apneas at advantage over the first one

- platelets released from the spleen but do not appear in the venous blood (hepatic sphincter?)

- large platelets (prothrombogenic) coming from spleen (stroke, acute myocardial infarction)?
Spleen volume and blood flow response to repeated breath-hold apneas

Diving response will appear in:

- breath hold diving in the depth
- the surface apnea with face immersion in the cold water
- the surface apnea without face immersion (with or without cold stimulus to the face)
Breath-hold diving and Obstructive sleep apnea

- Includes three most important symptoms of sleep apnea syndrome: cyclic hypoxemia, hypercapnia and absence of ventilation
- Extrapolation of the results to the OSA and connection between OSA and hypertension
- Unique human model of OSA?
Breath-hold divers as models for studying OSA


Isocapnic hypoxia

Conclusions

- Contrary to obstructive sleep apnea patients, breath hold divers are not exposed to excessive sympathetic activation (acute effects, long term unknown).

<table>
<thead>
<tr>
<th>Apnea divers</th>
<th>OSA</th>
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<tr>
<td>voluntary; end-inspiratory</td>
<td>involuntary; end-expiratory</td>
</tr>
<tr>
<td>3-4 times weekly; 1-1.5h</td>
<td>every time while sleeping</td>
</tr>
<tr>
<td>usually younger age</td>
<td>usually older age</td>
</tr>
<tr>
<td>usually healthy</td>
<td>usually have comorbidities</td>
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- Autonomic, ventilatory, and cardiovascular responses to hypoxia and hypercapnia are normal in elite divers.

- Repeated voluntary exposure to intermittent hypoxia/hypercapnia in the absence of additional risk factors do not have a negative chronic impact on central and peripheral chemosensitivity.
Fainting during breath-hold

Maximal breath hold time & pharma interventions

Figure 1. Maximal apnea duration during placebo and esmolol trials (Hoiland et al J Appl Physiol in press)

- Low dose dopamine increased apnea duration (Bain et al AJP R 2015)

Figure 1. Maximal apnea duration during indomethacin trial (Bain et al Transl Neurosci 2016)
Thank you

Welcome to The Department of Integrative Physiology

The Department of Physiology has been an integral part of the University of Split School of Medicine (USSM) since its establishment in 1997. Since then, it has grown into a prominent centre of scientific excellence within the region with a substantial scientific production, developed international ties and a growing number of incoming researchers. The main activities within the Department include basic research and teaching of the medical students and clinical practitioners.

Laboratories for Clinical and Exercise Physiology are equipped with instruments for non-invasive evaluation of cardiopulmonary system in humans at rest and during exercise. They include spiroergometry, ultrasonic scanners with different tissue and vascular probes, respiratory mass spectrometer, transcranial Doppler, various ergometers and different analytical instruments (lactate, blood gas machine, co-o2meter, blood count). In addition to

www.mefst.hr/physiology