

Research Article

Hypothermia Improves Oral and Gastric Mucosal Microvascular Oxygenation during Hemorrhagic Shock in Dogs

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Received 26 March 2013; Revised 3 September 2013; Accepted 1 October 2013

Academic Editor: Lance B. Becker

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Hypothermia is known to improve tissue function in different organs during physiological and pathological conditions. The aim of this study was to evaluate the effects of hypothermia on oral and gastric mucosal microvascular oxygenation (μHbO_2) and perfusion (μflow) under physiological and hemorrhagic conditions. Five dogs were repeatedly anesthetized. All animals underwent each experimental protocol (randomized cross-over design): hypothermia (34°C), hypothermia during hemorrhage, normothermia, and normothermia during hemorrhage. Microcirculatory and hemodynamic variables were recorded. Systemic (DO_2) and oral mucosal (μDO_2) oxygen delivery were calculated. Hypothermia increased oral μHbO_2 with no effect on gastric μHbO_2 . Hemorrhage reduced oral and gastric μHbO_2 during normothermia ($-36 \pm 4\%$ and $-27 \pm 7\%$); however, this effect was attenuated during additional hypothermia ($-15 \pm 5\%$ and $-11 \pm 5\%$). The improved μHbO_2 might be based on an attenuated reduction in μflow during hemorrhage and additional hypothermia ($-51 \pm 21 \text{ aU}$) compared to hemorrhage and normothermia ($-106 \pm 19 \text{ aU}$). μDO_2 was accordingly attenuated under hypothermia during hemorrhage whereas DO_2 did not change. Thus, in this study hypothermia alone improves oral μHbO_2 and attenuates the effects of hemorrhage on oral and gastric μHbO_2 . This effect seems to be mediated by an increased μDO_2 on the basis of increased μflow .

1. Introduction

The gastrointestinal tract is not only responsible for nutrient absorption but also functions as a metabolic and immunological system, forming an effective barrier against endotoxins and bacteria in the intestinal lumen. Maintenance of this mucosal barrier function by improving perfusion and oxygenation seems to be of vital importance [1–3].

However, during severe illness (e.g., septic or hypovolemic shock) blood flow is redistributed and splanchnic oxygenation is impaired early to preserve perfusion of more vital organs (i.e., heart and brain) [4, 5]. Insufficient microcirculatory oxygen supply impairs mucosal barrier function and has been shown to enable translocation of bacteria and bacterial toxins into portal venous and local lymphatic circulation [6] and to mediate an inflammatory response syndrome [7]. Therefore, adequate splanchnic perfusion and in particular oxygenation of the gastrointestinal mucosa are

considered crucial for the prevention and therapy of critical illness [1, 8, 9]. Alterations of the oral microcirculation are an independent predictor of organ failure and associated with a high mortality [10, 11]. Thus, growing effort is made to develop strategies to improve splanchnic mucosal oxygenation and to avoid tissue hypoxia. Under these circumstances, especially during hypoxia, hypothermia is known to improve tissue function in a variety of tissues, for example, heart, brain, liver, and spinal cord [12–14] during trauma, anemia, neonatal asphyxia, respiratory failure, reduced inspiratory oxygen, and carbon monoxide intoxication [14, 15]. In contrast, hypothermia has also been shown to exert negative effects like a reduction of CO, cardiac arrhythmia, immunosuppression with an increased risk for infection, and an impaired coagulation cascade [14].

The impact of hypothermia on gastrointestinal circulation is controversially discussed. In a hemorrhagic shock model in rats hypothermia led to an increase in blood flow

[16]. In contrast, in a study in piglets, blood flow decreased during hypothermia in separate layers of the intestinal wall [17]. It is yet unclear if the observed changes in blood flow have any impact on bacterial translocation from the gastrointestinal lumen. Hypothermia during hemorrhagic shock decreased bacterial translocation into the spleen, liver, and mesenteric lymph nodes [16], but also opposing results with increased bacterial translocation linked to hypothermia were published [18]. Another study did not observe any changes in bacterial translocation during hemorrhagic shock under hypothermia but hypothermia improved survival [19]. Since hemorrhage reduces gastric mucosal oxygenation, the effects of hypothermia on gastric mucosal oxygenation during hemorrhage are of particular importance. Despite intense effort to analyze the effects of hypothermia on splanchnic perfusion, there are no studies investigating the effect on splanchnic oxygenation.

The effect of hypothermia on splanchnic mucosal oxygenation is of clinical interest for mainly two reasons. Hypothermia is already widely used as a therapeutic approach in critical illness, for example, after resuscitation, and is currently discussed as a therapeutic approach with additional indications [20] without detailed knowledge about possible negative effects on splanchnic oxygenation. As hypothermia is protective in tissue hypoxia of miscellaneous tissues, it might have a positive impact on splanchnic oxygenation, especially on local hypoxia during hemorrhage.

The aim of our study was to evaluate the effects of hypothermia on splanchnic mucosal oxygenation and perfusion. We investigated two representative mucosal regions (oral and gastric) under physiological and hemorrhagic conditions.

2. Materials and Methods

2.1. Animals. The data were derived from repetitive experiments on five dogs (female foxhounds, weighing 28 ± 1 kg) treated in accordance with NIH guidelines for animal care. Experiments were performed with approval of the local animal care and use committee (North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection, Recklinghausen, Germany; ref. 87-51.04.2010.A073).

Prior to the experiments, food was withheld overnight with water ad libitum to ensure complete gastric depletion and to avoid changes in perfusion and oxygenation due to digestive activity. Each dog underwent each experimental protocol in a randomized order and served as its own control. Experiments were performed at least 3 weeks apart to prevent carry-over effects. The experiments were performed under general anesthesia (induction of anesthesia with $4 \text{ mg} \cdot \text{kg}^{-1}$ propofol, maintenance with sevoflurane, end-tidal concentration 3.0%, and 1.5 MAC in dogs [21]). The animals were mechanically ventilated after endotracheal intubation ($F_i\text{O}_2 = 0.3$, $\text{VT} = 12.5 \text{ mL} \cdot \text{kg}^{-1}$) with the respiratory frequency adjusted to achieve normocapnia (end-expiratory carbon dioxide, $\text{etCO}_2 = 35 \text{ mmHg}$), verified by continuous capnography (Capnomac Ultima, Datex Instrumentarium, Helsinki, Finland). During baseline conditions, the dogs were placed

on their right side and covered with warming blankets to maintain body temperature at 37.5°C (continuous arterial measurement). Throughout the experiments, no additional fluid replacement was administered to avoid volume effects that could influence tissue perfusion and oxygenation. However, after withdrawal of each blood sample, normal saline was infused three times the sampling volume to maintain blood volume.

2.2. Measurements

2.2.1. Systemic Hemodynamic and Oxygenation Variables. The aorta was catheterized via the left carotid artery for continuous measurement of mean arterial pressure (MAP, Gould-Statham pressure transducers P23ID, Elk Grove, IL) and intermittent arterial blood gas samples adjusted for temperature (Rapidlab 860, Bayer AG, Germany) from appropriate syringes (PICO 50, Radiometer, Copenhagen, Denmark). Oxygen saturation was calculated for canine blood from pO_2 and adjusted to pH and temperature [22]. Arterial oxygen content ($C_a\text{O}_2 = \text{hemoglobin} \cdot 1.34 \cdot \text{oxygen saturation} + \text{pO}_2 \cdot 0.0031$) and DO_2 ($\text{DO}_2 = C_a\text{O}_2 \cdot \text{CO}$) were calculated subsequently. Cardiac output was determined via transpulmonary thermodilution (PiCCO 4.2 non US, PULSION Medical Systems, Munich, Germany) at the end of each intervention, at least every 30 minutes, as previously described [23, 24].

Heart rate (HR) was continuously measured by electrocardiography (Powerlab, ADInstruments, Castle Hill, Australia). All hemodynamic and respiratory variables were recorded on a personal computer after analog to digital conversion (Powerlab, ADInstruments, Castle Hill, Australia) for later analysis.

2.2.2. Mucosal Oxygenation and Perfusion. μHbO_2 and μflow of the gastric and oral mucosa were continuously assessed by tissue reflectance spectrophotometry and laser Doppler flowmetry (O2C, LEA Medizintechnik, Gießen, Germany), as detailed previously [24, 25].

Briefly, white light (450–1000 nm) and laser light (820 nm, 30 mW) are transmitted to the tissue of interest via a microlightguide and the reflected light is analyzed. The wavelength-dependent absorption and overall absorption of the applied white light can be used to calculate the percentage of oxygenated hemoglobin (μHbO_2) and the amount of hemoglobin (μHb) [26]. Due to the Doppler effect, magnitude and frequency distribution of changes in wavelength are proportional to the number of blood cells multiplied by the measured mean velocity (μVel) of these cells. This product is proportional to flow and expressed in arbitrary perfusion units (aU) [27]. Hence, this method allows assessment and comparison of oxygenation and perfusion of the same region at the same time. Changes of flow can be attributed either to change of velocity or number of red blood cells, comparable to the information gained by intravital microscopy.

Since light is totally absorbed in vessels with a diameter $>100 \mu\text{m}$ [28] only microvascular oxygenation of nutritive

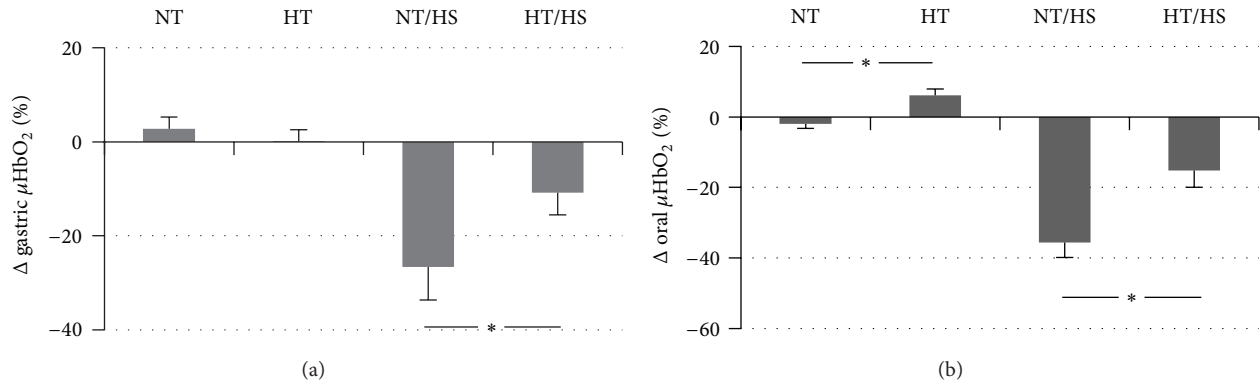


FIGURE 2: Effect of normothermia (NT), hypothermia (HT), hemorrhage during normothermia (NT/HS), and hemorrhage during hypothermia (HT/HS) on gastric and oral microvascular hemoglobin oxygen saturation (μHbO_2). Effects of hemorrhage: reduction of μHbO_2 after 30 minutes of shock (3.0 h) versus μHbO_2 before shock (2.5 h) during normothermia (NT/HS) and hypothermia (HT/HS). Effect of hypothermia without hemorrhage: change of μHbO_2 at the corresponding time point (3.0 h) versus baseline conditions under normothermia (NT) and hypothermia (HT). Data are presented as absolute changes for $n = 5$ dogs, mean \pm SE, * $P < 0.05$.

2.5.1. Hypothermia (HT). To study the effects of hypothermia on μHbO_2 , body temperature was reduced over 90 minutes. Hypothermia was maintained for two hours and all variables were recorded. Normal body temperature was restored over 120 minutes.

2.5.2. Control Experiment, Normothermia (NT). As time control experiment, body temperature was kept at 37.5°C without any further intervention.

2.5.3. Hypothermia + Hemorrhagic Shock (HT/HS). To study the effect of hypothermia on hemorrhage, hypothermia was induced as described above. During hypothermia, hemorrhagic shock was induced and maintained for 60 minutes, followed by retransfusion of the shed blood and rewarming of the animal.

2.5.4. Control Experiment, Normothermia + Hemorrhagic Shock (NT/HS). The effects of hemorrhage alone on μHbO_2 were studied under normothermia. Hemorrhagic shock was induced 120 minutes after baseline recording, followed by retransfusion of the shed blood.

Blood samples were obtained for blood gas analysis at the indicated measuring points (Figure 1). These time points reflect a steady state under baseline conditions (MP 1), under hypothermia after reaching the intended temperature of 34°C (MP 2) and during hemorrhage (MP 3 + 4).

2.6. Statistical Analysis. Data for analysis were obtained during the last five minutes of each intervention under steady state conditions. All data are presented as mean \pm standard error (mean \pm SE) for $n = 5$ animals. Normal data distribution was assessed and confirmed in Q-Q plots (IBM SPSS Statistics, International Business Machine Corp., USA). Differences within the groups and between the groups were tested using a Wilcoxon signed-rank test (StatView V4.1, SAS Institute Inc, Cary, NC, USA); $P < 0.05$ was considered significant.

3. Results

Hypothermia alone (HT) did not influence gastric μHbO_2 compared to baseline conditions (Figure 2). In contrast, hypothermia significantly increased oral μHbO_2 by $+6 \pm 2\%$. This was related to a reduction in μVO_2 of -159 ± 76 aU during hypothermia compared to almost unchanged μVO_2 (-26 ± 28 aU) during normothermia at the same time point, which, however, failed to reach significance ($P = 0.08$). Hypothermia neither changed DO_2 (Table 1) nor μDO_2 (Figure 3). The increase of oral μHbO_2 was independent of μflow which did neither change during normothermia (-2 ± 4 aU) nor during hypothermia (-16 ± 17 aU). Accordingly, μVel and μHb remained unchanged as well (Figure 4).

3.1. Hypothermia + Hemorrhage. During control experiments (37.5°C) with hemorrhage alone (NT/HS), gastric μHbO_2 decreased by $-27 \pm 7\%$ and oral μHbO_2 by $-36 \pm 4\%$ after 30 minutes of hemorrhage (Figure 2). This decrease was significantly attenuated during hypothermia for both oral and gastric μHbO_2 (gastric μHbO_2 decreased by -11 ± 4 and oral μHbO_2 by $-15 \pm 5\%$) (Figure 2). This effect was not related to DO_2 which was reduced during hemorrhagic shock independent of normo- or hypothermic conditions almost equally by -5 ± 1 mL/kg/min (normothermia) and by -5 ± 1 mL/kg/min (hypothermia). Reduction of DO_2 was caused by a lower CO that was equally reduced in both groups without any differences between normothermia and hypothermia.

The differences of μHbO_2 during hemorrhage are related to a decrease of μDO_2 during normothermia (-1690 ± 319 aU) that was ameliorated during additional hypothermia (-910 ± 366 aU), while μVO_2 did not change in both groups (Figure 3). These differences in μDO_2 are based on changes of μflow that decreased during hemorrhage under normothermia (-106 ± 19 aU) and improved under hypothermia (-51 ± 21 aU). Higher μflow values are attributed to both higher μVel and higher μHb (Figure 4). μVel decreased

TABLE 1: Hemodynamic variables of the experimental groups.

Variable	Group	Measuring point 1 (0.5 h)	Measuring point 2 (2.5 h)	Measuring point 3 (3.0 h)	Measuring point 4 (3.5 h)
Gastric μHbO_2 [%]	NT	70 \pm 4	70 \pm 4	68 \pm 5	67 \pm 5
	HT	72 \pm 2	73 \pm 2	73 \pm 2	73 \pm 1
	NT/HS	76 \pm 1	78 \pm 2	51 \pm 7*	56 \pm 8*
	HT/HS	74 \pm 1	71 \pm 2	60 \pm 6 [#]	60 \pm 8
Oral μHbO_2 [%]	NT	79 \pm 2	82 \pm 1	81 \pm 1	80 \pm 1
	HT	80 \pm 2	85 \pm 3*	86 \pm 1* [#]	84 \pm 1
	NT/HS	75 \pm 2	78 \pm 1	42 \pm 5*	48 \pm 4*
	HT/HS	76 \pm 1	81 \pm 1 [#]	65 \pm 4 [#]	62 \pm 4*
μflow [aU]	NT	127 \pm 29	129 \pm 24	125 \pm 26	119 \pm 25
	HT	140 \pm 33	124 \pm 26	125 \pm 22	122 \pm 21
	NT/HS	146 \pm 30	160 \pm 25	53 \pm 10*	63 \pm 13*
	HT/HS	131 \pm 22	136 \pm 20	85 \pm 18*	78 \pm 16
μVel [aU]	NT	23 \pm 3	23 \pm 3	23 \pm 3	22 \pm 3
	HT	27 \pm 4	25 \pm 2	25 \pm 2	26 \pm 2
	NT/HS	25 \pm 3	26 \pm 3	17 \pm 3	18 \pm 3*
	HT/HS	26 \pm 3	28 \pm 4	25 \pm 4	25 \pm 4
μHb [aU]	NT	87 \pm 3	86 \pm 3*	85 \pm 3*	85 \pm 3*
	HT	84 \pm 2	84 \pm 3	84 \pm 2	84 \pm 2
	NT/HS	87 \pm 3	84 \pm 4	64 \pm 7*	67 \pm 7*
	HT/HS	83 \pm 3	81 \pm 3	73 \pm 4*	73 \pm 3*
μDO_2 [aU]	NT	2082 \pm 481	2123 \pm 411	2073 \pm 440	1976 \pm 430
	HT	2374 \pm 558	2195 \pm 433	2177 \pm 382	2135 \pm 368
	NT/HS	2345 \pm 481	2517 \pm 411	828 \pm 154*	982 \pm 187*
	HT/HS	2187 \pm 359	2327 \pm 345	1417 \pm 262*	1310 \pm 262
DO_2 [mL·kg ⁻¹ ·min ⁻¹]	NT	15 \pm 1	14 \pm 1	14 \pm 1	14 \pm 1
	HT	14 \pm 1	13 \pm 1	13 \pm 1	13 \pm 1
	NT/HS	14 \pm 1	13 \pm 1	8 \pm 1*	9 \pm 1*
	HT/HS	15 \pm 1	14 \pm 1	9 \pm 1* [#]	10 \pm 1*
VO_2 [aU]	NT	380 \pm 64	351 \pm 62	354 \pm 62	349 \pm 64
	HT	423 \pm 92	273 \pm 27	265 \pm 23*	318 \pm 53
	NT/HS	527 \pm 108	512 \pm 90	447 \pm 85	474 \pm 88
	HT/HS	472 \pm 72	421 \pm 59	435 \pm 67	453 \pm 85
SVR [mmHg·L ⁻¹ ·min]	NT	26 \pm 2	27 \pm 2	28 \pm 2*	28 \pm 2*
	HT	27 \pm 2	28 \pm 2	29 \pm 2	30 \pm 2*
	NT/HS	26 \pm 2	26 \pm 2	35 \pm 2	35 \pm 2*
	HT/HS	25 \pm 2	27 \pm 2	33 \pm 2	34 \pm 2
CO [mL·kg ⁻¹ ·min ⁻¹]	NT	88 \pm 8	85 \pm 6	84 \pm 5	84 \pm 5
	HT	81 \pm 7	74 \pm 4	73 \pm 3	72 \pm 4* [#]
	NT/HS	88 \pm 6	85 \pm 3	52 \pm 3*	59 \pm 3*
	HT/HS	87 \pm 6	80 \pm 3	53 \pm 3*	57 \pm 4*
SV [mL]	NT	23 \pm 2	22 \pm 2	22 \pm 2*	22 \pm 2*
	HT	22 \pm 2	27 \pm 2* [#]	26 \pm 2* [#]	26 \pm 2* [#]
	NT/HS	22 \pm 2	22 \pm 2	14 \pm 1*	15 \pm 1*
	HT/HS	23 \pm 2	27 \pm 3* [#]	16 \pm 1* [#]	17 \pm 1* [#]

TABLE 1: Continued.

Variable	Group	Measuring point 1 (0.5 h)	Measuring point 2 (2.5 h)	Measuring point 3 (3.0 h)	Measuring point 4 (3.5 h)
MAP [mmHg]	NT	63 ± 2	65 ± 1	65 ± 1	65 ± 2
	HT	62 ± 2	61 ± 1 [#]	61 ± 1	61 ± 2
	NT/HS	65 ± 1	65 ± 1	53 ± 1*	61 ± 2
	HT/HS	62 ± 2	62 ± 3	50 ± 4*	55 ± 3 [#]
HR [min ⁻¹]	NT	111 ± 6	111 ± 5	111 ± 5	110 ± 6
	HT	108 ± 5	82 ± 4 ^{**}	81 ± 4 ^{**}	81 ± 4 ^{**}
	NT/HS	117 ± 5	112 ± 4*	114 ± 8	117 ± 8
	HT/HS	112 ± 6 [#]	88 ± 6 ^{**}	96 ± 8 ^{**}	97 ± 8 ^{**}

Effect of normothermia (NT), hypothermia (HT), hemorrhage during normothermia (NT/HS), and hemorrhage during hypothermia (HT/HS) on gastric and oral mucosal hemoglobin oxygenation (μHbO_2), microvascular flow (μflow), velocity (μVel) and amount of haemoglobin (μHb), regional (μDO_2), and systemic oxygen delivery (DO_2), oral mucosal oxygen consumption (μVO_2), systemic vascular resistance (SVR), cardiac output (CO), stroke volume (SV), mean arterial pressure (MAP), and heart rate (HR); data are presented as absolute values, mean \pm SE, $n = 5$, * $P < 0.05$ versus baseline, [#] $P < 0.05$ versus NT for group HT and versus NT/HV for group HT/HV.

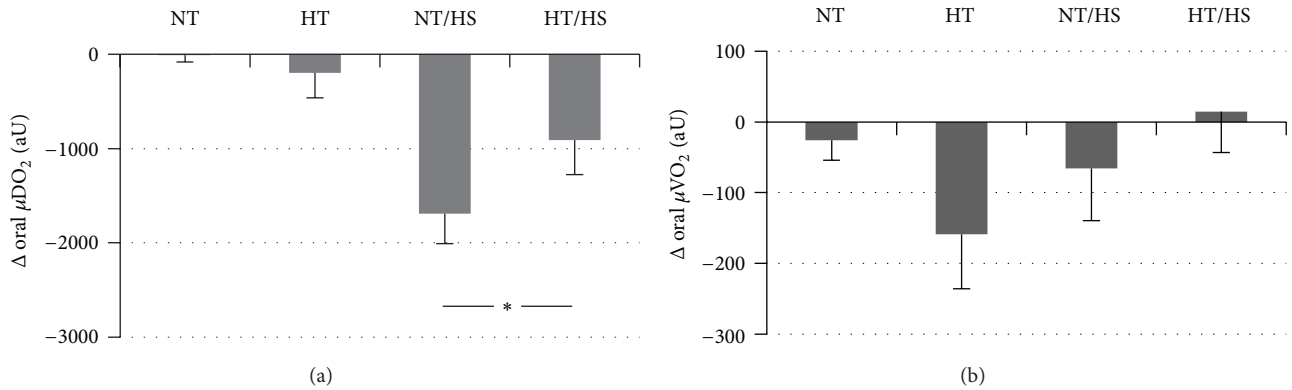


FIGURE 3: Effect of normothermia (NT), hypothermia (HT), hemorrhage during normothermia (NT/HS), and hemorrhage during hypothermia (HT/HS) on oral mucosal oxygen delivery (μDO_2) and oxygen consumption (μVO_2). Effects of hemorrhage: change of μDO_2 and VO_2 after 30 minutes of shock (3.0 h) versus μDO_2 and μVO_2 before shock (2.5 h) during normothermia (NT/HS) and hypothermia (HT/HS). Effect of hypothermia without hemorrhage: change of μDO_2 and μVO_2 at the corresponding time point (3.0 h) versus baseline conditions under normothermia (NT) and hypothermia (HT). Data are presented as absolute changes for $n = 5$ dogs, mean \pm SE, * $P < 0.05$.

during hemorrhage by -9 ± 3 aU under normothermia but only by -4 ± 2 aU under hypothermia. In addition, hypothermia attenuated the decrease of μHb from -20 ± 4 during normothermia to -8 ± 2 aU.

4. Discussion

The aim of our study was to evaluate the effects of hypothermia on oral and gastric μHbO_2 and μflow under physiological and hemorrhagic conditions. We have observed in this study that hypothermia increases oral μHbO_2 under physiological conditions without influencing gastric μHbO_2 . According to our results, hypothermia attenuates the effects of hemorrhage on oral and gastric μHbO_2 . This effect could be related to the observed increase of μDO_2 based on the increase of μflow with unchanged μVO_2 .

These results are quite interesting and of clinical importance, since hypothermia is widely used after resuscitation, but data on the effect of hypothermia on oral and gastric μHbO_2 are lacking so far. Since hypothermia did not affect

gastric μHbO_2 under otherwise physiological conditions, its benefit as a therapeutic approach to improve gastric oxygenation remains controversial. Our data did not reveal any detrimental effects and hypothermia might thus be applied after resuscitation without further compromising gastric microcirculation. Nevertheless, other variables and thus possible negative effects of hypothermia have to be considered as well. Additionally, the presented data are derived from an animal study on five dogs. Therefore, their impact on the therapeutic application in humans has to be interpreted with care.

Additionally, both groups investigated during normothermia (NT and NT/HS) and accordingly both groups investigated during hypothermia (HT and HT/HS) were treated equally before hemorrhage (MP 2). Those groups were not tested for significant differences; however, suspected differences might be attributed to minor differences in baseline values. To exclude differences in baseline values as confounding factor, our main findings are based on relative changes of the variables (Figures 2–4) and not on absolute values.

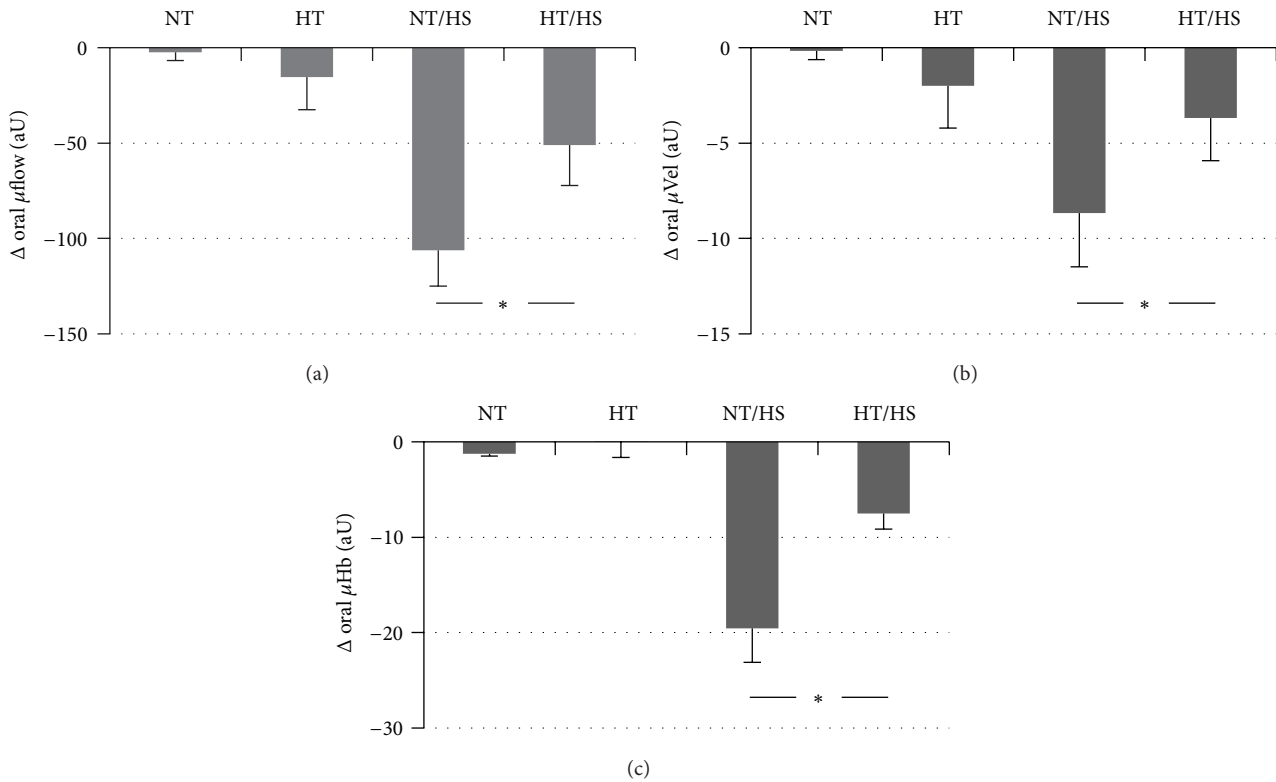


FIGURE 4: Effect of normothermia (NT), hypothermia (HT), hemorrhagic shock during normothermia (NT/HS), and hemorrhage during hypothermia (HT/HS) on oral mucosal perfusion (μ flow), red blood cell velocity (μ Vel), and amount of tissue haemoglobin (μ Hb). Effects of hemorrhage: change of μ flow, μ Vel, and μ Hb after 30 minutes of shock (3.0 h) versus μ flow, μ Vel, and μ Hb before shock (2.5 h) during normothermia (NT/HS) and hypothermia (HT/HS). Effect of hypothermia without hemorrhage: change of μ flow, μ Vel, and μ Hb at the corresponding time point (3.0 h) versus baseline conditions under normothermia (NT) and hypothermia (HT). Data are presented as absolute changes for $n = 5$ dogs, mean \pm SE, * $P < 0.05$.

Oral μ HbO₂ increased under hypothermia whereas gastric μ HbO₂ remained unchanged. Oral microcirculation, like gastric microcirculation, is known to represent microcirculation of other gastrointestinal mucosa regions [31, 32]. Our observed results indicate that μ HbO₂ is improved in some regions of the gastrointestinal tract while others remain unchanged. This increase is observed without changes in blood flow or μ DO₂ and might be related to reduced metabolism and thus reduced μ VO₂ under hypothermia. It remains speculative why hypothermia increased oral but not gastric μ HbO₂ during physiological conditions. One explanation could be the difference in local temperature which might be lower in the oral mucosa as a more peripheral compartment compared to the gastric mucosa as a more central organ. Though oral temperature was not measured, this local hypothermia could induce a higher reduction of metabolism and μ VO₂ in the oral compared to the gastric mucosa.

Concerning the effect of hypothermia during hemorrhage we could show in the present study that oral and gastric mucosa are partially protected by hypothermia during hemorrhage. Interestingly, the higher level of μ HbO₂ during hemorrhage under hypothermia is associated with a higher μ DO₂ and an unchanged DO₂. Similarly, μ flow is increased without increase of CO. Thus, the observed effects might

be related to local microcirculatory vasoregulation rather than alterations of systemic circulation. There are several possible reasons for the observed increase of μ HbO₂ and μ flow. μ HbO₂ increases due to increased oxygen supply, that is, DO₂, or due to a reduction of μ VO₂. The reduced oxygen consumption could be related to a reduced oxygen demand or to the inability to extract oxygen. The inability to extract oxygen might be related to the left shift of the oxygen-hemoglobin dissociation curve during hypothermia with an increased oxygen binding capacity of hemoglobin. The measurement of μ flow in our experiments demonstrates that the observed increase of μ HbO₂ seems to be linked to an increased μ flow and μ DO₂ rather than changes of μ VO₂. Thus, the improved oxygenation during hemorrhage in this study seems not to be based on reduced oxygen consumption or to the inability to extract oxygen. The increase of μ flow might be attributed to higher μ Vel and higher μ Hb (Table 2). Increase of μ Hb is particularly desirable whereas high velocity solely can occur in regions with low capillary density and extended diffusion distances. In contrast, μ Hb correlates with the amount of blood in the tissues and thus probably indicates high capillary density.

Being concordant with our results others showed an increase in portal venous flow during hemorrhage [16] while data on microcirculatory oxygenation are lacking so far. In

TABLE 2: Metabolic and respiratory variables of the experimental groups.

Variable	Group	Measuring point 1 (0.5 h)	Measuring point 2 (2.5 h)	Measuring point 3 (3.0 h)	Measuring point 4 (3.5 h)
S _a O ₂ [%]	NT	99 ± 1	99 ± 1	99 ± 1	99 ± 1
	HT	99 ± 1	99 ± 1 [#]	99 ± 1 [*]	99 ± 1 [#]
	NT/HS	99 ± 1	99 ± 1	98 ± 1 [*]	98 ± 1 [*]
	HT/HS	99 ± 1	99 ± 1 [#]	98 ± 1 [#]	98 ± 1 [#]
pCO ₂ [mmHg]	NT	39 ± 1	39 ± 1	40 ± 1	39 ± 1
	HT	40 ± 1	41 ± 1 [*]	40 ± 1	41 ± 1 [#]
	NT/HS	40 ± 1	42 ± 1	45 ± 1 [*]	44 ± 1 [*]
	HT/HS	39 ± 1	40 ± 1 [*]	44 ± 1 [*]	43 ± 1 [*]
pO ₂ [mmHg]	NT	160 ± 4	164 ± 1	161 ± 2	164 ± 2
	HT	157 ± 1	159 ± 2 [#]	156 ± 3	160 ± 3
	NT/HS	155 ± 2	158 ± 2	147 ± 3 [*]	151 ± 2
	HT/HS	158 ± 3	163 ± 3	148 ± 2 [*]	149 ± 3 [*]
pH	NT	7,42 ± 0,01	7,40 ± 0,01 [*]	7,39 ± 0,01 [*]	7,39 ± 0,01 [*]
	HT	7,41 ± 0,01	7,39 ± 0,01 [*]	7,39 ± 0,01	7,38 ± 0,01 [*]
	NT/HS	7,39 ± 0,01	7,38 ± 0,01	7,33 ± 0,01 [*]	7,34 ± 0,01 [*]
	HT/HS	7,41 ± 0,01	7,38 ± 0,01 [*]	7,33 ± 0,01 [*]	7,33 ± 0,01 [*]
Hb [g·100 mL ⁻¹]	NT	12 ± 1	12 ± 1	12 ± 1	12 ± 1
	HT	13 ± 1	13 ± 1 [#]	13 ± 1 [*]	13 ± 1 [#]
	NT/HS	12 ± 1	12 ± 1	12 ± 1	12 ± 1
	HT/HS	12 ± 1	13 ± 1	12 ± 1	12 ± 1
Lactate [mmol·L ⁻¹]	NT	0,6 ± 0,1	0,9 ± 0,1	1,0 ± 0,1	0,9 ± 0,1 [*]
	HT	1,3 ± 0,2 [#]	1,1 ± 0,2 [#]	1,1 ± 0,2 [#]	1,1 ± 0,2 [#]
	NT/HS	0,9 ± 0,3	1,2 ± 0,2	1,3 ± 0,2	1,2 ± 0,2
	HT/HS	0,8 ± 0,1	0,7 ± 0,1	0,7 ± 0,1 [#]	0,7 ± 0,1 [#]

Effect of normothermia (NT), hypothermia (HT), hemorrhage during normothermia (NT/HS), and hemorrhage during hypothermia (HT/HS) on systemic oxygen saturation (SAT), carbon dioxide partial pressure (pCO₂), oxygen partial pressure (pO₂), pH, hemoglobin (Hb), and lactate; data are presented as absolute values, mean ± SE, $n = 5$, ^{*} $P < 0.05$ versus baseline, [#] $P < 0.05$ versus NT for group HT and versus NT/HV for group HT/HV.

contrast to our results, red blood cell flux of the gastric mucosa was reduced during hypothermia in humans [37]. However, this study was conducted during cardiopulmonary bypass with several confounders, for example, extracorporeal circulation, insertion depths of the venous cannulas, or the release of proinflammatory cytokines. Nevertheless, during hemorrhage survival was increased under hypothermia after 24 h in a hemorrhagic shock model in rats [19]. Though bacterial translocation was not studied, other data indicates that regional hypothermia during gut ischemia protects against histological injury and impaired intestinal transit [38]. The reasons for these effects are still unknown but could be attributed to a reduced ischemia/reperfusion injury [39], to induction of heme oxygenase-1 [38], or, according to our results, to an increased splanchnic oxygenation and perfusion.

Besides the potential protective effects of hypothermia negative effects have to be taken into account. It has been shown that hypothermia reduces blood clotting during hemorrhage and reduced survival in trauma patients [40]. Furthermore, hypothermia triggers shivering with a considerable increase of oxygen consumption and patients therefore require deep sedation. Additional negative effects can be

ameliorated by a relatively slow induction phase and a fast rewarming [14]. For these reasons its use will stay restricted to certain conditions, like postcardiac arrest and during heart surgery.

Measurement of flow or μHbO_2 alone cannot serve as an indicator of oxygen supply per se. The assessment of flow does not distinguish between impaired and increased oxygen supply and the measurement of μHbO_2 does not distinguish between increased oxygen supply and the inability to extract oxygen. Our approach to analyze oxygenation and perfusion and thus μDO_2 as well as μVO_2 seems to be more reliable than the singularly approach of other studies analyzing either perfusion or oxygenation. Additionally, splanchnic oxygenation and perfusion are not necessarily linked and thus have to be evaluated separately. Another advantage is our assessment of splanchnic oxygenation at two independent measurement sites. The assessment of μVel and μHb allows evaluation of the reasons for changes in μflow and gives information comparable to intravital microscopy with additional analysis of oxygenation that cannot be assessed by microscopy.

Limitations of This Study. This is an animal study with $n = 5$ dogs. The number of animals seems to be rather small

since we are forced by law to minimize animal experiments. However, the use of a cross-over design where each animal serves as its own control and eliminates interindividual differences warrants the use of a rather small number of animals. However, we did not correct for multiple comparisons. This increases the power to detect differences with small sample sizes. Correcting for multiple comparisons requires a large amount of dogs or reduces the power to detect effects (increasing type II error). This, in contrast, includes an increased chance for type I errors. Thus, the implications of our results have to be interpreted with care and the results of this animal study have to be analysed in a clinical setting in the future.

5. Conclusions

In this study, hypothermia improves oral and gastric μHbO_2 and oral μflow during hemorrhagic shock in dogs. This effect might be explained by an increase of μDO_2 on the basis of increased μflow with unchanged μVO_2 .

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