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REVIEW ARTICLE

CEREBRAL BLOOD FLOW AND METABOLISM DURING VERTICAL IMMERSION AND IN-WATER EXERCISE

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ABSTRACT

Vertical head-out water immersion has different physiological effects on the human body system due to hydrostatic pressure and different water temperatures. This review examines the changes in cerebral blood flow and metabolism during head-out water immersion and in-water exercise. Systematic research was conducted in PubMed, ScienceDirect, Scopus databases, by binary research methods. It included 11 articles that met the inclusion criteria. Studies have shown that acutely vertical head-out immersion in thermoneutral water and in-water exercise positively affects the circulation and metabolism of the brain. In healthy people, vertical immersion in thermoneutral water increases brain activity by increasing cerebral artery velocity and oxygenation. But, acutely, immersion in hot and cold water does not have a positive effect on cerebral circulation.

Keywords: Water Immersion; Cerebral Blood Flow and Metabolism; In-Water Exercise

INTRODUCTION

While the human brain needs about 15% of total cardiac output at rest, it consumes about 20% of total oxygen. The brain can be considered a center with a high blood supply level, which needs successful management in terms of hemodynamics to ensure the effective coordination of all physiological systems in our body. Decrease in cerebral blood flow due to any pathology, cognition decline (1), and increased risk of neurodegenerative diseases (such as dementia) (2) are closely related. Therefore, effective regulation of blood flow to the brain is vital for the proper functioning of the brain. Although this information is related to the regulation in the resting condition, the brain hemodynamic regulating centers organize the blood flow with different workloads in the processes that cause an increase in metabolism and are related to motor movement (2). Environmental factors can also change the cerebral blood flow response. Recently, brain blood flow responses in water exercise and water immersion conditions have been evaluated in a limited number of studies. Physiological mechanisms that regulate cerebral blood flow are triggered differently in water, depending on the temperature of the water and hydrostatic pressure (3,4).

Table 1. Keywords used in screening and research results

Databases	Key Words	Year	Total
PubMed	water immersion	1966–2021	911
	water immersion AND cerebral blood flow	1982–2021	45
	immersion AND cerebral blood flow	1982–2021	67
	hemodynamics AND water immersion	1989–2021	183
	hemodynamics AND aquatic exercise	1986–2021	34
	water immersion AND cerebral blood flow AND exercise	1992–2021	19
ScienceDirect	Hemodynamics	1996–2021	192
	cerebral blood flow AND water immersion	1998–2021	2969
	cerebral blood flow AND treading water	1994–2021	127
	cerebral blood flow AND water immersion AND aquatic exercise	1994–2021	33
	water immersion AND exercise AND cerebral blood flow	1998–2021	526
	water immersion AND exercise	1998–2021	7057
Scopus	cerebral blood flow AND water immersion	2012–2021	49
	cerebral blood flow AND water immersion AND exercise	2016–2021	13
	Hemodynamics	2008–2019	43
	cerebral blood flow AND immersion AND aquatic exercise	2017–2019	2
	cerebral blood flow AND immersion AND treading water	2016	1
	treading water	2010–2021	43

Looking at the physiology of immersion, immersion in thermoneutral water (TNW, 30–34°C) causes blood to shift from the extremities toward the heart (5). This blood shift creates an increase in cardiac stroke volume, resulting in increased stroke volume (SV) and cardiac output (CO). Peripheral resistance decreases in water. The increase in cardiac stroke volume reduces the effort required for blood circulation (6). Thus, the efficiency of the heart increases. During heat out water immersion (HOWI), heart rate volume increases by ~12-37%, while heart rate (HR) decreases by ~4-6% (7). In short, cardiac output increases by ~14-29% at hip level, ~19-48% at xiphoid level, and ~29-66% at head-out dip (7).

The physiological mechanisms and interactions in regulating cerebral blood flow during HOWI are not fully understood. Studies have shown an increase of ~7%-23% in cerebral blood flow velocity (CBFv) in thermoneutral water conditions (4,8,9). Many physiological mechanisms affect the regulation of CBFv during water immersion. It is unknown whether physiological mechanisms such as arterial blood gases, arterial pressure, and cardiac output directly or combined affect cerebral perfusion. However, there are a limited number of studies in which the separate effects of these mechanisms during HOWI were investigated. This review aimed to examine the physiological mechanisms involved in CBF regulation during HOWI and the responses that occur in the condition of in-water exercise.

This review examines the studies on the effects of HOWI and water exercise on cerebral blood flow.

METHOD

Systematic reading was carried out according to PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guideline (10). Studies were reached using the keywords ‘cerebral blood flow, hemodynamics, immersion, water immersion, exercise, treading water and aquatic exeris’ together or separately. Three separate databases were used for reading (PubMed, ScienceDirect, Scopus). The research was conducted using a binary research method. In this context, keywords were linked using 'AND.' Table 1. shows the keywords used and the results of the research

Research articles were included or excluded using criteria defined by PICO (Population, Intervention, Comparison, and Outcome) (10). Reviews, theses, and conference papers were excluded from the review. Studies were determined according to the following items;

i. The research was written in English and published in a peer-reviewed journal,
ii. Conducting studies on people without health problems,
iii. Reporting physiological outputs related to the brain (middle and posterior cerebral artery velocities, brain oxy-hemoglobin, deoxy-hemoglobin, total-hemoglobin amount, etc.,

iv. The participants' entry into the water up to a certain point of their body (such as the hip or xiphoid).

In the first step, 65 studies were determined by reading the titles of the studies. The repetitive articles in the search were eliminated, and this number was reduced to 43. After reviewing the abstracts of these 43 articles, the actual number was reduced to 18 based on the exclusion criteria above. After the rest of the articles were read fully, the study was conducted with 11 studies according to the eliminations in figure 1.

DISCUSSION

Cerebral Blood Flow in Thermoneutral Water

Arterial blood gases, blood pressure, and activities affect cerebral blood flow in water. The hydrostatic pressure during HOWI increases the venous pressure and carries blood to the thorax. Cardiac preload and stroke volume increase as the central blood volume expands. As the immersion depth increases, the preload increases the stroke volume. Increased cardiac output decreases peripheral resistance of the vessels and increases blood flow velocity. The decrease in peripheral resistance occurred due to the temperature gradient difference between the skin and water temperature during immersion (6) and weakened sympathetic nerve activity (18). This reduction in peripheral resistance is approximately 27-51% (7). An increase in blood flow rate occurs throughout all organs. The middle cerebral artery velocity (MCAv) (4,9) and posterior cerebral artery velocities (8) increase in thermoneutral water. The increase in the middle cerebral artery is about 7%-23% (4,8,9). Carter et al. (7) reported that this increase in cerebral arteries was due to blood pressure and positively correlated between the middle cerebral artery velocity and the mean blood pressure (MAP). HOWI increases the amount of oxy-hemoglobin transported to the brain (11,12). This oxy-hemoglobin transport allows the brain to function more efficiently in cognitive processes (19).

With heat out water immersion, as central blood volume increases, pulmonary blood flow increases, increasing pulmonary artery blood pressure, and volume (6). With these developments, when we enter thermoneutral water, the minute ventilation (MV) does not change compared to land (4,9,20,21). However, alveolar hyperventilation does not differentiate with a change in MV, and the CO_2 pressure in the body begins to increase (9). Studies report that ventilation in thermoneutral water and end-of-tidal CO_2 pressure ($PETCO_2$) begins to increase simultaneously, so there may be a shift in the respiratory work point (9,22). This shift in respiration is hypothesized to be due to the central chemoreceptors (9), and respiration MV begins to increase at higher $PETCO_2$ levels in thermoneutral water (21). However, Sackett et al. (9), respiratory sensitivity CO_2 in water play an important role in cerebral perfusion changes. Studies have reported that one of the important causes of high cerebral circulation in thermoneutral water is the delay of MV increase, thus allowing work at high arterial CO_2 levels in water for a longer period. (9,16,21).

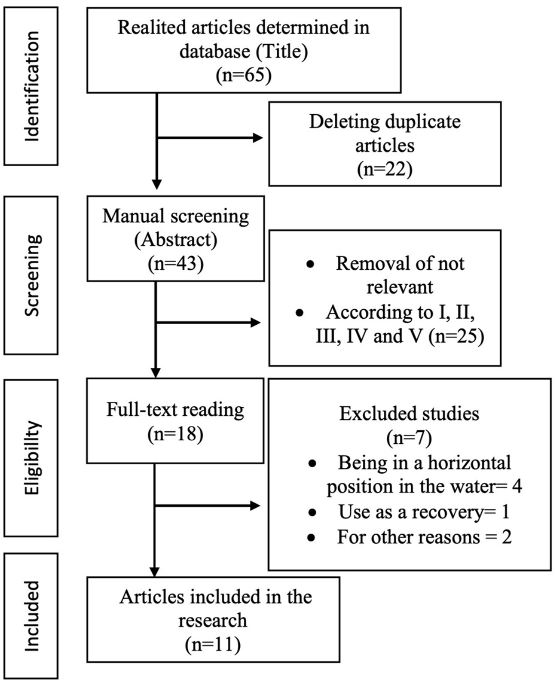

Figure 1. Flowchart of literature selection studies

Cerebral Blood Flow in Warm Water

Different physiological responses occur in hot water compared to TNW. In Hot Water, the body is exposed to heat stress. Since the density of water is high during immersion, no heat loss occurs with sweating and, thus body core temperature begins to increase. Hyperventilation occurs because of the increase in body core temperature. With hyperventilation, the amount of CO_2 in the blood begins to decrease. Additionally, an increase in HR and a decrease in MAP are observed. CBFv is reduced when diving into

Table 2. The effect of vertical water immersion and in-water exercise on cerebral blood flow and metabolism.

Studies	Participants	Exercise Protocol	Experimental Conditions	Water Temperature	Immersion Level	Immersion Time	Physiological Measurements	Results
Carter et al. (8)	9 Male (Age: 24.6 ± 2)	X	Thermoneutral Water vs. Land	30°C	Right Atrium	10-min	MCAv, PCAv, MAP, CO, SV, HR, $PETCO_2$	TNW > LA ↑ MCAv, PCAv, MAP, CO, $PETCO_2$ ($p < 0.05$)
Sato et al. (11)	11 Male (Age: 21.8)	X	Thermoneutral Water vs. Land	34°C	Femur Level	10-min	OxyHB, DeoxyHB, TotalHB, HR, SBP, DBP	TNW > LA ↑ OxyHb (S1, PAA, SMA, M1) ($p < 0.01$)
Sato et al. (12)	9 Male (Age: 21.8)	X	Thermoneutral Water vs. Land	34°C	Femur Level	35-min	OxyHB, DeoxyHB, TotalHB, MAP, HR, SBF, VO_2, QMO	TNW > LA ↑ OxyHb (SMA, M1, S1, PPC)
Sackett et al. (9)	12 (8 Male, 24 ± 3)	X	Thermoneutral Water vs. Land + CO_2	35°C	Neck	60-min	MCAv, MAP, CO, SV, HR, MV	TNW> LA + CO_2 ↑MCAv ($p < 0.01$) ↓ MV ($p < 0.01$)
Worley et al. (4)	18 (10 Male, Age: 23 ± 2)	X	Thermoneutral Water vs. Hot Water	35°C vs 39°C	Sternal Lotch	45-min	MCAv, MAP, CO, SV, HR, MV, $PETCO_2$	TNW> HW ↑ MCAv, MAP, CO, ($p < 0.01$)
Tsuji et al. (3)	14 Male (Age: 24 ± 3)	X	Hot Water + vs. Hot Water + CO_2	41°C	İliac Crest	~35-min	MCAv, ET, MST, HR, MAP, MV, TV, VO_2, VCO_2, $PETCO_2$, RER	HW + CO2 > HW ↑ MCAv, $PETCO_2$ ($p < 0.05$)
Tsuji et al. (13)	10 Male (Age: 24 ± 2)	X	Hot Water vs. Hot Water + voluntarily breathing	41°C	İliac Crest	~40-min	MCAv, ET, MST, HR, MV, TV, VO_2, VCO_2, $PETCO_2$, RER	HW + voluntarily breathing > HW ↑ MCAv, PETCO2, MAP ($p < 0.05$) ↓ DV ($p < 0.05$)
Mantoni et al. (14)	13 Male (Age: 32 ± 7)	X	Cold Water vs. Land	0°C	Sternal Notch	30-sec	MCAv, HR, RF, TV, MV, $PETCO_2$,	CW < LA ↓ MCAv, $PETCO_2$ ↑HR,MV ($p < 0.05$)
Mantoni et al. (15)	9 (5 Male, Age: 29 ± 3.4)	X	Cold Water vs. Land	0°C	Sternal Notch	60-sec	MCAv, KAH, RR, TV, MV, $PETCO_2$	CW < LA ↓ MCAv, $PETCO_2$ (NS) ↑ HR, MV ($p < 0.05$)
Pugh et al. (16)	15 (8 Male, Age: 26 ± 4)	Low-intensity stepping exercise	Thermoneutral water vs. Land	30°C	Heart Level	20-min	MCAv, PCAv, MAP, CO, SV, PCO_2	TNW > LA ↑ MCAv, PCAv, MAP, PCO_2 ($P < 0.01$)
Parfitt et al. (17)	11 (4 Male, Age: 27 ± 5)	Exhausted aquatic treadmill exercise	Thermoneutral water vs. Land	32°C	Mid-thigh mid-chest	~20-min	MCAv, HR	TNW > LA ↑ MCAv (NS) ↓ HR ($P < 0.01$)

LA: Land; TNW: Thermoneutral Water; HW: Hot Water; CW: Cold Water; MAP: Mean Arterial Pressure; CO: Cardiac Output; SV: Stroke Volume; HR: Heart Rate; SBP and DBP: Systolic and Diastolic Blood Pressure; SBF: Skin Blood Flow; QMO: Quadriceps Muscle Oxygenation; ET: Esophagus Temperature; MST: Mean Skin Temperature; VO_2: Oxygen Uptake; VCO_2: Carbon Dioxide Output; PCO_2: Partial Pressure of Expired Carbon Dioxide; RER: Respiratory Exchange Ratio; $PETCO_2$: End-Tidal CO2 Pressure; MV: Minute Ventilation; RR: Respiratory Rate; TV: Tidal volume; RF: Respiratory Frequency; MCAv and PCAv: Middle and Posterior Cerebral Arterial Velocity; OxyHb: Oxyhemoglobin; DeoxyHb: Deoxyhemoglobin; TotalHb: Total-Hemoglobin; S1: Primary Somatosensory Area; M1: Primary Motor Area; SMA: Supplementary Motor Area; PPC: Posterior Parietal Cortex; PAA: Parietal Association Area; NS: Not Significant.

hot water (3,4,13). Although CBFv is reduced, no change in cerebrovascular reactivity to hypercapnia is observed during or after hot water (3,4). Nitric oxide produced in the vasculature contributes to CBFv increases (8,23). Although this bioavailability is beneficial in thermoneutral water, this effect is not seen when HOWI is in hot water. Carotid artery blood flow and shear rate increase in hot water (4). These increases do not positively affect the MCAv (3,4,13). Worley et al. (4) stated that this increased blood flow in the carotid artery could be directed to the external carotid artery for thermoregulation. Bailey et al. (24) reported that 8 weeks of head immersion in hot water increased middle cerebral artery velocity and slowed the decline of MCAv in passive supine heat stress. Also, a possible increase in the MCAv by repeatedly entering the hot water had been shown (24). However, it is seen that there is no improvement in cerebrovascular circulation from the hyperthermia and thermoregulation responses caused by acutely entering hot water (3,4,13).

Cerebral Blood Flow in Cold Water

When we enter cold water, heat loss is prevented by vasoconstriction of the skin and subcutaneous vessels (25). The core temperature and muscle blood flow decrease gradually if the skin layer is not thick enough to prevent heat loss. A strong cold physiological response triggers cutaneous peripheral cold receptors a few seconds after immersion in cold water (25). These responses begin with a rapid rise in blood pressure and HR, an increase in hyperventilation, and a decrease in arterial $PaCO_2$. The sympathetic stimulus produced by immersion in cold water suddenly decreases the rate of MCAv (14,15). Mantoni et al. (14) stated that this sudden decrease in cerebral blood flow was due to rapidly occurring hyperventilation. In another study conducted by Mantoni et al. (15) participants were asked to suppress the reflex ventilator response that occurs when they enter the water for the first time before immersion and to breathe normally and control as much as possible after water immersion. The author stated that compared to his previous study, the decrease in MCAv was reduced by 43%, and the MCAv returned to base values more quickly after immersion (15). In addition to this decrease in MCAv in cold water, there is a decrease in the oxygenation level of the brain (oxy-hemoglobin and total hemoglobin) (26).

Cerebral Blood Flow During In-Water Exercise

The velocity of cerebral blood flow and cerebral oxygenation increase in exercises performed up to 60% of the maximal O_2 consumption in land conditions (2,27). Pugh et al. (16) compared the low-intensity stepping exercise in thermoneutral water (20 minutes) and in the land. According to the study results, it was found that the middle and posterior cerebral blood flow velocity of the water exercise was higher than the land exercise condition of the same intensity. The authors noted that MAP and $PetCO_2$, enhanced by hydrostatic pressure, can help with this difference (16). Similarly, Parfitt et al. (17) compared the exhausting treadmill exercise in thermoneutral water and land conditions. As a result, the middle cerebral artery velocity of the exhausted treadmill exercise was higher than the land condition. Studies have indicated that the greatest contributors to acutely increased CBFv is due to an increased MAP (16), decreased HR (17), increased $PetCO_2$ (16,28), and posture (28).

CONCLUSION

As a result, this review provides preliminary information about cerebral circulation and metabolism during HOWI. When examined, cerebral blood velocity responds differently in different water temperatures. Rest and exercises in thermoneutral water increase middle and posterior cerebral artery velocity (8,9,16,17). With this increase in the cerebral circulation, oxygenation in the sensory and motor areas of the brain (S1, M1, SMA, PPK, PPA) is increased (11,12). Thus, head-out immersion in thermoneutral water improves background activation of the cortex, increasing signal processing and learning. Studies examined in this review reported that hot water (3,4,13) and cold water (14,15) decreased cerebral blood flow. Moreover, with this decrease in the cerebral circulation of cold water, another study also confirmed a decrease in brain oxy-hemoglobin levels during the cold water immersion (26).

This review displays that acute thermoneutral water immersion and in-water exercise have a therapeutic effect on human cerebrovascular function and brain health. Therefore, thermoneutral water and intra-thermoneutral water exercise can be used as an alternative tool for a population with neurodegenerative disease or impaired functional capacity. In the future, there is a need for more studies examining the responses in different parts of the brain (such as Prefrontal, S1, M1, SMA, PPK, PPA) using different exercise loads and intensity in exercises performed at different water temperatures.

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