Effect of Different Thermal Stimuli on Improving Microcirculation in the Contralateral foot

Weiyan Ren
Beihang University
Liqiang Xu
Beihang University
Xuan Zheng
Beihang University
Fang Pu
Beihang University
Deyu Li
BeiHang University
Yubo Fan (yubofan@buaa.edu.cn)
BeiHang University School of Biological Science and Medical Engineering https://orcid.org/0000-0002-3480-4395

Research

Keywords: Microcirculation disorders, contralateral thermal effect, warm bath, infrared radiation, plantar foot

Posted Date: August 25th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-62448/v1

Version of Record: A version of this preprint was published on February 2nd, 2021. See the published version at https://doi.org/10.1186/s12938-021-00849-9.

Abstract

Backgroud: The lower extremities of the body often suffer from impaired microcirculation, particularly in the elderly or people with underlying conditions such as diabetes. Especially for people suffering from peripheral vascular diseases, skin lesions or wearing an external fixator in one side of limbs, direct contact treatments are not suitable for them to improve microcirculation. Heating the contralateral limb has been reported to improve blood flow in the impaired limb. However, its effect on microvascular responses has not been previously investigated. Thus, the aim of this study was to explore how heating by warm bath and infrared radiation affects the circulations in the contralateral foot. Twelve healthy adults participated in this study and were randomly assigned to either placing the left foot in a warm bath or exposing it to infrared radiation every other day. The temperature (Temp) and skin blood flow (SBF) in the second metatarsal head of the contralateral foot were measured before and after the intervention.

Results: The results showed that both Temp (Bath: from 29.05±3.56 °C to 31.03±4.14 °C; Infrared: from 29.98±3.86 °C to 31.07±3.92 °C) and SBF (Bath: from 62.26±48.12 PU to 97.76±63.90 PU; Infrared: from 63.37±39.88 PU to 85.27±47.62 PU) in the contralateral foot were significantly increased after heating in both tests ($P<0.05$). However, the increase in contralateral SBF lasted 5 minutes after heating in a warm bath, but only lasted for 1 minute after infrared exposure. Moreover, the increase in Temp from the baseline in the first minute of the Recovery stage was significantly greater when using the warm bath than infrared radiation.

Conclusions: The results of this study show that both heating methods are the effective at increasing contralateral Temp and SBF, but the warm bath has a stronger residual thermal effect.

1. Background

Insufficient blood supply often occurs in the lower extremities in people with microcirculation disorder, especially in people with diabetes[1, 2]. Poor circulation in the foot can cause ischemia and hypoxia of the foot tissue, and also affect the neural nutritional supply, which may reduce sensory perception to external stimuli and affect nerve regulation of microvasculature[3–5].

Heating is a well-known conservative method for improving blood circulation. It can effectively induce vasodilation and increase blood flow, which contributes to nutritional supply, wound healing and tissue repair[6, 7]. However, for people suffering from peripheral vascular diseases, skin lesions or wearing an external fixator, it is often unsuitable to apply a thermal stimulus directly to the affected area. In such instances, an effective method to improve blood supply insufficiency in the affected limbs is necessary for people with microcirculation disorder.

The study of Kubo et al. pointed out that heating the contralateral limb can increase the blood volume in the injuried tendon in a plaster cast [8]. Astrup et al. found that contralateral heating can increase the circulation of the unheated forearm and affect metabolism of the unheated hand [9]. And Gorodkin et al. reported that the vasodilator responses to heating stimulus was similar in affected and unaffected limbs

[10]. These previous studies have demonstrated that applying heating to the contralateral side of the limb can improve the blood circulation in the unheated side of the limb.

A warm bath and infrared radiation are the most common methods for heating the body. Warm bath can transfer heat directly to the skin tissue via water medium, and induce cutaneous vasodilation by stimulating peripheral and core thermoreceptors[11]. And infrared radiation can improve local microcirculation by inducing molecular response and thermal effect[12, 13]. Kim et al. reported that warm bath is a effective method to increase blood flow in the contralateral mid-forearm of healthy people [14]. And Marshall et al. reported that a warm bath could evoke reflexive microvascular vasodilation in the contralateral hand of healthy people[11]. Rutkowski et al. found that infrared radiation could increase skin temperature in the contralateral dorsal side of hand[12]. However, previous studies tended to focus on the thermal effects in the upper limbs, but for human foot that often suffers from microcirculation disorders, few studies have been reported the heating effects on it[15]. Thus, exploring the effects of warm bath and infrared radiation on improving microcirculation in contralateral foot, may be helpful to develop protection methods for people with foot microcirculation disorders.

This study used either a water bath or infrared radiation to heat one foot of each subject and recorded the cutaneous temperature and blood flow responses in the contralateral foot. The aim was to compare and understand the differences in contralateral thermal effects of the two heating methods.

2. Results

The Temp and SBF of M2 in the subjects' right feet before and immediately after thermal stimuli are shown in Fig. 1. In the warm bath test, there was a significant increase in mean instant Temp from the Baseline (29.05 ± 3.56 °C) to post-intervention (31.03 ± 4.14 °C), and the mean instant SBF increased significantly from 62.26 ± 48.12 PU to 97.76 ± 63.90 PU. Similarly in the infrared radiation test, the mean instant Temp increased significantly from a Baseline temperature of 29.98 ± 3.86 °C to a post-intervention temperature of 31.07 ± 3.92 °C, and the mean instant SBF increased significantly from 63.37 ± 39.88 PU to 85.27 ± 47.62 PU. These results indicate that both a warm bath and infrared radiation can increase the cutaneous temperature and blood flow in the contralateral foot.

Figure 2 shows the mean Temp and SBF of M2 in the subjects' right feet during the Baseline stage and for the duration of the Recovery stage. It can be seen that for both tests the Temp was significantly higher during the Recovery stage than in the Baseline stage. However, while the SBF increased significantly for the initial 5 minutes of the Recovery stage in the warm bath test, there was only a significant increase for the first 1 minute of the infrared radiation test. These results indicate that both two heating methods have a thermal effect on the contralateral foot, but the warm bath has a stronger residual effect.

The increments of Temp and SBF of M2 in the subjects' right feet during the Recovery stage are shown in Fig. 3. Although the mean values of the increments of Temp during recovery stage in the warm bath test were higher than the infrared radiation test, only the Temp increment in the first minute showed a significant difference. There was no significant difference in the increments of SBF during the Recovery stage between the two tests.

3. Discussion

This study heated the left feet of subjects using two different thermal stimuli in order to investigate their effects on cutaneous temperature and blood flow responses in the contralateral plantar foot. The results showed that both the warm bath and infrared radiation increase the cutaneous temperature and blood flow in the contralateral foot, and the warm bath has a stronger residual thermal effect.

Studies have shown that physiological thermoregulation is mainly controlled by the preoptic/anterior hypothalamus (POAH), which regulates vasodilation and vasoconstriction of blood vessels by the internal and/or skin temperature [16]. When applying a thermal stimulus to one side of the foot, the skin thermoreceptors in the heated area will signal the POAH and activate temperature-sensitive neurons. In the efferent pathway, the projections from the rostral ventrolateral medulla and hypothalamus to the intermediolateral column of the spinal cord are predominantly ipsilateral, but also produce contralateral signals. Thus, the contralateral thermoregulatory effectors will also receive signals to induce skin vasodilation [17]. Cranson et al. reported that the temperature of arterial blood flow increased by 0.5 °C within 4 minutes when the forearm was placed in water at 40 °C[18]. The increased temperature of arterial blood flow would activate the central thermal receptors, consequently inducing vasodilation of bilateral skin vessels and increasing peripheral blood flow and cardiac output[19, 20]. Thus, a thermal stimulus applied to one side of the foot can induce contralateral responses in skin temperature and blood flow by the innervation of peripheral and central thermal receptors.

The plot in Fig. 2 shows that the residual effects of the two thermal stimuli on contralateral skin blood flow are different, and the skin temperature in the initial recovery stage is also different between the two tests (Fig. 3). The skin blood flow of M2 in the contralateral foot was significantly higher than the basal blood flow for 5 minutes after removal from the warm bath, while the temperature was only significantly higher for the first 1 minute after removing the infrared radiation heat. Moreover, when considering the increase in temperature from the baseline, the warm bath test showed a significantly greater increase in temperature than the infrared radiation test during the first minute of the Recovery stage. This indicates that heating the foot with a warm bath leaves a stronger residual contralateral effect than infrared radiation, which may be due to the different contralateral regulatory mechanisms between the two thermal stimuli.

Marshall et al. reported that if one hand was heated by a warm bath for 2 min, blood flow in the contralateral hand would increase, and there would be a further increase in blood flow and cardiac output after 5 minutes of heating[11]. The elevated cardiac output during thermal stimulation is primarily caused by the increase in internal temperature[21]. This suggests that the reflexive vasodilation of skin vessels in the contralateral limb during heating is not only mediated by skin thermoreceptors in the heated limb, but also by the central thermoreceptor activated by the increased temperature of arterial blood flow. Moreover, the perception and conduction of temperature by skin thermoreceptors occurs rapidly, but the peripheral response mediated by the central thermoreceptor is relatively slow. It can be speculated that when the source of heat is removed, the stimulation of skin thermoreceptors ceases and afferent signals to the POAH are greatly reduced. However, the internal temperature of arterial blood would not drop immediately, and would take longer for the volume and temperature of blood to recover to baseline values because the heat needs to be dissipated though vessel vasodilation. Thus, in this study, heating in a warm bath for 10 minutes may stimulate both the peripheral and central thermoreceptors by increasing the temperature of skin and arterial blood flow, resulting in a longer recovery time and a stronger residual effect on subjects' contralateral feet.

When soft tissue is heated by infrared radiation, heat will be generated by resonance and friction between molecules because the vibration frequency of partial far infrared rays is close to that of intracellular molecules in soft tissue, which causes an increase in temperature and accelerates blood circulation[22, 23]. The thermal effect in the heated side of limbs will be regulated by the thermoregulation of central nervous systems, making the temperatures in the contralateral side and the irradiated side close[24]. Another theory is that, the infrared radiation can induce the release of cytokines and growth factors in the circulation, contributing to the vasodilation of ipsilateral and contralateral vessels[12, 25]. However, the far infrared rays can only be transmitted into skin tissue in a depth of 3–5 mm, and may have a relatively slight effect than warm bath, which can induce vessels vasodilation regulated by both peripheral and central thermoreceptors[11, 13, 21].

Another reason for the different residual effects may be the conducting medium. Water is a good conductor and can transfer heat to the whole foot. When heating with infrared radiation, the stagnant air may attenuate heat from radiator to plantar foot[26]. To mitigate the difference in the heat transferred to the foot, the temperature of the measurement areas under infrared light was ensured to be 40 °C by controlling the device.

The second metatarsal head (M2) typically experiences high plantar pressure when walking and, as such, is a common site for foot ulcers in diabetics with impaired microcirculation [27]. Thus, this study chose M2 to investigate the thermal effects of two heating methods. Moreover, since 10 minutes of thermal stimulation can transmit heat stress into skin tissue to a depth of 1 cm, and a thermal stimulus with a temperature below 40 °C is generally safe[13, 28], this study used these parameters to achieve a thermal effect and avoid skin burns.

This study has some limitations that should be noted. Although the temperature of both thermal stimuli was 40 °C, it was not verified whether the two sources provided an equal level of heat to the foot needs to be further verified. In addition, this study only considered heating the feet of healthy subjects. Future studies may consider other limbs like dominant side or enrolling subjects with impaired microcirculation.

In conclusion, this study found that both the warm bath and infrared radiation are effective at increasing the temperature and skin blood flow in the contralateral foot, but there are differences in the duration and intensity of the residual effects. Heating with infrared radiation is generally more convenient for home use, and is more suitable for detecting nerve and vascular function because of the instantaneous change in temperature and blood flow in the contralateral limb. The warm bath has a better thermal effect, and may be more suitable for use by people who suffers from skin lesions or wears an external fixator, and cannot accept the heat source being focused on one side of the limb.

4. Conclusions

This study explored how heating the left foot with a warm bath and infrared radiation affected the temperature and blood flow in the contralateral foot. The results showed that both heating methods can effectively increase the cutaneous temperature and blood flow in the contralateral foot, but the warm bath produced a longer duration of cutaneous vasodilation and a greater increase in temperature.

5. Methods

5.1 Participants

Seven males and five females (23.50 ± 0.52 years, 20.70 ± 2.115 kg/m^2) participated in this study. The inclusion criteria were: (1) had no symptoms such as redness, callus, inflammation, or wounds on the skin of the feet or legs, and (2) had no diseases such as hypertension, peripheral neuropathy, vascular disease, heart disease, systematic inflammation, malignant tumor, etc. This study was conducted in accordance with clinical protocols approved by the institutional review board of Affiliated Hospital of National Research Center for Rehabilitation Technical Aids and in accordance with the Declaration of Helsinki. All subjects gave informed written consent prior to participation.

5.2 Procedures

Before the test, all subjects were asked to sit on the floor with legs straight and bare feet for 30 minutes in a room at a temperature of 25 ± 2 °C. To set a baseline, the skin temperature (Temp) and skin blood flow (SBF) of the second metatarsal head (M2) in each subjects right foot were measured for 5 minutes (Baseline stage). The left foot was then heated for 10 minutes using either a warm bath or infrared radiation randomly[28]. After heating, the Temp and SBF of M2 in the right foot were measured again for 10 minutes (Recovery stage).

The water temperature of the warm bath was controlled at 40 ± 1 °C, and the water level reached the medial malleolus of the foot. The infrared radiation was provided by a radiator placed 20 cm away from subjects' feet, and the temperature emanating on the feet was controlled at 40 ± 1 °C. The heating method (bath or infrared) was randomly applied to each subject at the same time in two days.

5.3 Data and Statistical Analysis

The Temp and SBF were recorded during the Baseline stage and averaged to give a mean basal value (T_base, SBF_base). For the Recovery stage, the instantaneous values of Temp and SBF in the first 10 seconds were averaged to give mean values immediately after heating (T_postI, SBF_postI). For the remaining 10 minutes of the Recovery stage, the mean values of Temp and SBF were calculated for every minute ($T\_post_{1-10min}$, $SBF\_post_{1-10min}$). Moreover, the increase in Temp and SBF during the Recovery stage (relative to that of the Baseline stage) was compared between the two tests.

A Shapiro-Wilk test was used to test the normality of the variables. If the variables were normally distributed, a paired t-test was used to test the difference in Temp and SBF between pre- and post-intervention, and the difference in Temp and SBF response for the two thermal stimuli. If the variables were not normally distributed, a Wilcoxon matched-pair signed-rank test was used. A statistical significance level of 0.05 was used. All statistical analyses were performed in SPSS (Version 22.0, IBM, Armonk, NY, USA).

Abbreviations

Temp Temperature

SBF Skin blood flow

M2 The second metatarsal head

POAH Preoptic/anterior hypothalamus

T_base The mean value of temperature during the Baseline stage

SBF_base The mean value of skin blood flow during the Baseline stage

T_postI The mean values of instantaneous temperature in the first 10 seconds of the Recovery stage

SBF_postI The mean values of instantaneous skin blood flow in the first 10 seconds of the Recovery stage

T_ post1-10 min The mean values of temperature in each minute during the 10 minutes of the Recovery stage

SBF_post1-10 min The mean values of skin blood flow in each minute during the 10 minutes of the Recovery stage

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with clinical protocols approved by the institutional review board of Affiliated Hospital of National Research Center for Rehabilitation Technical Aids (NO. 20190102). All subjects were briefed on study aims and methods and gave informed written consent prior to participation.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

Funding

This work was supported by the National Natural Science Foundation of China [grant number 11672027].

Authors' contributions

FP, DL and YF conceived and designed research. WR, LX and XZ conducted experiments, completed data collection and analysis. WR and XZ wrote the manuscript. All authors read and approved the manuscript. All authors agree to approve the final version of the manuscript.

Acknowledgements

The authors thank all subjects who participated in this study.

References

1. Jan YK, Shen S, Foreman RD, Ennis WJ. Skin blood flow response to locally applied mechanical and thermal stresses in the diabetic foot. Microvasc Res. 2013;89:40–6. https://doi.org/10.1016/j.mvr.2013.05.004.
2. Ren W, Pu F, Luan H, Duan Y, Su H, Fan Y, Jan Y-K. Effects of local vibration with different intermittent durations on skin blood flow responses in diabetic people. Frontiers in bioengineering biotechnology. 2019;7:1–8. https://doi.org/10.3389/fbioe.2019.00310.
3. Veves A, Akbari CM, Primavera J, Donaghue VM, Zacharoulis D, Chrzan JS. et alFreeman R. Endothelial dysfunction and the expression of endothelial nitric oxide synthetase in diabetic neuropathy, vascular disease, and foot ulceration. Diabetes. 1998;473:457–63. https://doi.org/10.2337/diabetes.47.3.457.
4. Wang R. A New Work Mechanism on Neuronal Activity. Int J Neural Syst. 2015;2503:1450037. https://doi.org/10.1142/S0129065714500373.
5. Goncalves NP, V?Gter CB, Andersen H, stergaard L, Calcutt NA, Jensen TS. Schwann cell interactions with axons and microvessels in diabetic neuropathy. Nat Rev Neurol. 2017;133:135–47. https://doi.org/10.1038/nrneurol.2016.201.

6. Lohman EB, Bains GS, Lohman T, Deleon M, Petrofsky JS. A comparison of the effect of a variety of thermal and vibratory modalities on skin temperature and blood flow in healthy volunteers. Med Sci Monit. 2011;179:MT72–81. https://doi.org/10.12659/msm.881921.
7. Romero SA, Gagnon D, Adams AN, Cramer MN, Kouda K, Crandall CG. Acute limb heating improves macro- and microvascular dilator function in the leg of aged humans. Am J Physiol Heart Circ Physiol. 2017;3121:H89–97. https://doi.org/10.1152/ajpheart.00519.2016.
8. Kubo K, Yajima H, Takayama M, Ikebukuro T, Mizoguchi H, Takakura N. Changes in Blood Circulation of the Contralateral Achilles Tendon During and After Acupuncture and Heating. Int J Sports Med. 2011;3210:807–13. https://doi.org/10.1055/s-0031-1277213.
9. Astrup A, Simonsen L, Bulow J, Christensen NJ. Measurement of forearm oxygen consumption: role of heating the contralateral hand. Am J Physiol. 1988;2554:E572–8. https://doi.org/10.1152/ajpendo.1988.255.4.E572.
10. Gorodkin R, Herrick AL, Murray AK. Microvascular response in patients with complex regional pain syndrome as measured by laser Doppler imaging. Microcirculation. 2016;235:379–83. https://doi.org/10.1111/micc.12286.
11. Marshall JM, Stone A, Johns EJ. Analysis of the responses evoked in the cutaneous circulation of one hand by heating the contralateral hand. J Auton Nerv Syst. 1991;322:91–9. https://doi.org/10.1016/0165-1838(91)90059-c.
12. Rutkowski R, Straburzyńska-Lupa A, Korman P, Romanowski W, Photochemistry MGJ. and Photobiology. Thermal Effectiveness of Different IR Radiators Employed in Rheumatoid Hand Therapy as Assessed by Thermovisual Examination. Photochem Photobiol. 2011;876:1442–6. https://doi.org/10.1111/j.1751-1097.2011.00975.x.
13. Shui S, Wang X, Chiang JY, Zheng LJEB. Far-infrared therapy for cardiovascular, autoimmune, and other chronic health problems: A systematic review. Experimental Biology Medicine. 2015;24010:1257–65. https://doi.org/10.1177/1535370215573391.
14. Kim Y-M, Park S-Y, Choi H-S, Kwon O-Y. Contralateral heating effects of contrast bath and warm bath. Physical Therapy Korea. 1996;32:49–54.
15. Tomesová J, Gruberova J, Lacigova S, Cechurova D, Jankovec Z, Rusavy Z. Differences in Skin Microcirculation on the Upper and Lower Extremities in Patients with Diabetes Mellitus: Relationship of Diabetic Neuropathy and Skin Microcirculation. Diabetes Technol Ther. 2013;1511:968–75. https://doi.org/10.1089/dia.2013.0083.
16. 10.4065/78.5.603
    Charkoudian N. Skin blood flow in adult human thermoregulation: how it works, when it does not, and why. Mayo Clin Proc. 2003; 785: 603–612. https://doi.org/10.4065/78.5.603.
17. Kanosue K, Niwa K-I, Andrew PD, Yasuda H, Matsumura K. Lateral distribution of hypothalamic signals controlling thermoregulatory vasomotor activity and shivering in rats. Am J Physiol. 1991;2:R486–93. https://doi.org/10.1152/ajpregu.1991.260.3.R486. 2603 Pt.
18. Cranston W. Temperature regulation. British medical journal. 1966;25505:69.

19. Pickering G. The vasomotor regulation of heat loss from the human skin in relation to external temperature. Heart. 1932;16July:115–35.
20. Johnson JM PDW Cardiovascular adjustments to heat stress.In: Handbook of Physiology, Environmental Physiology. American Cancer Society; 2011. 215–243.
21. Shibasaki M, Umemoto Y, Kinoshita T, Kouda K, Tajima F. The role of cardiac sympathetic innervation and skin thermoreceptors on cardiac responses during heat stress. Am J Physiol Heart Circ Physiol. 2015;30811:H1336–42. https://doi.org/10.1152/ajpheart.00911.2014.
22. Yu SY, Chiu JH, Yang SD, Hsu YC, Wu CW. Biological effect of far-infrared therapy on increasing skin microcirculation in rats. Photodermatol Photoimmunol Photomed. 2006;222:78–86. https://doi.org/10.1111/j.1600-0781.2006.00208.x.
23. Vatansever F, Hamblin MR. Far infrared radiation (FIR): its biological effects and medical applications. Photonics Lasers Med. 2012;14:255–66. https://doi.org/10.1515/plm-2012-0034.
24. Jones BF. A reappraisal of the use of infrared thermal image analysis in medicine. IEEE Trans Med Imaging. 1998;176:1019–27. https://doi.org/10.1109/42.746635.
25. Schindl A, Heinze G, Schindl M, Pernerstorfer-Schn H. and Schindl L. Systemic Effects of Low-Intensity Laser Irradiation on Skin Microcirculation in Patients with Diabetic Microangiopathy. Microvasc Res. 2002;642:240–6. https://doi.org/10.1006/mvre.2002.2429.
26. Borrell RM, Parker R, Henley EJ, Masley D, Repinecz M. Comparison of in vivo temperatures produced by hydrotherapy, paraffin wax treatment, and Fluidotherapy. Phys Ther. 1980;6010:1273–6. https://doi.org/10.1093/ptj/60.10.1273.
27. Caselli A, Pham H, Giurini JM, Armstrong DG, Veves A. The forefoot-to-rearfoot plantar pressure ratio is increased in severe diabetic neuropathy and can predict foot ulceration. Diabetes Care. 2002;256:1066–71.
28. Prentice WE, Quillen WS, Underwood FB. Therapeutic modalities for physical therapists. New York: McGraw-Hill New York; 2002.

Figures

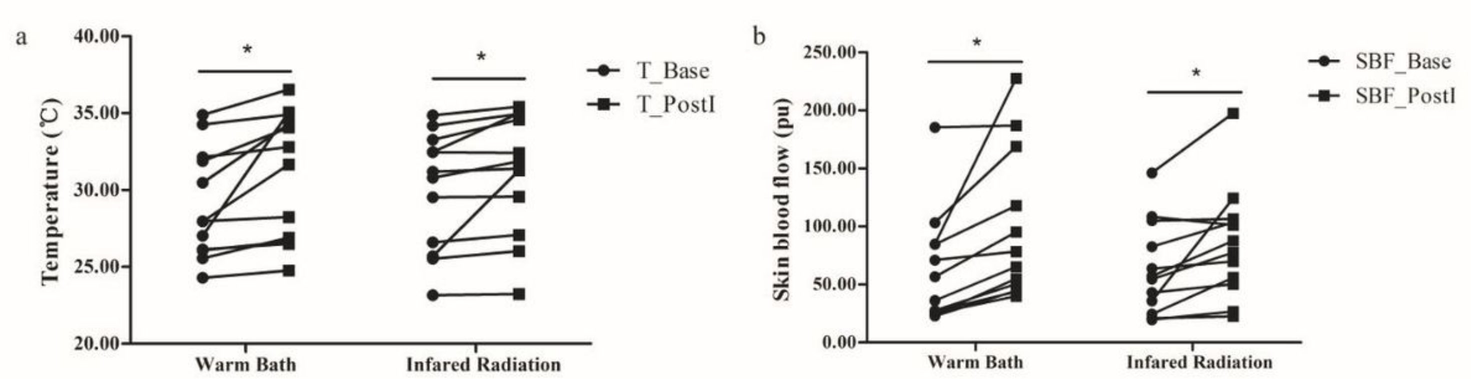

Figure 1

The plantar temperature (a) and skin blood flow (b) before and immediately after heating. T_Base and SBF_Base indicate the mean skin temperature and skin blood flow in the baseline stage, respectively. T_ PostI and SBF_PostI indicate the mean skin temperature and skin blood flow in the Recovery stage during the first 10 seconds after heating. ** indicates a significant difference between the Baseline stage and Recovery stage, p<0.01.

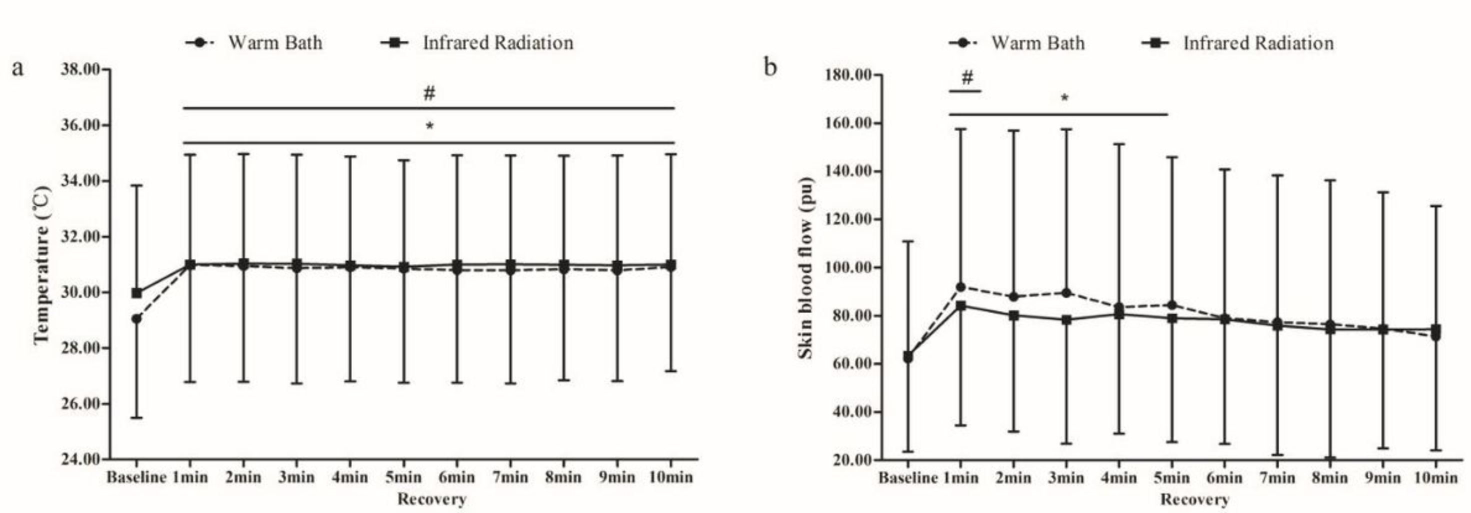

Figure 2

The plantar temperature (a) and skin blood flow (b) during the Baseline and Recovery stage. * indicates a significant difference between the Baseline and Recovery stages of the warm bath test; *: p<0.05. # indicates a significant difference between the Baseline and Recovery stages of the infrared radiation test; #: p<0.05.

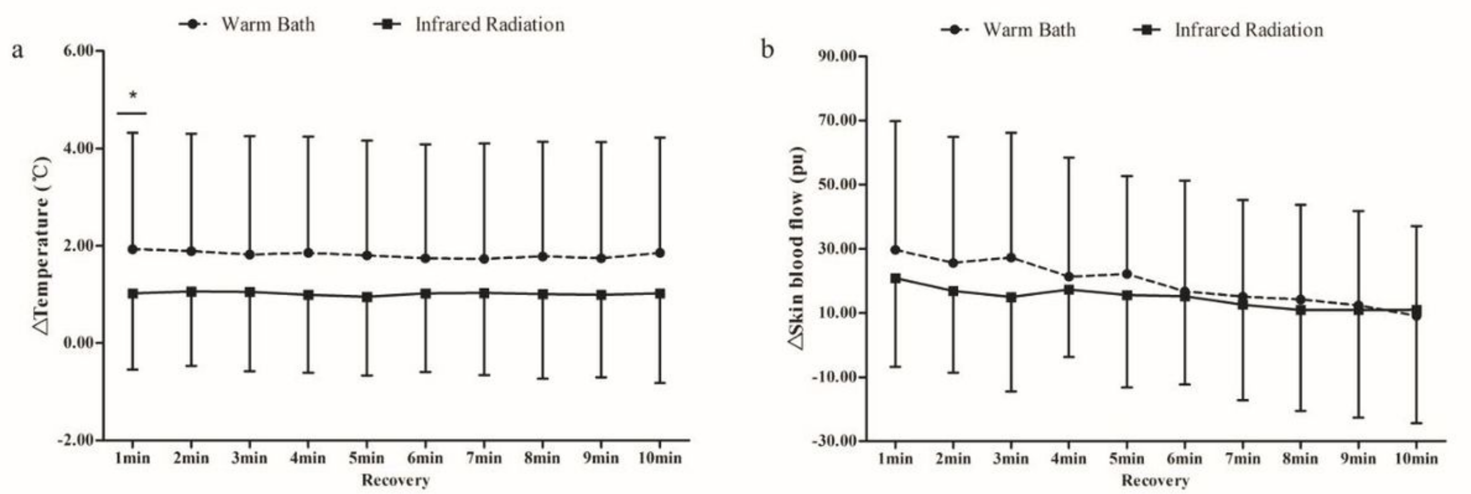

Figure 3

Increments of plantar temperature (a) and skin blood flow (b) in the Recovery stage. * indicates a significant difference in the temperature increment between the two tests; *: p<0.05.