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Heat-retention effects of hydrogen-rich water bath assessed by thermography for humans

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ABSTRACT

Hydrogen-rich water bath devices are commercially available, but have been scarcely clarified for heat-retention effects. In this study, heat-retention effects of hydrogen-rich water bath were assessed by thermographic clinical trials, which employed twenty-four healthy subjects. The thermograms indicated that, under the same conditions (41 °C, 10-min bathing), hydrogen-rich water bath (hydrogen concentrations: 185–548 μg/L; oxidation-reduction potentials: −167 to −91 mV, versus 0.8 μg/L and +479 mV for normal bath, respectively) brought about the heat-retention being more marked than those of normal water bath for several body-parts in the order as follows: abdomen > upper legs > arms > hands > feet, for 30- and 60-min post-bathing, being in contrast to scarce heat-retention for head, armpits and lower legs. Then, as reflection to promotive effects on blood stream, we also examined the thickness of fingertip-capillary in hands. The thickness was expanded in the hydrogen-rich water bath more markedly than that in the normal water bath, suggesting that the hydrogen-rich water bath may have the hydrogen-based promotive effect, exceeding over mere heat retention-based effects, on blood circulation of the whole body. Meanwhile, the heat-retention in hydrogen-rich water bath weakly or moderately correlated with contents of the subcutaneous fat, whole body fat and body mass index, and inversely correlated with skeletal muscle rates, although their correlation degrees did not obviously exceed over normal water bath, with a poor relation with the basal metabolism rate. Thus, the hydrogen-rich water bath was suggested to exert heat-retention effects exceeding over normal water bath, in diverse body-parts such as abdomen, upper legs, arms and hands, via promotion to blood flow which was reflected by expanding the thickness of capillary. The heat-retention after bathing can be noted as effects of the hydrogen-rich water bath, which is applicable for most of people widespread regardless of their body composition index.

1. Introduction

Nowadays, the so-called “hydrogen society” is being realized from the viewpoint of sustainable energy source (Aymar et al., 2001; Brandon and Kurban, 2017; Kreuter and Hofmann, 1998; Winsche et al., 1973), and on the other hand, there are many reports showing various medical applications of hydrogen water (Asada et al., 2019; Kajisa et al., 2017; Kato et al., 2020; Yoritaka et al., 2018). In the human body, reactive oxygen species (ROS) are generated through oxygen respiration, and excess ROS are neutralized by the antioxidant enzyme system (Nantapong et al., 2019). However, the activity of the antioxidant enzyme system is deteriorated by stress of daily life or aging, in which case excess ROS can be a factor in various diseases (Chwa et al., 2006; Valko et al., 2006). Hydrogen scavenges harmful hydroxyl radicals to generate water as the resultant product, so there is little concern about side effects (Ohsawa et al., 2007; Ohta, 2011). Therefore, it is expected that the exogenously administered hydrogen can partially supplement the deterioration of the antioxidant enzyme system and potently support our health.

It is generally considered that bathing is useful for alleviating stress in daily life, promoting metabolism, and maintaining and improving immunity such as relative $CD8^+$ T lymphocyte and NK (natural killer) cell activity (Blazickova et al., 2000). For example, it is known that carbon dioxide-containing hot springs promote the efficient blood circulation and bring the excellent heat-retention properties, and commercially available bath salts usually contain sodium hydrogen

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carbonate. Recently, the home hydrogen-rich water bath devices that generate hydrogen by electrolyzing warm water are commercially available (Tanaka et al., 2018). In our previous study, it was confirmed that hydrogen water scavenged oxidative stress and prevented agglutination of erythrocytes to promote blood flow in an in vitro rheological test using horse blood (Kato et al., 2012). However, the effect of hydrogen-rich water bath has not been sufficiently clarified. In the present study, we verified the heat-retention effect of hydrogen-rich water bath versus normal water bath in a clinical trial by thermography, and investigated their promotive effects on blood stream in the capillaries of the fingertips of the hands.

2. Materials and methods

2.1. The participants in the clinical trial of a home hydrogen-rich water bath and informed consents

In this clinical trial, twenty-four healthy subjects at the age of 24– to 58 years old participated (Table 1), after their proposal of informed consents and the official certification as Research Number #17T01 from Research Ethic Committee of Japanese Center for Anti-Aging MedSciences (JCAAMS) which was a nonprofit organization corporate authenticated by Hiroshima Prefectural Government.

2.2. Preparation of the hydrogen-rich water bath

The hydrogen-rich water bath, “Lita Life Ver.2” (WCJ Co., Ltd., Osaka, Japan) was used for hydrogen-rich water generation by electrolyzing warm water in a bath. The electrode of Lita Life was placed in the center of a normal water bath which was filled for non-treated warm Osaka-city-supplied tap water (41 °C, 160 L). Hydrogen-rich water bath was prepared by electrolyzing in normal water bath for 30 or 120 min. The dissolved hydrogen concentration of each bath was measured by using a diaphragm-polarographic electrode-type dissolved-hydrogen meter KM2100DH (Kyoei Electronic Laboratory Co., Ltd., Saitama, Japan). The oxidation-reduction potential of each bath was measured using an oxidation-reduction potential meter YK-23RP-ADV (Mother Tool Co., Ltd., Nagano, Japan) with an electrode Sota (Endress + Hauser Japan Co., Ltd., Osaka).

2.3. Procedures for subjects taking the hydrogen-rich water bath

The twenty-four subjects took a hydrogen-rich water bath or a normal water bath for 10 min at 41 °C, both of which were separately executed at an interval longer than seven days. In each bathing, the subject was immersed in warm water up to the neck for 10 min after preparing the hydrogen-rich water bath by 30-min or 120-min electrolysis of warm water in a bathtub. In addition, subjects were left without intense exercise and intake or contact to other hydrogen-containing materials for 24 h before and during the present examination. Intervals were secured for 7 days among three types of bathing treatments to the same subject. Drinking and eating of subjects were restricted to only drinking water of 100 mL from 3 h before to after, because they may influence body temperatures of subjects. Subjects were led not to be informed whether they bathed in normal water bath or hydrogen-rich water bath, because the body-temperature-measurer operated two Lita Life apparatuses, one connected electrode in the bath, the other did in the bathtub as the dummy before immediately bathing, from a viewpoint of the double-blind-handled examination. In addition, another data-analyzer was arranged not to be informed about the correlation among thermographic data, subject names and bathing types.

Table 1
The participants in the thermographic clinical trials of the hydrogen-rich water bath.

Age (years)	Number of subjects	
	Male	Female
20–29	0	4
30–39	2	3
40–49	4	1
50–59	5	5
Total	11	13

2.4. Thermography of subjects after taking the hydrogen-rich water bath

The heat-retention effects of the home hydrogen-water bath was assessed by thermography at four time-points, “immediately before bathing”, “immediately after bathing finish”, “30 min after bathing finish” and “60 min after bathing finish”. The subject got out a bath, put on a bathrobe, and then, at each time point, underwent measurement of body temperature and thermograph while sitting in a rest room at 26 °C and 60% relative humidity. The distribution of body temperatures on the body surface was analyzed by thermography with the thermographic camera VIM-640G2ULC (Vision Sensing Co., Ltd., Osaka, Japan) and a dedicated software, “shutter Less Viewer for VIM”. Body temperature in the armpit was measured as a body-depth temperature by using an electronic thermometer ET-C205S (Terumo Corporation, Tokyo, Japan). The body composition and parameters were measured by using a body composition monitor HBF-701 (Omron Healthcare Co., Ltd., Kyoto, Japan). For example, body weight, body mass index (BMI), body fat percentage, visceral fat level, subcutaneous fat percentage, skeletal muscle rate and basal metabolism rate were recorded.

Thermograms and the measured values were randomly arranged, and the third party (neither subjects, the measurer nor the analyst) shuffled the order of data so that the data and subjects were inconsistent, which enabled the approval as “a double-blind handled test”. The body-surface temperature was read from thermograms by using the dedicated software. The entire body surface temperatures were calculated by Hardy and DuBois 7 body-parts formula using temperatures of 7 body-parts (head, arms, hands, abdomen, upper legs, lower legs and feet) which were randomly selected by the analyst.

To clarify the correlation between body types of subjects and heat-retention effects by hydrogen-rich bath, six body composition index values, that is, body mass index (BMI), body fat percentage (%), subcutaneous fat percentage (%), skeletal muscle rate (%) and basal metabolism rate (%) were simultaneously measured with a body composition monitor HBF-701 (Omron Healthcare Co. Ltd., Kyoto, Japan). The basal metabolism rate (%) was evaluated by expression as a value per body weight.

2.5. Thickness of fingertip-capillary measurement

The thickness of fingertip-capillary was assessed by a charge coupled device (CCD)-based capillaroscopy for immersed-hand-mediated administration of hydrogen-rich warm water to subjects (Tanaka et al., 2018). Twenty-four healthy subjects were enrolled in this test. The subjects immersed their hands into hydrogen-rich water bath of 15 L at 40 °C for 10 min, and then capillary images of the subject’s ring finger of left hand immediately before bathing and after 30 min or 60 min after bathing finish were taken with GOKO Bscan-Z (Goko International Co., Ltd., Nagano, Japan), under the condition that the position of hands was located so as to be high similarly at the heart position in sitting posture. The thickness of the loop vertices of the capillaries were measured with the dedicated software “ICMeasure”. The measured values of subjects at each of 10 points were averaged and differences the capillary thickness between before and after bathing were compared as an indicator of the blood-stream-promoting effect.

2.5.1. Statistical analysis

The data were shown as the representative mean ± SEM. Wilcoxon test was used for comparison of hydrogen-rich water bath versus normal water bath at each time point, and it was regarded as the statistical significance at the level of $*p < 0.05$ or $**p < 0.01$.

3. Results

3.1. The hydrogen-rich water bath

The dissolved hydrogen concentrations were 1 μg/L for normal water bath at pre-bathing time, 185 μg/L and 548 μg/L for hydrogen-rich water bath prepared with 30- and 120-min electrolysis, respectively, according to measurements immediately after 20-s stirring all over warm water in a bathtub so as to make hydrogen-distribution uniform (Fig. 1). Furthermore, the oxidation-reduction potential of each bath was measured in a manner similar to the manipulation prior to measurements of the dissolved hydrogen concentrations. The oxidation-reduction potentials were +479 mV for normal water bath, −91 mV and −167 mV for hydrogen-rich water bath prepared with 30- and 120-min electrolysis, respectively (Fig. 1).

3.2. The heat-retention effects of hydrogen-rich water bath assessed by thermography

The thermograms show that heat-retention effects of each bathing as indicated by the pseudo-color expression for increasing warm color (Figs. 2–7). The average temperatures of entire body surfaces of 24 subjects were calculated by the Hardy and DuBois formula using temperatures at 7 body-parts; head, arms, hands, abdomen, upper legs, lower legs and feet (Mochida et al., 1994). Then we noted the concerned body-parts, and compared the heat-retention effects of hydrogen-rich water bath versus normal bath on each body-part of 24 subjects (Figs. 2–7). The graph of each result is the average of all the subjects, and the thermogram shows a typical example, so it may not always match, although most of tendencies were relatively accorded.

3.2.1. The entire body surface and armpit

Upon 30- and 60-min post-bathing, the entire body surface temperatures were significantly higher in hydrogen-rich water bath of 30-min and 120-min electrolysis than those in normal water bath (Fig. 2). The thermal elevation on entire body surfaces was 0.65 °C in the hydrogen-rich water bath for 30-min electrolysis and 0.90 °C in the hydrogen-rich water bath for 120-min electrolysis, but that was 0.12 °C in normal water bath for 60-min post-bathing (Fig. 2). The armpit temperatures were slightly higher in hydrogen-rich water bath of 120-min electrolysis than those in normal water bath and hydrogen-rich water bath of 30-min electrolysis, but there was no significant difference (Fig. 2).

Heat-retention effects for all the examined body-parts were summarized in Fig. 3, and the thermal elevations in each of body-parts were shown in Figs. 4–7. It was shown that hydrogen-rich water bath brought about the heat-retention being more marked than those of normal water bath for several body-parts in the order as follows: abdomen > upper legs > arms > hands > feet, for 30- and 60-min post-bathing (Fig. 3). In contrast, head, armpits and lower legs exhibited scarcely the warm-retention by hydrogen-rich water bath as well as normal water bath (Fig. 3). The heat-retention capacity of the hydrogen-rich water bath of 120-min electrolysis was lower than that of hydrogen-rich water of 30-min electrolysis.

3.2.2. The head

The thermal elevations on head were 0.47 and 0.57 °C in the hydrogen-rich water bath of 30-min electrolysis, and 0.08 and 0.46 °C in the hydrogen-rich water bath of 120-min electrolysis, but those were −0.04 and 0.09 °C in normal water bath for 30- and 60-min post-bathing (Fig. 4).

3.2.3. The arms

The thermal elevations on arms were 1.06 and 1.04 °C in the hydrogen-rich water bath of 30-min electrolysis and 1.17 and 1.01 °C in the hydrogen-rich water bath of 120-min electrolysis, but those were 0.45 and 0.24 °C in normal water bath for 30- and 60-min post-bathing (Fig. 5).

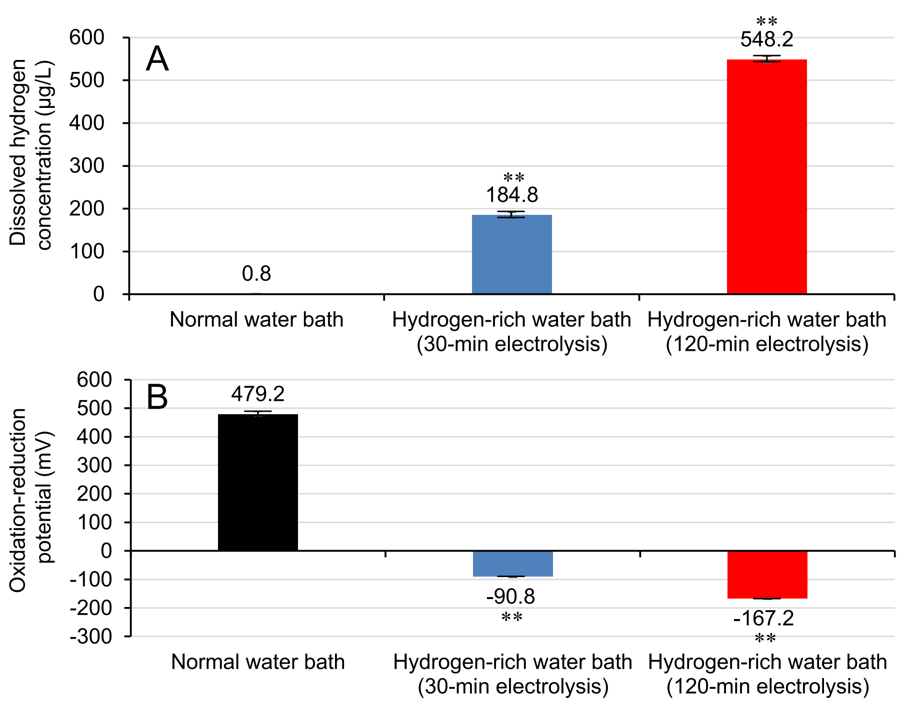

Fig. 1. Characterizations of the normal water bath and the hydrogen-rich water bath. (A) Dissolved hydrogen concentration (μg/L) and (B) Oxidation-reduction potential (mV). The hydrogen-rich water bath was prepared by 30-min or 120-min electrolysis. Mean ± SEM, n = 5, $**p < 0.01$ (vs. normal water bath).

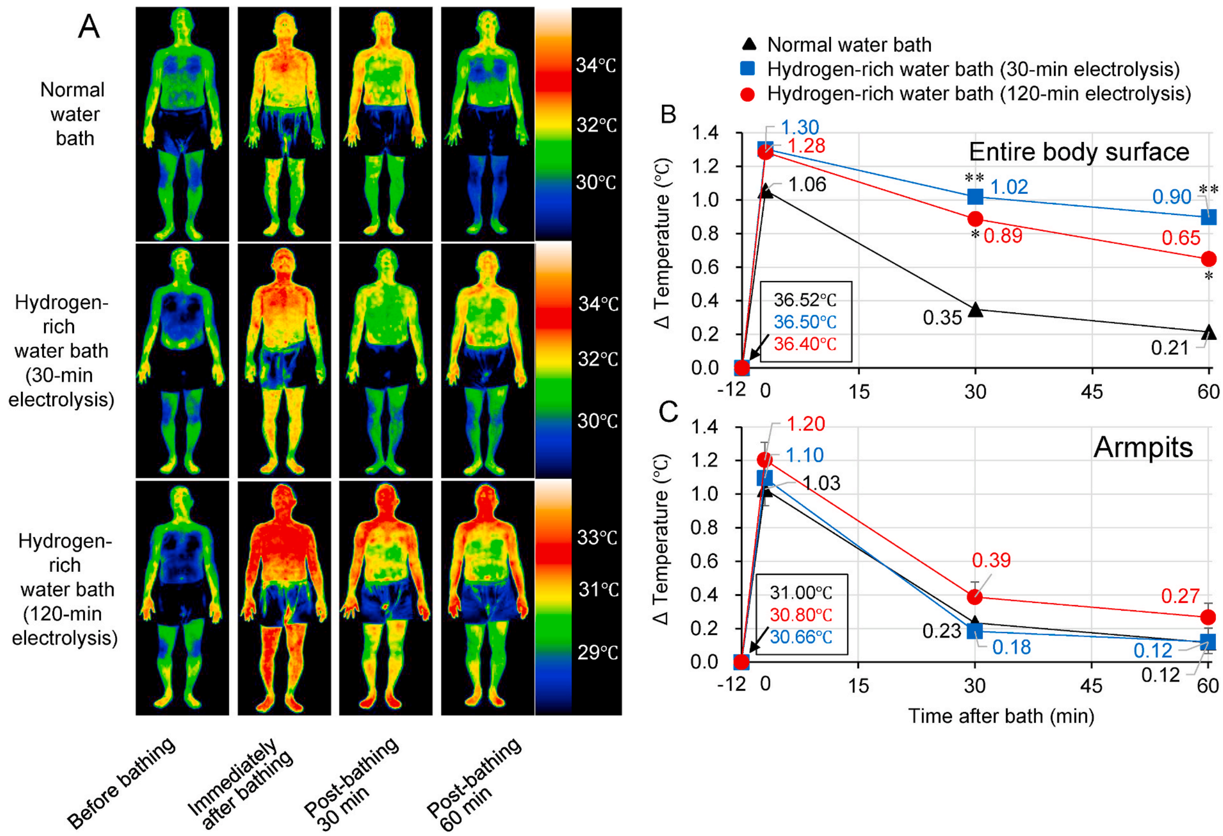

Fig. 2. Heat-retention effects of the hydrogen-rich water bath on entire body surfaces and armpits. (A) Thermograms of entire body of the subject: male, 40 years old, immediately before bathing and at the indicated times after bathing-finish. That was displayed as one sample out of thermogrphys of 24 subjects. (B), (C) The average temperatures of entire body surfaces and armpits of 24 subjects, which were estimated by thermography immediately before bathing. And the thermal elevation in temperatures of entire body surfaces and armpits were compared immediately before bathing and at each time point. The average temperatures of entire body surfaces of 24 subjects were calculated by Hardy and DuBois 7-point formula using temperatures at 7-points, heads, arms, hands, abdomen, upper legs, lower legs and feet. Mean ± SEM, n = 24. *p < 0.05, **p < 0.01 (vs. normal water bath at the same time point).

3.2.4. *The abdomen*

The thermal elevations on abdomen were 1.82 and 1.96 °C in the hydrogen-rich water bath of 30-min electrolysis, and 1.17 and 1.12 °C in the hydrogen-rich water bath of 120-min electrolysis, but those were 0.44 and 0.66 °C in normal water bath for 30- and 60-min post-bathing (Fig. 6).

3.2.5. *The upper legs and lower legs*

The thermal elevations on upper legs were 1.52 and 1.24 °C in the hydrogen-rich water bath of 30-min electrolysis, and 1.33 and 0.86 °C in the hydrogen-rich water bath of 120-min electrolysis, but those were 0.60 and 0.32 °C in normal water bath for 30- and 60-min post-bathing (Fig. 7). The thermal elevations on lower legs were 0.09 and −0.37 °C in the hydrogen-rich water bath of 30-min electrolysis and −0.27 and −0.80 °C in the hydrogen-rich water bath of 120-min electrolysis, but those were −0.42 and −0.88 °C in normal water bath for 30- and 60-min post-bathing (Fig. 7).

3.3. *The correlation between heat-retention effects of hydrogen-rich water bath and body composition index of subjects*

The heat-retention capacities on the entire body surfaces were plotted in relation to the body composition index of subjects, such as body mass index (BMI), body fat percentage (%), subcutaneous fat percentage (%), skeletal muscle rate (%) and basal metabolism rate (%) (Fig. 8). And the correlation coefficients were calculated for each index (Fig. 8).

3.3.1. *BMI*

Upon 30- and 60-min post-bathing, there was a low positive correlation between BMI and the heat-retention capacity in normal water bath (Fig. 8-A, B). And the correlation between BMI and hydrogen-rich water bath of 30-min electrolysis or hydrogen-rich water bath of 120-min electrolysis was weaker than that in normal water bath (Fig. 8-K, L). The correlation between BMI and hydrogen-rich water bath of 30-min electrolysis was slightly stronger than that in hydrogen-rich water bath of 120-min electrolysis (Fig. 8-K, L). It is presumed that BMI does not affect the heat-retention capacity regardless of the hydrogen concentration in the hydrogen-rich water bath.

3.3.2. *Body fat percentage*

There was a moderate positive correlation between body fat percentage and the heat-retention capacity in normal water bath for 30- and 60-min post-bathing (Fig. 8-C, D). And the correlation between body fat percentage and hydrogen-rich water bath of 30-min electrolysis was a little stronger than that in normal warm water for 60-min post-bathing, though in other cases of hydrogen-rich water bath of 30-min or 120-min electrolysis, the correlation between body fat percentage and the heat-retention capacity was weaker than that in normal water bath (Fig. 8-C, D). The correlation between body fat percentage and hydrogen-rich water bath of 30-min electrolysis was stronger than that in hydrogen-rich water bath of 120-min electrolysis (Fig. 8-K, L). It is presumed that body fat percentage does not affect the heat-retention capacity regardless of the hydrogen concentration in the hydrogen-rich water bath.

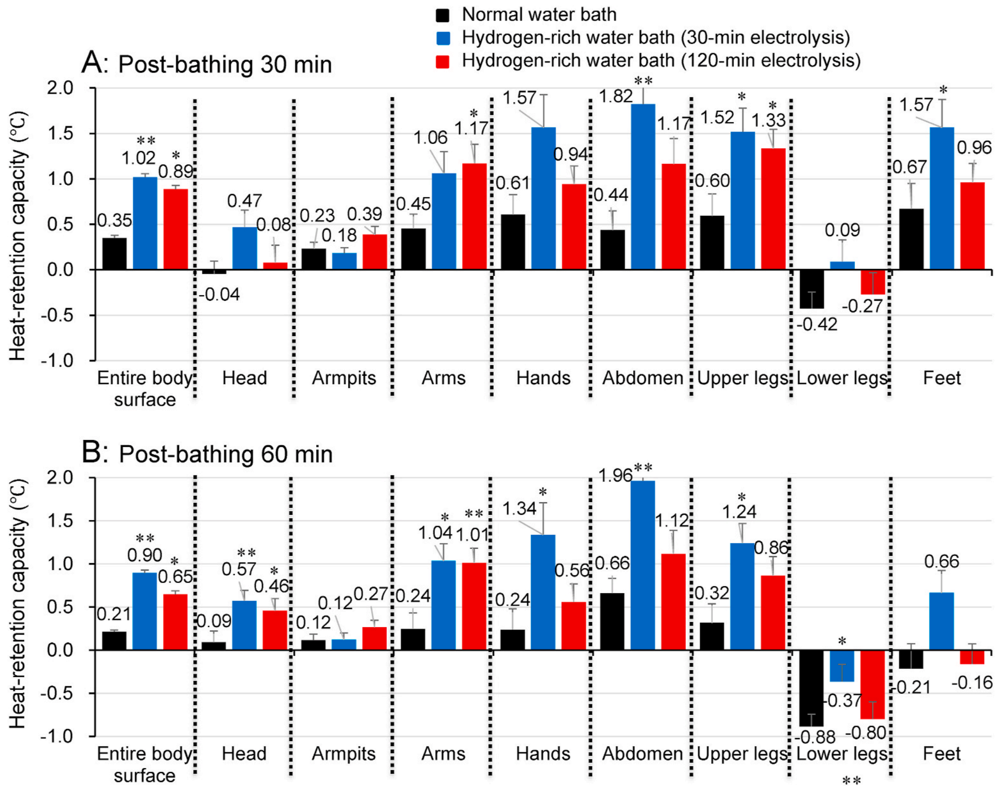

Fig. 3. Heat-retention capacities of the hydrogen-rich water bath on each body-part. The heat-retention capacities (°C) of 24 subjects represent differences between the temperatures immediately before bathing and the temperatures at 30 min (A) or 60 min (B) after 10-min-hydrogen-rich water bathing in each body-part. Mean ± SEM, n = 24. *p < 0.05, **p < 0.01 (vs. normal water bath at the same time point).

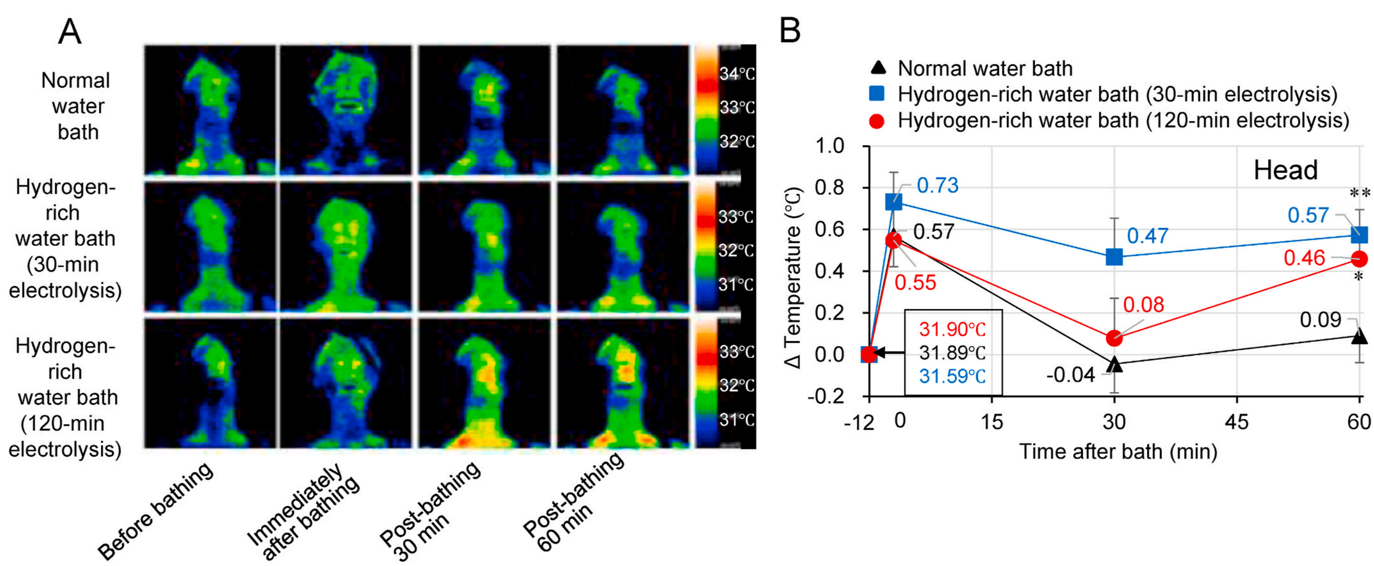

Fig. 4. Heat-retention effects of the hydrogen-rich water bath on heads. (A) Thermograms of head of the subject: female, 27 years old, immediately before bathing and at the indicated times after bathing. (B) The average temperatures of foreheads of 24 subjects, which were estimated by thermography immediately before bathing. And the thermal elevation in temperatures of foreheads were compared immediately before bathing and at each time point. Mean ± SEM, n = 24. *p < 0.05, **p < 0.01 (vs. normal water bath at the same time point).

3.3.3. Subcutaneous fat percentage

There was a moderate positive correlation between subcutaneous fat percentage and the heat-retention capacity in normal water bath for 30- and 60-min post-bathing (Fig. 8-E, F). And the correlation between body fat percentage and hydrogen-rich water bath of 30-min electrolysis was a little stronger than that in normal warm water (Fig. 8-E, F). On the contrary, in the case of hydrogen-rich water bath of 120-min electrolysis, the correlation between subcutaneous fat percentage and the heat-retention capacity was weaker than that in normal water bath (Fig. 8-E, F). The correlation between subcutaneous fat percentage and hydrogen-rich water bath of 30-min electrolysis was stronger than that in hydrogen-rich water bath of 120-min electrolysis (Fig. 8-K, L). In the hydrogen-rich water bath of 30-min electrolysis, the entire body surface was warmed easily, but there was not much difference between normal

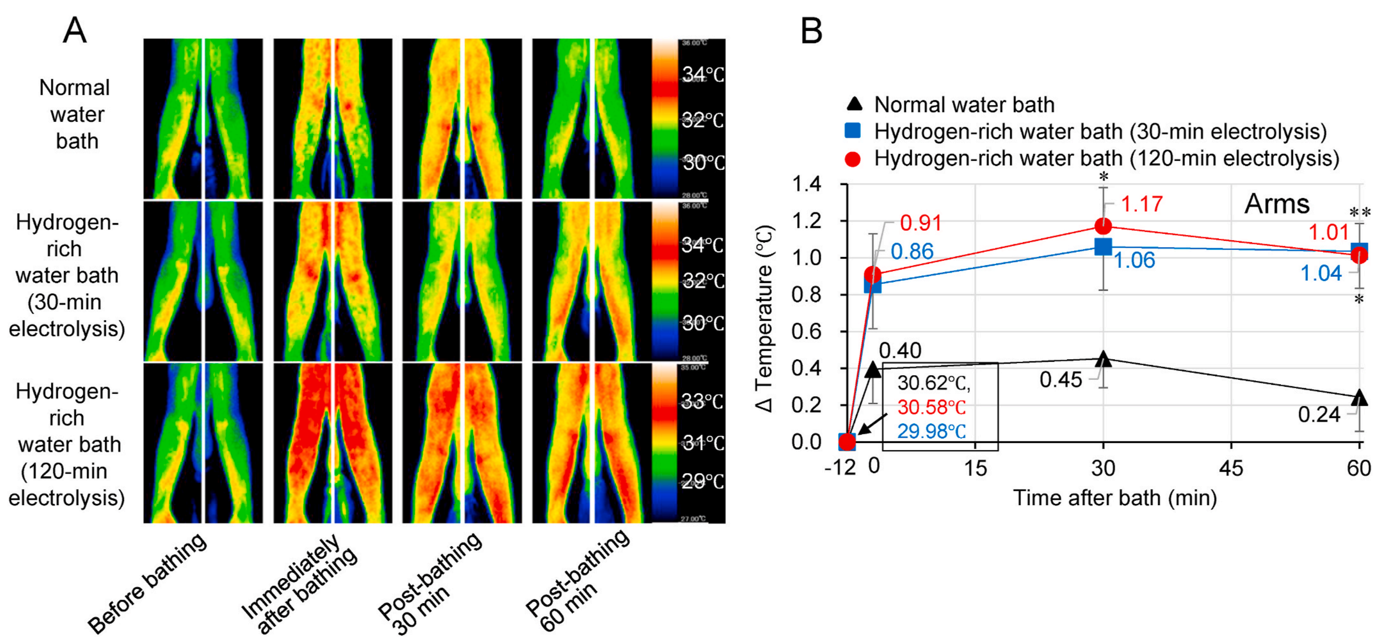

Fig. 5. Heat-retention effects of the hydrogen-rich water bath on arms. (A) Thermograms of both arms of the subject: male, 40 years old, immediately before bathing and at the indicated times after bathing. (B) The average temperatures of both arms of 24 subjects, which were estimated by thermography immediately before bathing. And the thermal elevation in temperatures of arms were compared immediately before bathing and at each time point. Mean ± SEM, n = 24. *p < 0.05, **p < 0.01 (vs. normal water bath at the same time point).

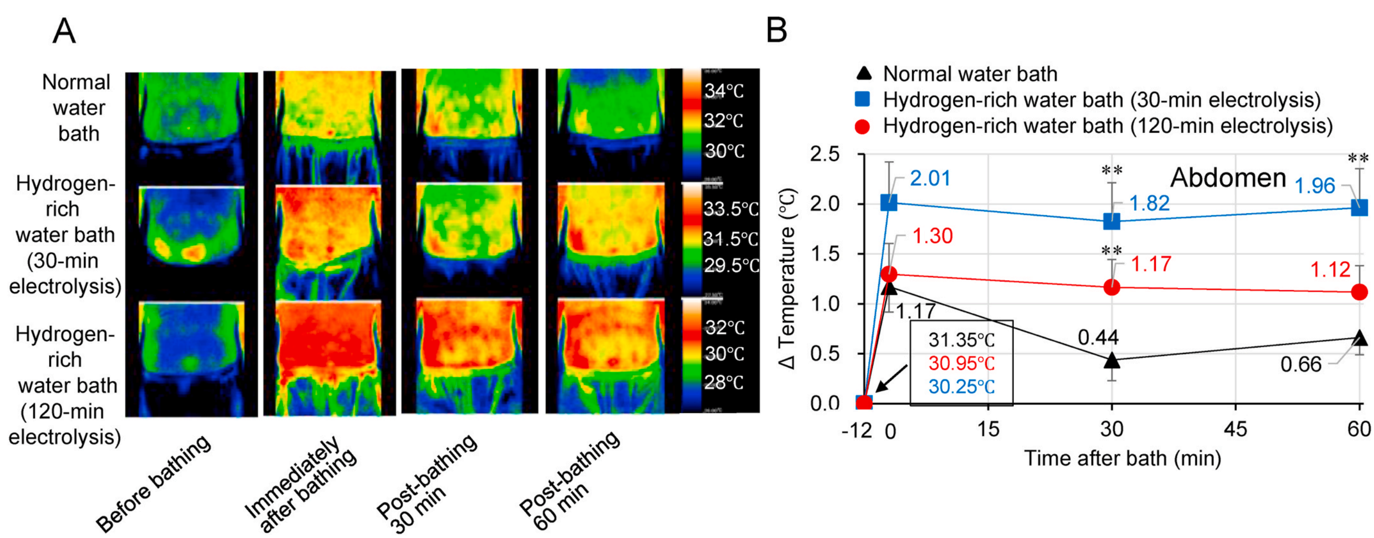

Fig. 6. Heat-retention effects of the hydrogen-rich water bath on abdomen. (A) Thermograms of both legs of the subject: male, 40 years old, immediately before bathing and at the indicated times after bathing. (B) The average temperatures of abdomen of 24 subjects, which were estimated by thermography immediately before bathing. And the thermal elevation in temperatures of hands were compared immediately before bathing and at each time point. Mean ± SEM, n = 24. **p < 0.01 (vs. normal water bath at the same time point).

warm water and hydrogen-rich water. It is presumed that subcutaneous fat percentage does not affect the heat-retention capacity regardless of the hydrogen concentration in the hydrogen-rich water bath.

3.3.4. Skeletal muscle rate

Different from the above-mentioned results, a moderately negative correlation between skeletal muscle rate and the heat-retention capacity was shown in normal water bath for 30- and 60-min post-bathing (Fig. 8-G, H). And the correlation between skeletal muscle rate and hydrogen-rich water bath of 30-min electrolysis was a little stronger than that in normal warm water (Fig. 8-G, H). On the contrary, in the case of hydrogen-rich water bath of 120-min electrolysis, the correlation between skeletal muscle rate and the heat-retention capacity was weaker than that in normal water bath (Fig. 8-G, H). The correlation between skeletal muscle rate and hydrogen-rich water bath of 30-min electrolysis was stronger than that in hydrogen-rich water bath of 120-min electrolysis (Fig. 8-K, L). In hydrogen-rich water bath of 30-min electrolysis, the entire body surface was easy to cool down a little, but there was not much difference between normal warm water and hydrogen-rich water. It is presumed that skeletal muscle rate seemed to rather counteract the heat-retention capacity regardless of the hydrogen concentration in the hydrogen-rich water bath.

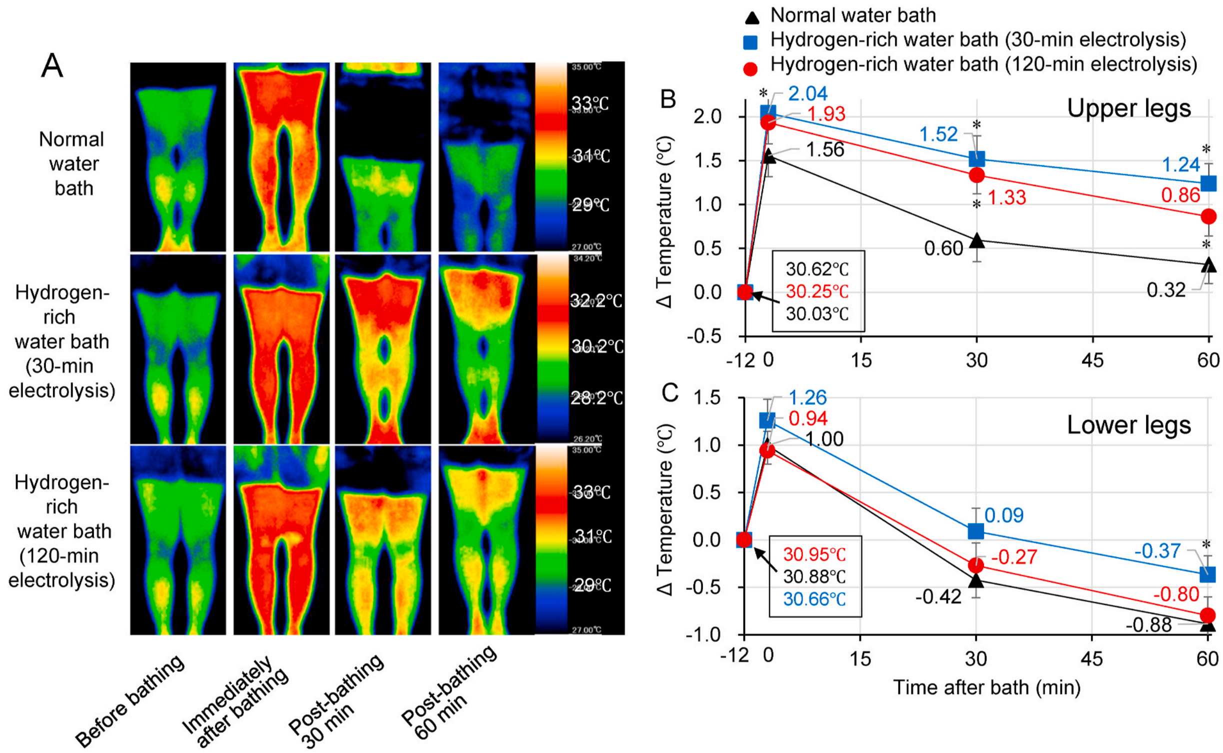

Fig. 7. Heat-retention effects of the hydrogen-rich water bath on legs. (A) Thermograms of both legs of the subject: female, 27 years old, immediately before bathing and at the indicated times after bathing. (B), (C) The average temperatures of both upper or lower legs of 24 subjects, which were estimated by thermography immediately before bathing. And the thermal elevation in temperatures of upper legs or lower legs were compared immediately before bathing and at each time point. Mean ± SEM, n = 24. *$p < 0.05$ (vs. normal water bath at the same time point).

3.3.5. Basal metabolism rate

Then, there was an almost negligible correlation between basal metabolism rate and the heat-retention capacities in each bathing (Fig. 8-I, J). The correlation in hydrogen-rich water bath of 30-min electrolysis was slightly stronger than that in normal water bath. It is presumed that basal metabolism rate does not affect the heat-retention capacity regardless of the hydrogen concentration in the hydrogen-rich water bath.

3.4. Thickness of fingertip-capillary measurement

Capillary images of the subject's ring finger of left hand before and after bathing were taken with a CCD-based capillaroscope GOKO Bscan-Z as shown in Fig. 9. We selected the data of the 16 subjects that could be distinctly observed, and measured the thickness of the loop vertices of the capillaries (Fig. 10). Upon 30- and 60-min post-bathing as compared with pre-bathing, the capillary thickness of 16 subjects increased by 1.03 and 1.12 μm in the hydrogen-rich water bath of 30-min electrolysis, and 1.93 and 1.03 μm in the hydrogen-rich water bath of 120-min electrolysis, indicating that the increases in capillary thickness were statistically significant, and corresponded to the thickness as large as 14.7–27.6% of the entire capillary thickness. In contrast, increases in capillary thickness were −0.14 and −0.59 in normal water bath (Fig. 10-A), suggesting that warm-retention of the body might be executed not by the merely bathing-based transient elevation of the body temperature, but by hydrogen-based persistence of blood stream and circulation even at 30-/60-min post-bathing. The typical example of a male at age of 30's years old was shown in Fig. 10-B. Capillary thickness was expanded in the hydrogen-rich water bath more markedly than in the normal bath, but there was not obviously related to the difference between hydrogen concentrations for 30- and 120-min electrolysis. It is suggested that the hydrogen-rich water bath has the promotive effect on blood flow by expanding the thickness of the capillaries.

4. Discussion

In the present study, we assessed the heat-retention effect of hydrogen-rich water bath by thermographic clinical trials, and examined the promotive effects on blood stream in the capillaries of the fingertips of hands, which were selected because of the rare thin skin-corneum enabling the blood streams visible. The heat-retention capacities in hydrogen-rich water bath were compared to those in normal water bath on each body-part for 30- and 60-min post-bathing. It was emphasized that hydrogen-rich water bath brought about the heat-retention being more marked than those of normal water bath for several body-parts in the order as follows: abdomen > upper legs > arms > hands > feet, for 30- and 60-min post-bathing (Fig. 3). These hydrogen-dependent warm-keeping body-parts can be regarded to be located near the body-center where blood circulation from the heart abundantly reach. In contrast, head, armpits and lower legs exhibited scarcely the warm-retention by hydrogen-rich water bath as well as normal water bath (Fig. 3). These hydrogen-/water-warmness-independent warm-losing body-parts can be regarded as peripheral body-parts which are not directly connected to blood circulation from the heart. It is presumed that the hydrogen-rich water bath is more effective in warming the visceral/internal organs than the terminal parts of the body. However, body parts of the head, lower legs, hands, and feet tend to be less warm, which may also be related to the fact that these parts are not covered with a bathrobe. The heat-retention capacity of the hydrogen-rich water bath of 120-min electrolysis was rather lower than that of hydrogen-rich water of 30-min electrolysis (Fig. 3), although being decisively higher than that of normal water bath. From a viewpoint of the correlation with hydrogen parameters (Fig. 1), the heat-retention effects are suggested to be attributed to either the dissolved hydrogen concentrations or the oxidation-reduction potentials which are heightened near the definite necessary levels, but not necessarily beyond the minimum levels.

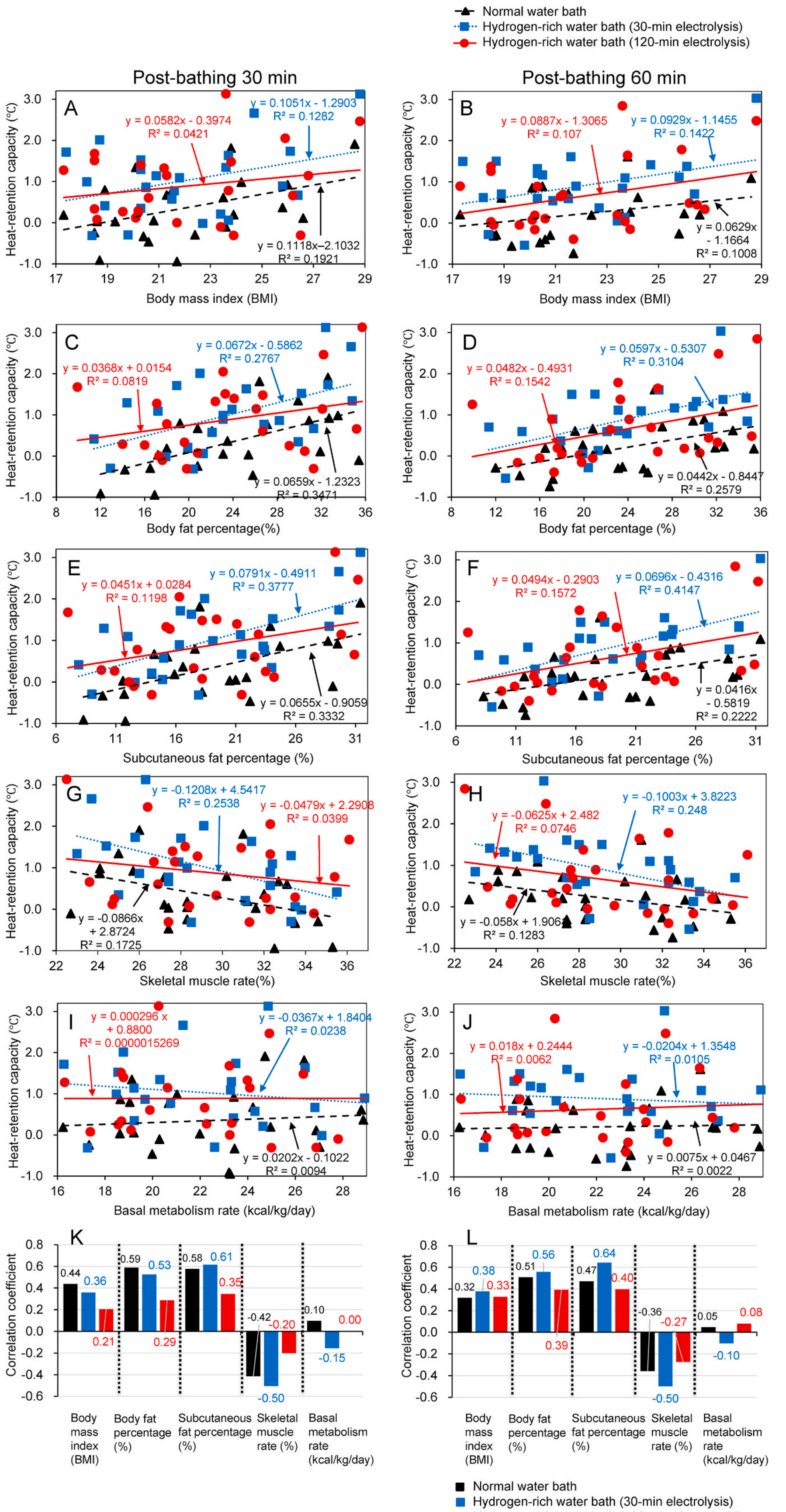

Fig. 8. The relationships between a heat-retention capacity and each body composition index value. The heat-retention capacities (°C) of 24 subjects represent elevation in temperatures of entire body surfaces between immediately before bathing and the 30 min or 60 min after 10-min-hydrogen-rich water bathing in Fig. 2B. The heat-retention is shown versus (A, B) body mass index (BMI), (C, D) body fat percentage, (E, F) subcutaneous fat percentage, (G, H) skeletal muscle rate, (I, J) basal metabolism rate. (K, L) And the correlation efficient between heat-retention capacity and each body composition index value.

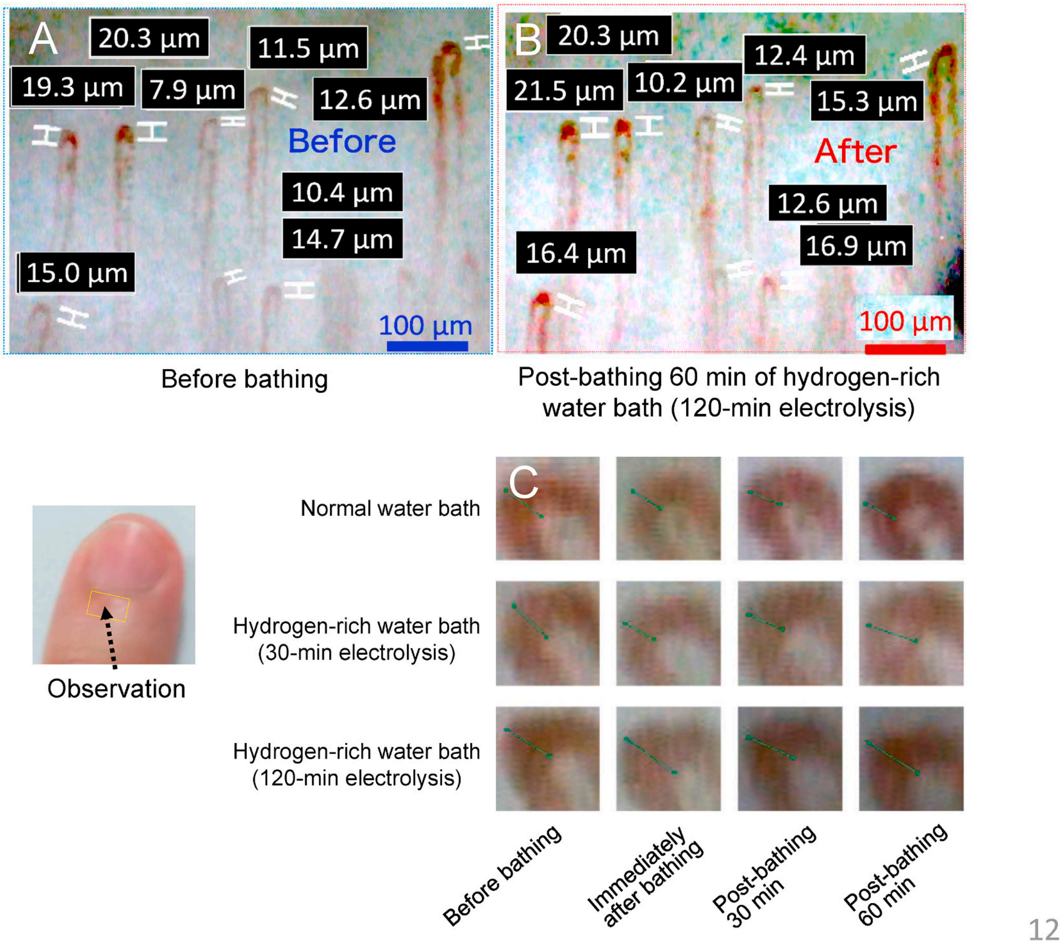

Fig. 9. Capillary blood vessel measurement. (A) Immediately before bathing and (B) at 60 min after bathing-finish in hydrogen-rich water bath prepared by 120-min electrolysis. (C) The capillary loop apex images of typical 20's years old female that could be obviously observed immediately before bathing and 30- and 60-min post-bathing. Magnification: × 400, area: 540 × 720 µm.

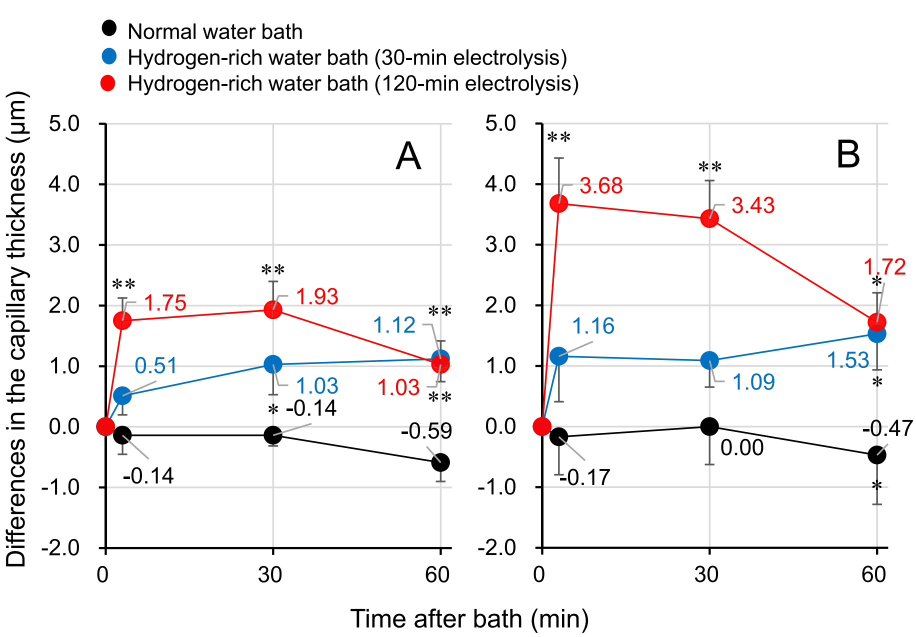

Fig. 10. Capillary thickness before and after bathing and its difference. (A) The capillary thickness value as average of 16 subjects and (B) typical 30's years old male at each 10 points were averaged, and differences of the capillary thickness between before and after bathing were compared. Capillary images of the subject's ring finger of left hand before and after bathing were taken with a CCD-based capillaroscope GOKO Bscan-Z as shown in Fig. 9. We selected the data of the 16 subjects that could be clearly observed and measured the thickness of the loop vertices of the capillaries with the dedicated software "ICMeasure". Mean ± SEM, n = 10. *p < 0.05, **p < 0.01 (vs. normal water bath at the same time point).

The thickness of fingertip-capillary was expanded in the hydrogen-rich water bath more markedly than that in the normal water bath (Fig. 9). The thickness expansion of fingertip-capillary was higher in the hydrogen-rich water bath of 120-min electrolysis than that in the hydrogen-rich water bath of 30-min electrolysis from immediately after bathing to 30-min post-bathing, but they were calmed down to the same extent for 60-min post-bathing (Fig. 10). It is reported that oral supplementation of hydrogen water reduces pulmonary hypertension associated with its antioxidant ability and action of reducing pulmonary inflammatory response (He et al., 2013). And the antifatigue effects of hydrogen water is found in chronic forced swimming mice, which is attributed to antioxidative and anti-inflammatory activities of hydrogen water (Ara et al., 2018). In our present study, although the relation between hydrogen concentration and capillary thickness expansion cannot be clearly explained, the results suggest that the hydrogen-rich water bath may have the promotive effect on blood flow by expanding the thickness of fingertip-capillary. Thickness of fingertip-capillary may reflect the blood circulation of the whole body, and is suggested to contribute to warm-keeping by hydrogen potently through prevention against erythrocyte-aggregation and promotion of blood stream.

Hydrogen nano-bubbles were shown to increase in a rough proportion to dissolved hydrogen concentrations within the definite concentration range, but not increase over the surplus dissolved hydrogen concentration, assumedly through bubble mutual fusion and the subsequent bubble-explosion. Capillary dilatation is suggested to contribute to body heat-keeping in hydrogen bathtub, and to be controlled through the beneficial effects of hydrogen nano-bubbles on both prevention against erythrocyte aggregation and promotion to blood stream as demonstrated by comb-shaped blood-stream-channel rheological apparatus (Kato et al., 2012). Thus, heat-retention effects of hydrogen bath might not be affected directly by hydrogen concentrations, but complicatedly by the density of hydrogen nanobubbles and the hematological dynamic effects.

Meanwhile, the heat-retention capacities in 30-/120-min electrolytic hydrogen-rich water bath weakly or moderately correlated with contents of the subcutaneous fat, whole body fat and body mass index, and inversely correlated with skeletal muscle rates, although no obvious exceeding over normal water bath, but had little relation with the basal metabolism rate (Fig. 8). Adipose tissue levels, especially for the brawn adipose tissue, are known to be associated with heat generation, and subcutaneous adipose tissue provides an insulating layer that prevents body-heat loss to the external space. Skin temperature of most body surfaces was lower in obese subjects than normal body-mass subjects (Chudecka et al., 2014). It is reported that hydrogen-rich water significantly reduced blood cholesterol and glucose levels etc., and promoted a mild reduction in BMI and waist-to-hip ratio (LeBaron et al., 2020). Our results suggest that the BMI which is indicative of obesity degrees may be correlated with largeness of warm-keeping capacities, and contributes slightly to bathing-based heat-retention regardless of presence or absence of hydrogen (Fig. 10). In home baths, bath salts are added to improve heat-retention, but their use may require maintenance such as cleaning the bath heater. The hydrogen-rich water bath apparatus can electrolytically generate hydrogen bubbles before bathing, which is safe and does not pollute a bath heater (Asada et al., 2019). The underlying mechanisms that mediate the heat-retention effects induced by the hydrogen-rich water bath need further study.

5. Conclusion

In conclusion, our results suggest that the hydrogen-rich water bath has heat-retention effects exceeding over normal water bath, in diverse body-parts such as abdomen, upper legs, arms and hands, via promoting blood flow being reflected by expanding the thickness of capillary. The heat-retention after bathing can be noted as an effect of the hydrogen-rich water bath, which is applicable for most of people widespreadly regardless of their body composition index.

Author contributions

All authors have contributed to this article as follows: NM participated in the design and coordination of the study, NM and YT conceived and performed the experiments, SK analyzed data and wrote the manuscript. All authors approved the final version of the manuscript.

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Data availability

All relevant data are within this article.

Declaration of competing interest

The authors confirm that there are no conflicts of interest associated with this article.

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