# Predive Sauna and Venous Gas Bubbles Upon Decompression from 400 kPa

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**Blatteau J-É, Gempp E, Balestra C, Mets T, Germonpre P.** ***Predive sauna and venous gas bubbles upon decompression from 400 kPa.*** **Aviat Space Environ Med 2008; 79:1100–5.**

***Introduction:*** This study investigated the influence of a far infrared-ray dry sauna-induced heat exposure before a simulated dive on bubble formation, and examined the concomitant adjustments in hemodynamic parameters. ***Methods:*** There were 16 divers who were compressed in a hyperbaric chamber to 400 kPa (30 msw) for 25 min and decompressed at 100 kPa · $min^{-1}$ with a 4-min stop at 130 kPa. Each diver performed two dives 5 d apart, one with and one without a predive sauna session for 30 min at 65°C ending 1 h prior to the dive. Circulating venous bubbles were detected with a precordial Doppler 20, 40, and 60 min after surfacing, at rest, and after flexions. Brachial artery flow mediated dilation (FMD), blood pressure, and bodyweight measurements were taken before and after the sauna session along with blood samples for analysis of plasma volume (PV), protein concentrations, plasma osmolality, and plasma HSP70. ***Results:*** A single session of sauna ending 1 h prior to a simulated dive significantly reduced bubble formation [−27.2% (at rest) to 35.4% (after flexions)]. The sauna session led to an extracellular dehydration, resulting in hypovolemia (−2.7% PV) and −0.6% bodyweight loss. A significant rise of FMD and a reduction in systolic blood pressure and pulse pressure were observed. Plasma HSP70 significantly increased 2 h after sauna completion. ***Conclusion:*** A single predive sauna session significantly decreases circulating bubbles after a chamber dive. This may reduce the risk of decompression sickness. Sweat dehydration, HSP, and the NO pathway could be involved in this protective effect.

**Keywords:** diving, decompression sickness, bubble, sauna, heat shock protein, nitric oxide.

THE MOST LIKELY factor for initiating decompression sickness (DCS) is believed to be the formation of inert gas bubbles as a result of supersaturation of dissolved gas in the tissues and blood during decompression. Circulating bubble detection in the venous circulation with Doppler systems is considered an index of safety for diving and is used as a tool for validation of decompression procedures (30). It is generally accepted that the incidence of DCS is low when few or no bubbles are present in the circulation from hyperbaric exposures (13,30,34), whereas this relationship seems more controversial in hypobaric conditions (10,13,33).

Preventive measures to reduce the risk of DCS could involve several predive procedures reported in some experimental studies such as oxygen breathing (8), exercise before diving (3,5,41), intake of exogenous nitric oxide (nitroglycerin) (12), or prehydration (17). Heat stress is a non-pharmacological preconditioning strategy which can lead to protection against various types of subsequent insults, such as ischemia, hypoxia, inflammation, drugs (27), and even bubble-induced injury from decompression (23). It has been suggested that the protective effect of heat exposure against DCS in rats could be related to biochemical processes involving heat shock proteins (HSP) of the 70-kDa range (9,23), and such HSP70 induction could also be involved in the mechanisms responsible for diving acclimatization after repeated compression-decompression cycles (37). Moreover, it has been demonstrated that heat-inducible proteins are also able to interact with the endothelial nitric oxide (NO) pathway (20), which may influence the degree of bubble formation in hyperbaric conditions (40,41).

It is well recognized that high environmental temperatures lead to sweat response, resulting in dehydration. In a previous work, we have also shown that moderate dehydration resulting in stroke volume reduction induced by a predive exercise could decrease venous circulating bubbles in divers (5). The purpose of this study was to determine the efficacy of sauna-induced heat exposure prior to a simulated dive on bubble reduction and to examine the concomittant adjustments in HSP70 concentration and hemodynamic parameters.

## METHODS

There were 16 trained military divers, ages 28–59 yr (38.4 ± 7.7 yr, mean ± SD), who gave their written consent to participate. Their body mass index varied between 21.1 and 29.2 kg · $m^{-2}$ (25.2 ± 2.2 kg · $m^{-2}$, mean ± SD). None of them had experienced DCS in the past. All experimental procedures conformed to the standards set by the latest revision of the Declaration of Helsinki,

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and were approved by the ethics committee of University of Marseille.

*Experimental Protocol*

For the sauna, all subjects were seated for 30 min at 65°C in a far infrared-ray dry sauna system (Personal FIR Sauna, Model 08-12-04, China Golden Eagle Group Co. Ltd, Zhejiang, China) with the head out of the cabin. The sauna session ended 1 h before the simulated dive. In similar conditions, deep body temperature rises about 1°C during sauna exposure (38). The divers were not allowed to drink water during the entire protocol.

For the hyperbaric exposure, divers were compressed in a dry hyperbaric chamber (Sainte-Anne Hospital, Toulon, France) to 400 kPa (30 msw) at a rate of 150 kPa · $min^{-1}$ breathing air and remained at rest for 25 min. They were decompressed at a rate of 100 kPa · $min^{-1}$ with a 4-min stop at 130 kPa (French Navy MN90 procedure). Each diver performed two dives 5 d apart, one without sauna and one with sauna ending 1 h before the dive. The order of the two dives was randomly allocated. They were instructed to avoid physical exertion during the 2 d that preceded each trial. No divers performed diving 1 wk before the experiment.

*Measured Variables*

Blood samples were collected by venipuncture for hematocrit, hemoglobin, plasma proteins, and osmolality after resting in a supine position for 20 min. Measurements were determined 5 min before and 30 min after the sauna session. Percent changes in plasma volume (PV) were calculated using a hemoglobin-hematocrit transformation equation (21). Bodyweight was determined to the nearest 0.01 kg (using a scale model I5S, Ohaus Corporation, Pine Brook, NJ) with the subject wearing only running shorts. Weight measurements were taken immediately before and 35 min after the end of the sauna.

Heart rate (HR) and blood pressure were obtained immediately before each venipuncture by using a portable monitoring system (Propaq 104 EL, Protocol Systems, Inc., Beaverton, OR). Pulse pressure (PP) was defined as PP = SBP − DBP, where SBP and DBP were the systolic and diastolic arterial blood pressure, respectively. Mean arterial blood pressure (MBP) was calculated as MBP = DBP + 1/3(SBP − DBP).

Circulating bubble detection was performed by an experienced operator using a pulsed Doppler equipped with a 2-MHz probe (EZ-Dop®, Compumedics Germany GmbH, Singen, Germany) on the precordial area. Since bubble peak is usually observed 30–60 min after surfacing in similar diving conditions (13,30), monitoring was performed by the same blinded operator every 20 min for 60 min after surfacing (first measurement at 20 min after the dive). During bubble detection, divers were supine for 3 min at rest, then, in order to improve the detection, two successive lower limb flexions were performed. The bubble signal was graded according to the Spencer scale (36) before being converted into the Kissman Integrated Severity Score (KISS). This score takes into account the kinetics of the bubbles at the different recording times and is assumed to be a meaningful linearized measure of post-decompression intravascular bubble activity that may be treated statistically (30).

*Additional Evaluations*

In 10 of the 16 divers, we conducted an additional evaluation of sauna exposure as described above on the arterial response to reactive hyperemia and on HSP70 production without diving afterwards. These data were collected separately in order to avoid disruption of the dive and postdive bubble detection. Postsauna measurements were taken at 30 min, 2 h, 8 h, and 24 h. Venous blood samples were separated from blood cells and stored at −70°C. HSP70 in serum was detected using an in-house sandwich ELISA method previously described (31). HSP70 concentrations were detected by comparing sample absorbance with the absorbance of a reference purified human recombinant HSP70 protein. The absorbance was determined at 490 nm with background substraction at 620 nm using a microplate reader (CERES 900C, BioTek Instruments, Inc., Drongenbos, Belgium).

The arterial response to reactive hyperemia, flow mediated dilation (FMD), was measured before and 60 min after the sauna session at the level of the right brachial artery, according to a protocol previously described (29). FMD was assessed in the subject's right arm in the recumbent position after a 15-min equilibration period in a temperature-controlled room (about 20°C) with a Mindray DP-6600 (Mindray Shenzhen Bio-Medical Electronics Co., Ltd, Shenzhen, China) and a 7.5-MHz linear array transducer. FMD was measured according to the accepted protocol (11) with some additional aids in order to adequately choose the right moment to measure the maximal artery dilation after the cuff release (5 min of total occlusion of the brachial artery using a sphygmomanometer inflated at 250 mmHg). This was achieved by means of digital pulse plethysmography constantly measured after the cuff release. The echographic measurement was performed when the plethysmographic trace showed the maximal pulse with no further increase for the next 5 s.

*Statistical Analysis*

Data are presented as mean ± SD. Statistical tests were run on Sigmastat 3.0 software (SPSS Inc., Chicago, IL). Data were analyzed using nonparametric statistics because of the small sample size. The Wilcoxon signed rank test was used for paired data, whereas comparisons in different times for HSP70 kinetics were evaluated by Friedman test (repeated measures ANOVA on ranks). Differences between groups were considered significant at $P < 0.05$.

## RESULTS

None of the divers suffered from DCS postdive. The overall distribution of bubbles was not modified; the

maximum bubble count was observed 40 min after surfacing following the respective protocol (with or without sauna). The 30 min of sauna ending 1 h before the dive significantly reduced KISS bubble grades at rest (−27.2%; mean KISS 1.95 vs. 7.17, $P = 0.031$; **Fig. 1**) and after two lower limbs flexions (−35.4%; mean KISS 3.6 vs. 10.18, $P = 0.039$). Only one diver showed a slight increase in venous bubble grade after the sauna treatment.

PV decreased by 2.7% after the sauna ($P < 0001$). Plasma proteins significantly increased by 3% after the sauna (73.1 ± 2.9 vs. 70.9 ± 2.8 mg · $L^{-1}$, mean ± SD; $P < 0001$), whereas there were no significant differences in plasma osmolality before or after the sauna. We also observed a significant reduction of bodyweight by 0.6% after the sauna (−450 ± 18 g, mean ± SD; $P < 0.001$). SBP and PP decreased significantly (112 ± 10 vs. 119 ± 13 mmHg, $P = 0.013$ and 40 ± 17 vs. 46 ± 19 mmHg, mean ± SD; $P = 0005$, respectively), whereas DBP and MBP remained unchanged after the sauna. HR was not modified by the sauna.

Subjects performing a single sauna session had significantly elevated plasma HSP70 concentrations from baseline values 2 h after sauna completion (mean HSP values 1939 vs. 729 ng · $L^{-1}$, $P = 0.005$) with no significant differences at 30 min, 8 h, and 24 h (**Fig. 2**). We found a significant increase of FMD, observed 1 h after the sauna completion from baseline values measured 15 min before the sauna exposure (13 ± 2.8% vs. 7.7 ± 3%, mean ± SD; $P = 0002$).

## DISCUSSION

The main result of our study is that a single predive sauna session significantly decreased circulating bubbles. However, the mechanisms underlying the protective effect of heat exposure on decompression remain unclear and numerous parameters should be evaluated. Our working hypothesis is that heat preconditioning could contribute to reducing bubble burden by reducing nitrogen load during the dive and/or altering the population of gaseous nuclei from which bubbles form (3,4).

Based on theoretical considerations, the growth and stability of a gas bubble are affected by the surface tension of the fluid; a low surface tension favors all aspects

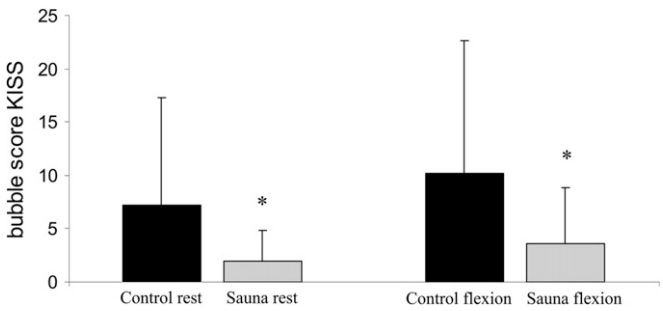


**Fig. 1.** Mean KISS bubble scores expressed at rest and after two lower limb flexions following hyperbaric exposure to 400 kPa (30 msw) for 25 min. Black bars represent controls and gray bars conditions with sauna ending 1 h prior to the dives. * denotes $P < 0.05$.

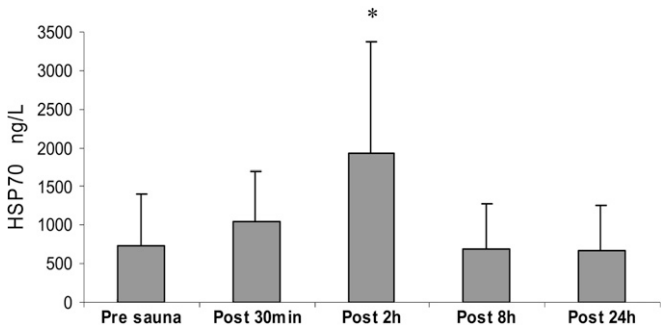


**Fig. 2.** Expression of plasma HSP70 (mean ± SEM) before and after far infrared ray sauna exposure (65°/30 min) in 10 subjects. * denotes $P < 0.05$.

of bubble development (39). It has been demonstrated experimentally that bubble formation after decompression in pigs was inversely proportional to serum surface tension (22), and it seems plausible that plasma surface tension might be elevated in well-hydrated divers (39). However, there is a lack of human data concerning the impact of surface tension on the course of bubble formation, and it remains to be established whether this parameter can be a decisive factor in DCS development (17). Possible ways of influencing changes in surface tension are numerous and not yet fully understood.

Although dehydration is commonly proposed as a risk factor for DCS in divers, there are no data that support this assertion in man. Animal studies are few and give contradictory results (7,14,28,35). In water-deprived rats, a trend toward fewer venous circulating bubbles than in the control animals has also been observed with a Doppler technique (35). On the other hand, one experiment in a rabbit model with analysis of electrophysiological parameters showed that preexisting and severe extracellular dehydration appeared to be a major factor in spinal cord injury during severe decompression (28). Another trial also supported the idea that normally hydrated pigs had a lower risk of severe DCS and death than those subjected to a severe fluid intake restriction and diuretic administration (14). Conversely, we have recently shown that moderate dehydration induced by predive exercise and declining stroke volume related to post-exercise hypovolemia might influence inert gas load and consequently decrease circulating bubbles (5). Finally, moderate dehydration could be beneficial for bubble formation, while severe dehydration appears to increase the risk of DCS.

It is well established that heat exposure provokes hypovolemia, which results from sweat response and dehydration (19,26). These data are consistent with our results that clearly show an extracellular dehydration associated with plasma volume reduction. The variables that determine the rate of inert gas uptake by any tissue in the body may be expressed as a simplified mass balance equation: $S_t(dP_t/dt) = Q \cdot S_b \cdot (P_a - P_v)$, where $S_b$ and $S_t$ are the solubilities of the gas in blood and tissue, Q is the blood flow, $P_t$ is mean tissue gas tension, and $P_a$ and $P_v$ are the gas tensions in arterial and venous blood. The uptake or release of gas by a particular tissue

depends on both the rate of blood flow to the tissue and the rate of gas diffusion into the tissue from blood. It may be seen that if blood flow Q is lower, the rate of inert gas uptake would be slower, and consequently bubble formation would be reduced (16). Declining stroke volume is the primary problem encountered with dehydration and hypovolemia, and since HR was unchanged after the sauna in our study, we hypothesized that Q could be reduced at the start and during the dive, thus limiting inert gas load and bubble formation afterwards. On the other hand, the reduction in cardiac output may decrease inert gas uptake, but can also reduce inert gas removal during decompression. Not only does cardiac output change uptake and removal, but also the blood flow distribution to various tissues. The latter may affect uptake and removal independently of total blood flow rate and such response is likely after a heat exposure. Further studies are needed to elucidate these questions.

The potential for a change in the subjects' body temperature may have influenced the subsequent solubility of nitrogen. The phase of the dive determines the effect that the thermal state will have upon decompression. A diver who is cold during decompression will eliminate less nitrogen, while a diver who is cold at depth will absorb less nitrogen. Divers who were cold at depth during no-decompression diving were shown to have fewer intravascular bubbles than warm divers. A diver who absorbs additional nitrogen at depth because he is warm will have an increased risk of decompression sickness compared with cold divers (2,16). Actually, a recent animal experiment did not confirm these data on DCS risk (15), while another study with divers has demonstrated that the deleterious effects of warm conditions during bottom time were less pronounced than the beneficial effects of warm conditions during decompression (18). Since heat exposure at depth should increase bubble formation, we believe that the thermal effects from the predive sauna session are not directly involved in reducing bubble formation in our study. Although we did not measure the deep body temperature of our divers, an elevation of 1°C was found in similar far infrared-ray sauna conditions (38), but it is likely that temperature re-equilibrated 1 h after the sauna completion. Our main hypothesis is that sauna-induced hypovolemia resulting from sweat dehydration may reduce inert gas uptake and bubble formation. Moreover, since immersion and exercise can also modify hemodynamic status and increase dehydration (6), it would be interesting to perform this survey in an underwater environment using subjects who had been rehydrated before diving as controls.

We found a significant increase in plasma HSP70 2 h after heat exposure completion. HSP are present in most cells, including endothelial cells, and play a key role in normal cellular homeostasis and cell protection from damage in response to stress stimuli. Researchers have subsequently demonstrated that most HSP have strong cytoprotective effects, are involved in many regulatory pathways, behave as molecular chaperones for other cellular proteins, and help the cell to cope with oxidative stress (27). The most abundantly and best studied HSP are the 70 kDa families. HSP70 are the most temperature sensitive and highly conserved of HSP. It is argued that hyperthermic preconditioning involves upregulated amounts of HSP70 associated with protective effects on DCS in animals. Indeed, it has been observed that heat shock pretreatment 4 h before a hyperbaric exposure could increase HSP70 in the lung and reduce the incidence of severe DCS in rats, but this failed to reach statistical significance. However, in the same study, prior heat exposure could attenuate lung injury induced by venous air embolism, the pathophysiology of which is similar to acute DCS (23).

Another animal study confirmed that heat shock pretreatment before diving induced HSP70 production and could increase the survival rate: whereas 11 of 12 control rats died, 6 out 12 rats survived in the heat shock group preconditioned 24 h before the hyperbaric exposure (9). Protection from air bubble-induced tissue injury may result from a smaller number of bubbles and/or from less tissue reaction to air bubbles. Numerous regulatory pathways should be considered in the real bioprotective mechanism of HSP70. Indeed, the complement system, leukocytes, clotting factors, and oxygen metabolites, are proven factors that mediate air-bubble-induced tissue injury. It has been demonstrated that gas bubbles lead to a dose-dependent increase in complement activation C5a, potentially influencing expression of adhesion molecules (1).

Morever, recent studies in animal models of acute lung injury demonstrated that the activation of HSP may attenuate the damage caused by oxidative stress in the lung by a direct inhibition of proinflammatory mediators (including adhesion molecules such as ICAM-1), and also by an inhibition in the sequestration of neutrophils in pulmonary capillaries (32). From the above findings, there is a need for additional studies that should provide information about the mechanisms regulating the stress protein responses during DCS. The role of HSP appears more related to the attenuation of tissue reaction to vascular bubbles than in a direct bubble reduction process.

It has been demonstrated that endothelial nitric oxide (NO), an important vasodilator with antiatherogenic properties, can attenuate bubble formation and DCS incidence, probably by reducing gaseous nuclei from which bubbles form (40,41). Since endothelial nitric oxide synthase (eNOS) is regulated by HSP90, a heat inducible protein, several investigators have focused on the interaction of eNOS with HSP90. Harris et al. (20) observed in rats that moderate heat shock (core temperature: 42°C, 15 min) increases HSP90 and HSP70 protein levels and vascular eNOS expression, which is associated with increased eNOS activity and endothelial-derived NO release as well as NO-mediated attenuation of vasoconstriction in isolated vessels. However, they also demonstrated that a longer heat exposure (42°C, 1 h) of endothelial cells results in an increase in eNOS protein content with no change in HSP70 and HSP90 expression, suggesting that the heat-induced change in eNOS expression could be induced by other mechanisms.

The cardiovascular effects of saunas have been previously reviewed. During a sauna, skin temperature increases rapidly and sweating begins quickly, reaching its maximum at about 15 min. Cardiac output is increased in relation to the increase in heart rate (19). Repeated sauna therapy is able to upregulate eNOS and increases NO production after 4 wk in hamsters (24). Using a noninvasive ultrasound method evaluating NO-dependent endothelial function (%FMD), it has been shown that 2 wk of repeated infrared dry sauna can improve impaired vascular endothelial function in patients with coronary risk factors (25). Whereas a single session of a sauna bath is able to decrease DBP and systemic vascular resistance in patients with severe congestive heart failure (38), the effect of a single sauna session on blood pressure remains variable in healthy subjects (19). In our study, we were able to confirm an increase in %FMD, suggesting an NO-mediated effect on endothelial function after a single sauna session (11). This was partially reflected in the observed reduction of SBP and PP observed 30 min after the sauna. It remains unclear, however, whether this NO-mediated endothelial function improvement is directly related to the HSP increase, or whether a different process is involved. Therefore, predive aerobic exercise performed within 24 h, including sweat dehydration, a potential increase in body temperature and HSP, and a rise in endothelial NO, may provide some of the observed benefits as identified in this paper.

This study demonstrated that a single sauna session ending 1 h before a simulated dive significantly attenuated the number of bubbles in the right heart of divers. This could offer a new way of reducing decompression sickness risk. Sauna-induced hypovolemia resulting from moderate dehydration might influence inert gas load and bubble formation. Further investigation is required to elucidate the preponderant mechanism underlying this heat exposure induced reduction in bubble formation.

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