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ORIGINAL ARTICLE

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Effects of repeated carbon dioxide-rich water bathing on core temperature, cutaneous blood flow and thermal sensation

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Abstract We examined the effects of repeated artificial CO_2 (1,000 ppm) bathing on tympanic temperature (T_{ty}), cutaneous blood flow, and thermal sensation in six healthy males. Each subject was immersed in CO_2-rich water at a temperature of 34°C up to the level of the diaphragm for 20 min. The CO_2-rich water was prepared using a multi-layered composite hollow-fiber membrane. The CO_2 bathing was performed consecutively for 5 days. As a control study, subjects bathed in fresh water at 34°C under the same conditions. T_{ty} was significantly lowered during CO_2 bathing ($P < 0.05$). Cutaneous blood flow in the immersed skin (right forearm) was significantly increased during CO_2 bathing compared with that during fresh-water bathing ($P < 0.05$), whereas cutaneous blood flow in the non-immersed skin (chest) was not different between CO_2 and fresh-water bathing. Subjects reported a "warm" sensation during the CO_2 bathing, whereas they reported a "neutral" sensation during the fresh-water bathing. The effects of the repeated CO_2 bathing were not obvious for core temperature and cutaneous blood flow, but the thermal sensation score during the CO_2 bathing was reduced sequentially by repeated CO_2 bathing ($P < 0.05$). These thermal effects of CO_2 bathing could be ascribed largely to the direct action of CO_2 on vascular smooth muscles and to the activity of thermoreceptors in the skin. Serial CO_2 bathing may influence the activity of thermoreceptors in the skin.

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Introduction

In Europe, carbonated springs have been used for balneotherapy of patients with hypertension or peripheral occlusive arterial disease. The physiological and clinical investigations performed on the effects of CO_2 on the cutaneous microcirculation suggest that the effects of carbonated spring water depend mainly upon the cutaneous vasodilation elicited by the CO_2 that diffuses into the subcutaneous tissues through the skin layers (Stein and Weinstein 1942; Diji 1959; Schnizer et al. 1985; Komoto et al. 1986; Ito et al. 1989; Hartmann et al. 1997). It has also been suggested that carbonated spring water exerts thermal effects, but studies on these effects are few (Gollwitzer-Meier 1937; Jordan 1985).

CO_2-rich water has been used to examine thoroughly the physiological effects of CO_2 bathing. Artificial CO_2-enriched water has been prepared by various methods, for example by dissolving tablets containing sodium bicarbonate and succinic acid in hot fresh water (Yorozu et al. 1984, 1985) or by bubbling CO_2 gas into ordinary bath water (Stein and Weinstein 1942; Ito et al. 1989). Carbonated spring water has been defined as containing more than 1,000 ppm of CO_2 (Schmidt 1989). With these methods, however, it is difficult to maintain the CO_2 concentration constantly above 1,000 ppm for a number of hours.

Recently, a device for obtaining CO_2-rich water with a concentration of 1,000 ppm using a special membrane (a multi-layered composite hollow-fiber membrane) has been developed (Kamo et al. 1985). In the study presented here, we employed this membrane method to investigate the effects of CO_2 at a concentration of 1,000 ppm on core temperature, cutaneous blood flow, and thermal sensation. We also studied the modifications of these effects evoked by serial bathing for five consecutive days.

Methods

Six male subjects aged [mean (SE)] 22.2 (0.9) years [height 173.5 (1.8) cm, weight 72.7 (2.6) kg] participated in the study. The subjects were informed of the potential risks involved and the purposes of the study (which were approved by the Ethics Committee, Aichi Medical University School of Medicine), after which they provided written informed consent to participate. None of the subjects had either cardiovascular abnormalities or skin lesions. All of the experiments were performed at the same time of the day in a climatic chamber, the ambient temperature and the relative humidity of which were maintained at 28.0 (0.5)°C and 40 (3)%, respectively.

Each subject, after entering the climatic chamber, assumed a recumbent position on a reclining chair for 30 min (rest stage). Subsequently, the subject immersed his right forearm in fresh water at 34°C, which was contained in a plastic bucket (pre-bathing stage; Fig. 1). After 15 min the subject withdrew his forearm from the water, and then quickly immersed his body, including both arms, up to the level of the diaphragm in CO_2-rich water (1,000 ppm) that was maintained at a temperature of 34°C (bathing stage). After the body immersion for 20 min, the subject left the bath and again immersed his right forearm in fresh water at 34°C for 15 min (post-bathing stage). The reason why the right forearm was immersed in water at 34°C during the pre- and post-bathing stages was to keep the skin temperature at the site of blood flow measurement constant throughout the pre-bathing, CO_2 bathing, and post-bathing stages. When cutaneous blood flow is compared at a skin site between the different stages, it should be measured at the same level of skin temperature since it has been suggested that cutaneous blood flow may be influenced by local skin temperature under the constant intensity of vasomotor nerve activity (Hales et al. 1978). The CO_2 bathing was repeated for five consecutive days. A few days prior to the serial CO_2 bathing, control studies were performed under the same conditions using fresh-water instead of CO_2-rich water.

The CO_2-rich water was prepared by dissolving CO_2 in tap water using a multi-layered composite hollow-fiber membrane (Mitsubishi Rayon Engineering, Tokyo, Japan; Kamo et al. 1985). The CO_2 concentration was adjusted so that it was maintained at 1,000 ppm (pH 4.5–4.6) throughout the bathing. The CO_2-rich water was colorless and odorless.

Tympanic temperature (T_{ty}) was measured with the aid of a thermistor (ST-21S, Sensor Technica, Aichi, Japan) inserted into the ear canal. The ear pinna was filled with a mass of cotton to fix the thermistor probe in place and to interrupt the transfer of heat and moisture. Cutaneous blood flow was measured on the right chest and the right forearm by laser-Doppler flowmetry (LDF). In the right forearm, which was immersed in fresh water during the stages of pre- and post-bathing and in CO_2-rich water during the bathing stage, the cutaneous blood flow was measured with an LDF probe attached at a distance of 3 mm from the skin surface (non-contact-type measurement: FLO, Omegawave, Tokyo, Japan). On the chest, which was not immersed throughout the experiment, the cutaneous blood flow was measured with an LDF probe that made close contact with the skin surface (contact-type measurement: ALF-21, Advance, Tokyo, Japan). Laser-Doppler instruments with a time constant of 1 s were used. T_{ty} and cutaneous blood flow were monitored continuously on a multi-channel pen-recorder (R-5X2RS, Rikadenki Kogyo, Tokyo, Japan). Attention was paid to maintaining the depth of the LDF probe under the water and that of the vertical distance from the probe to the heart when the forearm was immersed. T_{ty} and blood flow data were stored on a personal computer (PC-9821N, NEC, Tokyo, Japan). Data averages per minute were calculated at a later time.

Thermal sensation was assessed by the subjects every 5 min after the start of the pre-bathing, 1 min before and after the start of CO_2 bathing, and 1 min before and after the end of CO_2 bathing (Fig. 1). Thermal sensation was evaluated according to the conventional seven-point scale (Hardy 1970) comprising cold (1), cool (2), slightly cool (3), neutral (4), slightly warm (5), warm (6)and hot (7). The resulting scores were subjected to statistical analysis.

The differences between the CO_2 and fresh-water bathing were assessed by the paired *t*-test. The effects of repeated CO_2 bathing for 5 days were tested by Friedman's nonparametric analysis of variance. The Bonferroni-corrected Wilcoxon test was employed for comparison between the different day points. The level of statistical significance was set at $P < 0.05$. All data are expressed as mean (SE).

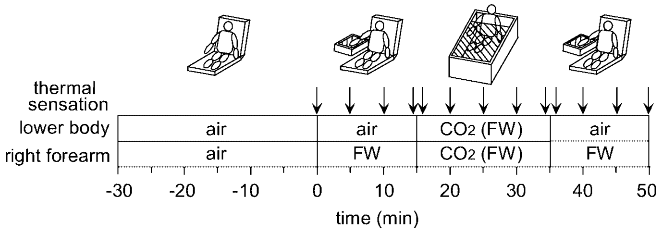

Fig. 1. Experimental set up for CO_2 and fresh-water (*FW*) bathing. Parentheses indicate control experiments. *Arrows* indicate the time at which thermal sensation was assessed by the subject

Results

Acute effects: 1st day experiment

Figure 2 shows the responses of T_{ty} to CO_2 and fresh-water bathing in all the subjects. T_{ty} declined slightly throughout the pre-bathing stage of both the CO_2 and fresh-water experiments. In the CO_2 experiments T_{ty} declined more rapidly during the bathing stage than during the pre-bathing stage, whereas in the fresh-water experiments T_{ty} continued to decline throughout the bathing stage at nearly the same rate as during the pre-bathing stage. Consequently, a difference of about 0.2°C was found at the end of bathing between the CO_2 and fresh-water bathing. Thus, T_{ty} was significantly lower in the CO_2 bathing than in the fresh-water bathing for a period of approximately 15 min from the later stage of CO_2 bathing to the early stage of post-bathing. T_{ty} then began to rise.

Figure 3 shows the responses of cutaneous blood flow in the right forearm and the chest to CO_2 and fresh-water bathing for all the subjects. A flush was

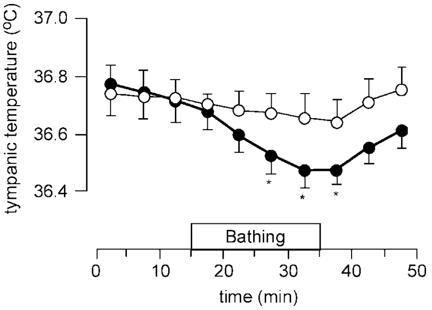

Fig. 2. Effect of CO_2 bathing (●) and fresh-water bathing (○) on tympanic temperature (T_{ty}) obtained on the 1st day of serial bathing from six subjects. Values are mean ± SE. *Significant difference CO_2 and fresh-water bathing ($P < 0.05$)

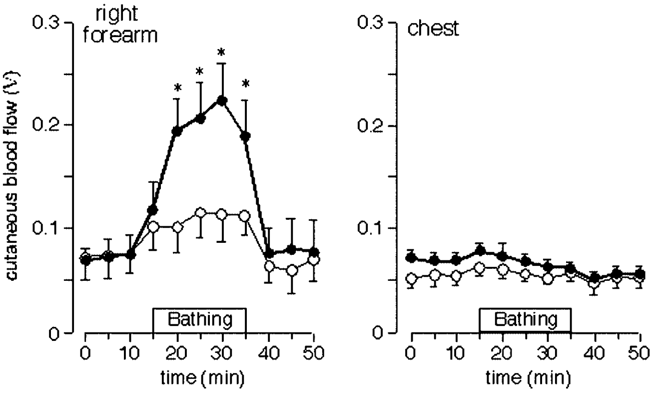

Fig. 3. Effect of CO_2 bathing (●) and fresh-water bathing (○) on cutaneous blood flow in the right forearm and the chest obtained on the 1st day from six subjects. Values are mean ± SE. *Significant difference between CO_2 and fresh-water bathing ($P < 0.05$)

observed over the immersed skin immediately after the start of the CO_2 bathing. Simultaneously, cutaneous blood flow in the immersed skin (right forearm) increased greatly, and during the CO_2 bathing reached 200–250% of the pre-bathing control value. The rate of increase was greatest during the first 10 min of CO_2 bathing, and then tended to lessen. A rapid decrease of cutaneous blood flow occurred after the subjects withdrew from the bath. In contrast, during the fresh-water bathing, cutaneous blood flow in the immersed forearm increased only slightly. A significant difference in cutaneous blood flow was found between CO_2 bathing and fresh-water bathing, during the bathing period. In the non-immersed skin (chest), cutaneous blood flow was not altered by the CO_2 bathing, and no significant differences were found in this parameter between the CO_2 and fresh-water bathing.

Figure 4 shows the changes in thermal sensation for all of the subjects. Each subject reported a "neutral" score during the pre-bathing stage. The thermal sensation score was then elevated to "slightly warm" during the CO_2 bathing, whereas it remained "neutral" during the fresh-water bathing. The score was significantly higher in the CO_2 bathing than in the fresh-water bathing after 5–20 min of the bathing period. After the subjects withdrew from the bath, in either the CO_2 or fresh-water bathing, the thermal sensation turned transiently to "cold", and thereafter gradually recovered toward "neutral".

Effects of serial CO_2 bathing

In any subject, the pattern of the rather rapid decline of T_{ty} during the CO_2 bathing was similar to each other among the 5 days. Figure 5a illustrates the 5-day trend of the magnitude of the depression of T_{ty} observed during the CO_2 bathing, where this magnitude is expressed as the difference between the pre-bathing control value and the value at the end of the bathing. The magnitude of the depression in T_{ty} did not change significantly throughout the 5 days ($P = 0.465$).

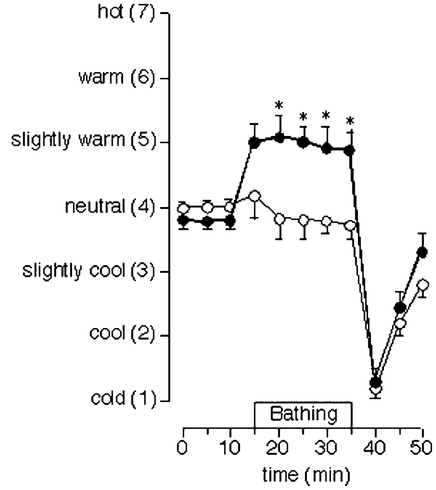

Fig. 4. Effect of CO_2 bathing (●) and fresh-water bathing (○) on thermal sensation during CO_2 bathing obtained on the 1st day from six subjects. Values are mean ± SE. *Significant difference between CO_2 and fresh-water bathing ($P < 0.05$)

Figure 5b shows the 5-day trend of the magnitude of the increase in cutaneous blood flow evoked by the CO_2 bathing. In this figure, the magnitude of this increase is represented as the percent change between the pre-bathing control value and the value at the end of the bathing. Although the increase in cutaneous blood flow was reduced temporarily on the 3rd day, the change over the 5 days was not significant ($P = 0.308$). No significant difference was noted in any comparison between the two different day points.

In contrast, serial bathing exerted an effect on thermal sensation. Figure 5c shows the 5-day trend of the elevation in thermal sensation caused by CO_2 bathing. This elevation is expressed as the difference in the score between the pre-bathing control period and the end of the bathing. It is evident that the magnitude of the elevation of thermal sensation was reduced sequentially for the first 3 days. The reduction was significant when tested throughout the 5 days of the experiment ($P < 0.05$), although no significant difference was noted in any comparison between the two different day points.

Discussion

The results of the study presented here indicate that CO_2 bathing produces a decline in core temperature, an increase in cutaneous blood flow, and an elevation of the score on thermal sensation, confirming the thermal effects of CO_2 bathing suggested previously (Gollwitzer-Meier 1937; Jordan 1985).

It is well known that CO_2 applied topically to the skin increases cutaneous blood flow (Diji 1959; Komoto et al. 1986; Ito et al. 1989; Hartmann et al. 1997). This effect is exerted as a direct action of CO_2 on the skin vessels,

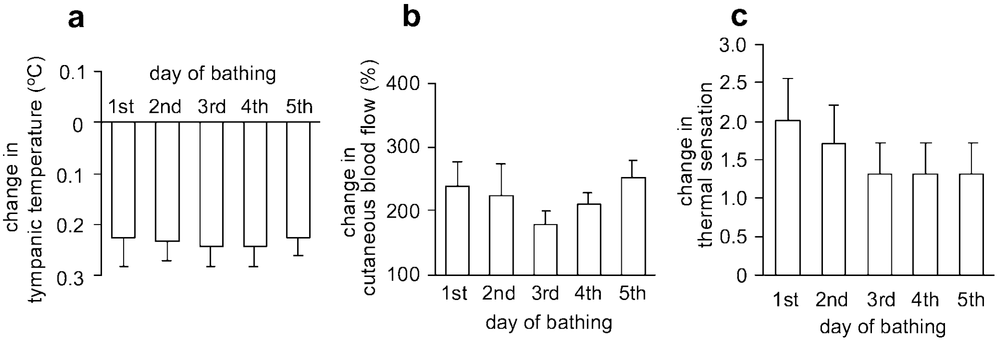

Fig. 5. Effect of serial CO_2 bathing on T_{ty} (**a**), cutaneous blood flow in the right forearm (**b**) and thermal sensation (**c**) for six subjects. Values are given as mean ± SE. The reduction of thermal sensation was significant when tested over the 5-day period (Friedman's test). See text for detailed explanation

evidence of which is provided by the observations that the denervated skin exhibits vasodilative effects (Ito et al. 1989) and that an elevation of subcutaneous CO_2 tension (PCO_2) occurs only in the skin immersed in CO_2-rich water (Komoto et al. 1986). However, the mechanism of the action of CO_2 on the smooth muscle of skin blood vessels has only been partially defined.

A plausible mechanism for CO_2-induced vasodilation is associated with extracellular acidosis. Previous studies have demonstrated that acidosis might reduce the contractility of the vascular smooth muscle, leading to vasodilation (Tobian et al. 1959; Vanhoutte and Clement 1968). The reduction in smooth-muscle contractility has been ascribed to a reduction in calcium influx or to the suppression of myofilament contractility (Breemen et al. 1972; Fabiato and Fabiato 1978). An in-vitro study that examined the contractility of the rat aorta when exposed to a small change in pH (from 7.4 to 7.0) demonstrated that even this small change in pH could reduce vascular smooth muscle contractility (Loutzenhiser et al. 1990). That study also indicated that H^+-induced vasodilation is associated with an increase in the amount of calcium sequestered into the norepinephrine-sensitive intracellular calcium store. Recently, work on the coronary, cerebral and aortic circulations has shown that nitric oxide (Fukuda et al. 1990; Gurevicius et al. 1995; Aalkjær and Peng 1997), or the activation of potassium channels (Ishizaka and Kuo 1996) may contribute to this acidosis-induced vasodilation.

It has been reported that CO_2 inhalation produces cutaneous vasodilation as well as drastic increases in the thermoregulatory sweating that accompanies hypothermia (Bullard 1964). The tentative mechanism underlying this phenomenon is that hypercapnia acts on the thermoregulatory center located in the pre-optic/anterior hypothalamus to lower the set-point temperature for body temperature regulation (Matsumura et al. 1987; Ogawa and Sugenoya 1993). It is documented that about 30 $ml \cdot min^{-1} \cdot cm^{-2}$ CO_2 is absorbed from the skin surface during whole-body bathing (Schmidt 1989). Since CO_2 absorbed through the skin during bathing is expired quickly, the blood CO_2 concentration will not be elevated (Schmidt 1989). Although the subjects inhaled CO_2 gas during bathing that was released from the bath water (Yorozu et al. 1985), it is thought that the CO_2 concentration of the air inhaled while bathing in water containing 1,000 ppm CO_2 is not high enough to elevate the blood concentration to a level at which hypercapnic effects may be elicited. In the present experiments, blood CO_2 concentration was not measured, but it is unlikely that the CO_2 effects observed in the present study were mediated by a central mechanism. This is supported by the observation that vasodilatory effects were not observed on the chest skin, which was not immersed in the CO_2-rich water during bathing (Fig. 3).

The decline in core temperature during the CO_2 bathing could be explained largely by increased cutaneous blood flow. In CO_2 bathing, increased cutaneous blood flow due to cutaneous vasodilation may facilitate heat transfer from the body to water. Since heat conduction in water is extremely high compared with air (25:1) an increase in cutaneous blood flow may elicit excess heat loss even if the water temperature is thermoneutral. It is unlikely that this decline in core temperature was caused by a lowered set-point temperature since it is assumed, as described above, that the activity of the central thermoregulatory mechanism was not altered by CO_2 bathing.

Although T_{ty} was significantly lowered during the CO_2 bathing, the subjects reported a "slightly warm" sensation during the CO_2 bathing (Fig. 4). It has been demonstrated that CO_2 inhibits the activity of cold receptors and facilitates that of warm receptors of the skin (Dodt 1956). Such modifications in the activity of skin receptors by CO_2 can explain the elevation of thermal sensation during CO_2 bathing, since thermal sensation is caused predominantly by the signals from the skin receptors, rather than central receptors (Hensel 1981). Whether the increased blood flow per se, by elevating the temperature of the subcutaneous tissue surrounding the thermoreceptors, contributes to the elevation of thermal sensation during CO_2 bathing is uncertain. Regardless of the causative mechanism, the water temperature at which subjects feel a "neutral" sensation may be lowered by 2°C during CO_2 bathing (Schmidt 1989).

Carbonated spring water has been used for the treatment of peripheral vascular diseases. It is assumed that the rationale for CO_2 therapy depends largely upon the vasodilatory effects of CO_2. To attain long-lasting, stable effects of CO_2 for peripheral vascular diseases, CO_2 bathing is usually repeated. Hildebrandt and Steinke (1962) examined the effects of 11 days of consecutive CO_2 bathing on peripheral circulatory resistance, and indicated that this parameter was improved as CO_2 bathing progressed, although transient deteriorations might occur.

In the present study, serial CO_2 bathing did not produce a sequential change in core temperature depression during the observation period of 5 days (Fig. 5a). This observation implies that the rate of heat loss due to cutaneous vasodilation was not altered during the 5 days, but this is not in agreement with the gradual improvement of peripheral circulatory resistance observed during serial CO_2 bathing reported by Hildebrandt and Steinke (1962). A possible reason for this discrepancy may be that the CO_2 exposure of 5 days was too short to evaluate such sequential effects.

Characteristically, a sequential reduction in the elevation of thermal sensation during bathing was observed over the 5 days of serial CO_2 bathing. Two mechanisms are suggested accordingly: first, the central integrating mechanism was altered during the serial CO_2 bathing, and secondly, the modifications of the activities of skin thermoreceptors by CO_2 application were altered. We have no direct evidence for the first central mechanism, but the second peripheral mechanism is more plausible. Sunakawa et al. (1986) examined the tissue $P\text{CO}_2$ before and after a series of CO_2 bathing for 4 weeks, and observed that whereas subcutaneous tissue $P\text{CO}_2$ was increased by 27% in the first bathing, it was increased by only 10% after the serial bathing. From these results they speculated that the suppression of the increase rate in tissue $P\text{CO}_2$ during CO_2 bathing was associated with an increased washout rate of CO_2 due to improved tissue perfusion, and not caused by a decreased permeability of CO_2 through the skin. If the elevation of subcutaneous $P\text{CO}_2$ during CO_2 bathing is suppressed sequentially by serial bathing, it is expected that the modification of the activity of skin thermoreceptors by CO_2 is diminished in degree, so that the elevation of thermal sensation score by CO_2 bathing is sequentially suppressed. However, a question still remains as to why in the present study, the cutaneous blood flow rate did not show sequential enhancement in response to serial CO_2 bathing.

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