Determination of the Conductive Heat Exchange of the Skin in Relation to Environmental Temperature

Jerrold S. Petrofsky, PhD, JD*†
Everett Lohman III, DPT Sc*
Hye Jin Suh, DPT*
Jason Garcia, BS†
Alexa Anders, BS†
Cassandra Sutterfield, BS†
Joseph Grabicki, MPT*
Chetan Khandge, BS*

*Deparment of Physical Therapy, School of Allied Health Professions, Loma Linda University, Loma Linda, California
†Deptartment of Physical Therapy, Azusa Pacific University, Azusa, California

KEY WORDS: skin, autonomic system, injury, heat

ABSTRACT

For more than 2,000 years, local tissue heating has been used to treat rheumatism, arthritis, muscle strains and sprains, and a variety of other afflictions. Heat can be applied with hot packs, ultrasound, diathermy, microwave, lasers, or a whirlpool bath. The overall effect is the same. Heat is applied to the surface of the skin in an effort to transfer the heat deep into the tissue. However, there is always a possibility of harmful as well as beneficial effects from the heating of the skin. Numerous models have been developed, including the Pennes equation, to understand how blood flow and skin conductivity are related. However, this model does not take into consideration the effect of central sympathetic outflow on skin thermal conductivity. Therefore, the present study examined heat dissipation in the skin on 4 areas on the body in 10 subjects in thermally neutral and warm environments to alter skin sympathetic activity. The results of the experiments showed that if skin thermal conductivity is measured with subjects exposed to a warm environment, heat loss is more pronounced in the skin. Thus in a cold room, hot packs cause a greater change in skin temperature and provide greater stress on the skin.

INTRODUCTION

Unlike the core tissues of the body where tissue is maintained at a fairly constant temperature of approximately 37ºC, the shell tissues of the body, that is the arms, legs, and superficial areas of the skin, are maintained at considerably lower temperatures.[1,2] For more than 2,000 years, heating of tissue has been used to increase vasodilatation of the

Table 1. Skin Blood flow, skin temperature and skin thermal index after exposure to a thermally neutral and warm environment

	Thermally Neutral Room				
	Skin Thermal Index	**Blood Flow Rest**	**Blood Flow Change**	**Skin Temp Rest ºC**	**Skin Temperature Change ºC**
Back	14.4	84.0	41.6	31.8	3.4
Hand	22.6	118.1	68.7	31.8	3.1
Quadriceps	22.8	57.6	60.4	30.6	3.3
Toe	20.8	173.9	70.4	24.4	4.7
Mean	20.2	108.4	60.3	29.7	3.6
Hand occluded	16.4	n/a	n/a	31.8	3.3

Skin thermal index = number of calories to increase skin temperature 1ºC;
blood flow change = the increase in blood flow during local heating over the 30-second period;
skin temp rest ºC = the skin temperature at each area examined at rest;
skin temperature change ºC = the skin temperature at each area examined after 30-second exposure to the brass disc

skin and the tissues below.[3] Numerous studies point to the therapeutic benefits of warming tissue.[4-6] Irrespective of the means of warming the tissue, be it diathermy, microwave, or ultrasound, [4-6] there is an increase in temperature of both the skin and the tissue below that allegedly increases tendon extensibility,[7] reduces joint stiffness,[8] and increases local tissue blood flow.[9]

Although numerous studies argue the advantages and disadvantages of one therapeutic modality versus the other in heating tissue,[10] or using combined modalities such as hot packs and ultrasound together,[7] the fact remains that heat must be transferred from the skin to deep tissue in order to be effective. By warming the skin, a thermal gradient is established between the surface of the skin and the deep arteries of the body, thereby warming the tissue in between. For example, typical forearm temperature at the surface of the skin is approximately 31ºC, whereas temperature of the bone is approximately 33ºC.[1] To increase deep tissue temperature, considerably higher temperatures are necessary at the surface of the skin. For example, increasing skin temperature to 42ºC causes an increase in circulation, which then dissipates some of the heat but allows other heat to transfer through conductive heat loss to deep tissues below.[1,11]

Body fat has a strong influence on skin and deep tissue temperature in men at rest.[12] Subjects with a high body fat content have poor conductive heat loss to the deep tissues, and therefore require higher surface temperatures for heat transfer.[13] There is also a tendency to use higher temperatures in some populations where local tissue temperatures are sometimes elevated to 42ºC or 43ºC using microwave,[14,15] ultrasound,[16] or lasers.[17] When thermal conduction of the skin is overloaded, damage can result to the skin.[18]

To understand the factors that influence the conduction of heat across the skin, Pennes heat equation is commonly used.[19,20] Recently, Gowrishankar showed that a transport lattice matrix is also a good approach to understanding heat dissipation in the skin.[18] However, neither model takes into consideration changes in skin blood flow associated with altered sympathetic outflow.

		Warm Room		
Skin Thermal Index	Blood Flow Rest	Blood Flow Change	Skin Temp Rest ºC	Skin Temperature Change ºC
41.1	94.3	46.8	35.8	1.1
33.8	184.8	71.5	36.3	1.3
27.0	128.2	107.5	34.8	1.9
50.8	198.2	100.9	35.5	1.2
38.2	151.4	81.7	35.6	1.4
26.3	n/a	n/a	36.5	1.4

Because sympathetic vasoconstriction can override all other stimuli to the skin and reduce skin blood flow even in the face of noxious stimuli,[2] alteration in sympathetic outflow due to global heating, for example, may alter the thermal conductivity of the skin.

Therefore, in the present investigation, conductivity of the skin was assessed in 10 subjects at 2 environmental temperatures, a thermally neutral temperature and a warm temperature. The ability of the skin to dissipate heat was then assessed under both environmental conditions by applying a heated brass disc to the skin and monitoring the change in skin temperature and skin blood flow as the brass disc cooled. By knowing the number of calories added to the skin and the change in skin temperature, the thermal conductivity of the skin could be calculated.

SUBJECTS

A group of 10 subjects was examined. The average age of the subjects was 25.9 ± 3.4 years. The average height was 165.3 ± 3.3 cm and the average weight was 61.8 ± 7.6 kg. All subjects were medically screened prior to the investigation and signed a form acknowledging their consent to participate in the study. All protocols and procedures were approved by the Committee on Human Experimentation at Loma Linda University.

METHODS

Measurement of Heat Dissipation

The ability of the skin to dissipate heat was measured by applying a 48-gram brass disc to the surface of the skin (diameter 25 mm). The disc was coated with 3 coats of polyurethane rubber to avoid heat loss except on the bottom surface. A hole was drilled (5 mm) through the center of the disc to allow simultaneous blood flow measurements under the area where the disc was applied by allowing the laser (Moor Instruments, Oxford England) to scan through the brass disc. Furthermore, a small hole was drilled (1 mm) through the side of the disc so that a thermistor could be inserted into the center to measure the temperature of the brass disc (Biopac Systems, Goletta, CA). The disc was then held by a thin wire and

placed in a water bath at a temperature of 41ºC for 1 minute prior to use. This brought the brass disc to a uniform temperature. The disc was then lifted out of the bath, quickly blotted dry, and placed on the skin. Once the disc was placed on the skin, the change in brass disc versus skin temperature was assessed over a 30-second period to measure the heat transfer from the disc to the skin. Temperature of the skin was measured by a second thermistor (Biopac Incorporated, Goleta, CA). The data from the 2 thermistors were amplified with 2 Biopac amplifiers and digitized with a 16-bit analogue-to-digital converter and a Biopac MP 150 system. Before each experiment, the thermistors were calibrated in a controlled temperature water bath against a standard thermometer to assure accuracy in the temperature measurements.

Measurement of Blood Flow

Blood flow was measured by a Moor Instruments laser Doppler imager (Oxford, England). The imager was used in the single point mode such that a single laser beam continually monitored blood flow in 1 location. The laser was calibrated with standard calibration beads on a weekly basis to assure its accuracy and repeatability in flow measurements. The laser was kept at a distance of 20 centimeters above the skin for all measurements.

Method of Clamping Skin Temperature

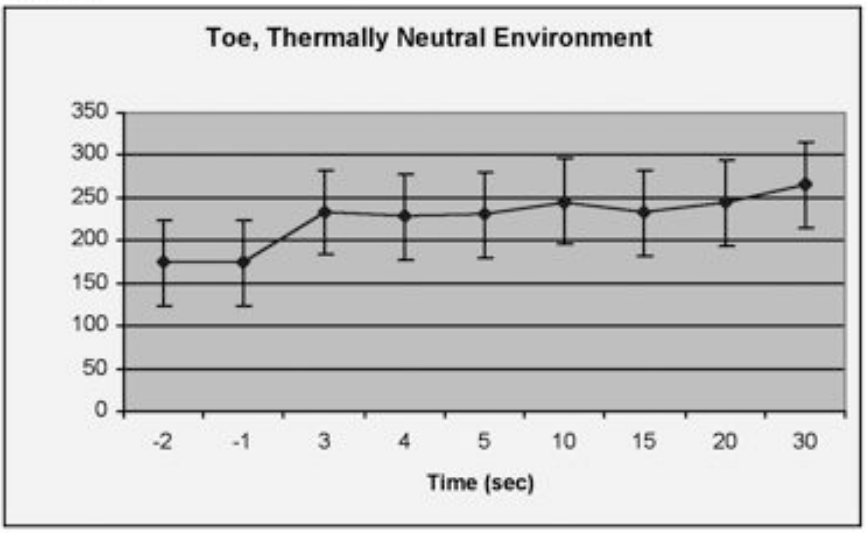
Skin temperature was clamped using a Peltier junction. The Peltier junction had heat sinks mounted on the top to dissipate cold and was connected to a 12-volt variable current power supply. As the current was increased into the Peltier junction, heat was applied to the skin. Generally, the current used was 300 milliamps at 1.5 volts or 0.45 watts. Current was applied to the Peltier junction to slowly increase the temperature of the skin to 29º, 32º, 35º, 38º, and 40ºC, and then at each temperature, current was reduced to clamp skin at that temperature for 30 seconds prior to blood flow measurements.

PROCEDURES

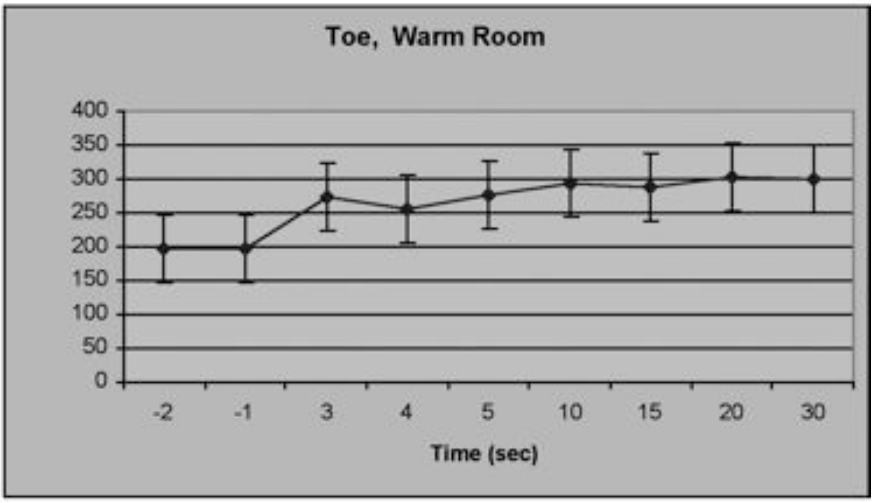
On any 1 day, subjects entered the laboratory and sat in either a thermally neutral room or a warm room (38ºC) at rest for 20 minutes. Subjects wore short sleeve shirts and shorts during this period of time. The temperature of the room was regulated either at 18º ± 2ºC (thermally neutral environment) or 38º ± 2ºC (warm environment) with humidity at 35 ± 10%. After the subject rested, he or she lay in a horizontal posture and points were marked on the lower back, above the quadriceps muscle, toe, and hand where measurements would be taken. In random order, the heated brass was applied to the skin for a period of 1 minute and changes in skin temperature, skin blood flow, and the temperature of the brass disc were measured continuously as described previously. This was accomplished both in the thermally neutral and warm rooms at each body location. Finally, in an additional set of experiments, only on the toe and the back, the skin was heated in stages to 29º, 32º, 35º, 38º, and 40ºC with a Peltier junction, and blood flow was measured through a hole in the center of the Peltier junction. This latter series of experiments was performed to see the interaction between central sympathetic outflow and local heat on altering skin blood flow.

Statistical Analysis

Statistical analyses involve the calculations of means, standard deviation (SD), and Student's *t*-tests. In addition, a repeated measure analysis of variance (ANOVA) was used to compare the changes within groups. The level of significance was $P<0.05$.



A



B

Figure 1. The blood flow (flux) measured on the toe in 10 subjects as the mean ± SD at 2 seconds before, 1 second before, and at 3, 4, 5, 10, 15, 20, and 30 seconds after the application of the brass disc; (A) shows the response of the 10 subjects in the thermally neutral room whereas (B) shows the response of the subjects in the heated room.

RESULTS

When the disc was applied to the skin, there was an exponential decrease in disc temperature and an exponential increase in skin temperature. As shown in Table 1, the skin temperature average for the 4 regions of the body started at 29.7ºC before the application of the disc and then increased by an average of 3.6ºC after application of the brass disc in the thermally neutral environment. The lowest temperature recorded for the

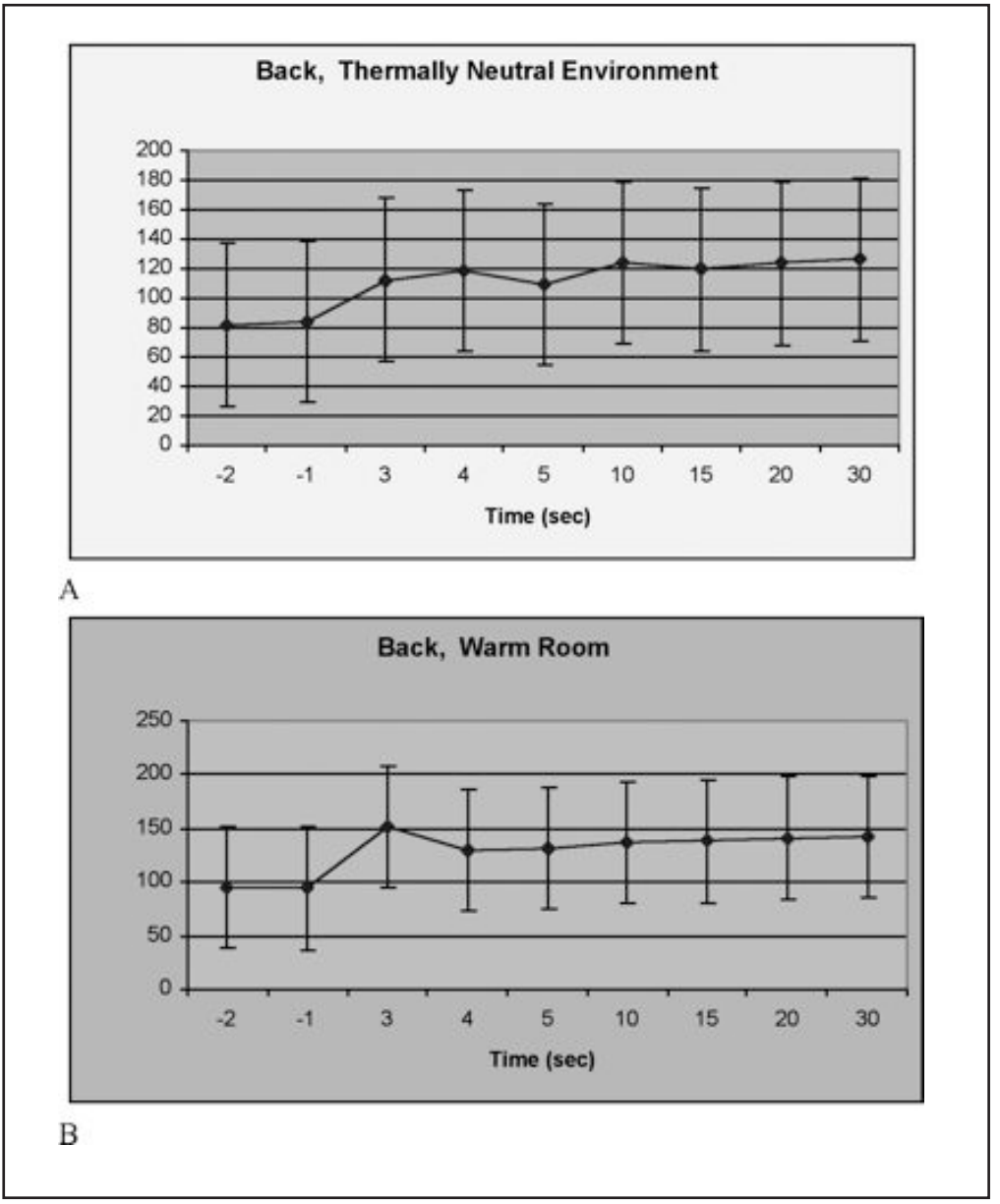


Figure 2. The blood flow (flux) measured on the back in 10 subjects as the mean ± SD at 2 seconds before, 1 second before, and at 3, 4, 5, 10, 15, 20, and 30 seconds after the application of the brass disc; (A) shows the response of the 10 subjects in the thermally neutral room whereas (B) shows the response of the subjects in the heated room.

skin was on the toe where the temperature was significantly cooler than the other 3 regions of the body ($P<0.01$) by ANOVA. Coincidentally, this area showed the greatest increase in temperature after application of the disc, increasing by 4.7ºC. In contrast, in the warm environment (hot), average skin temperature started much higher (35.6ºC) than when the subjects were in the neutral room. Here, there was no statistical difference between the skin temperatures and location.

Interestingly, the change in the skin

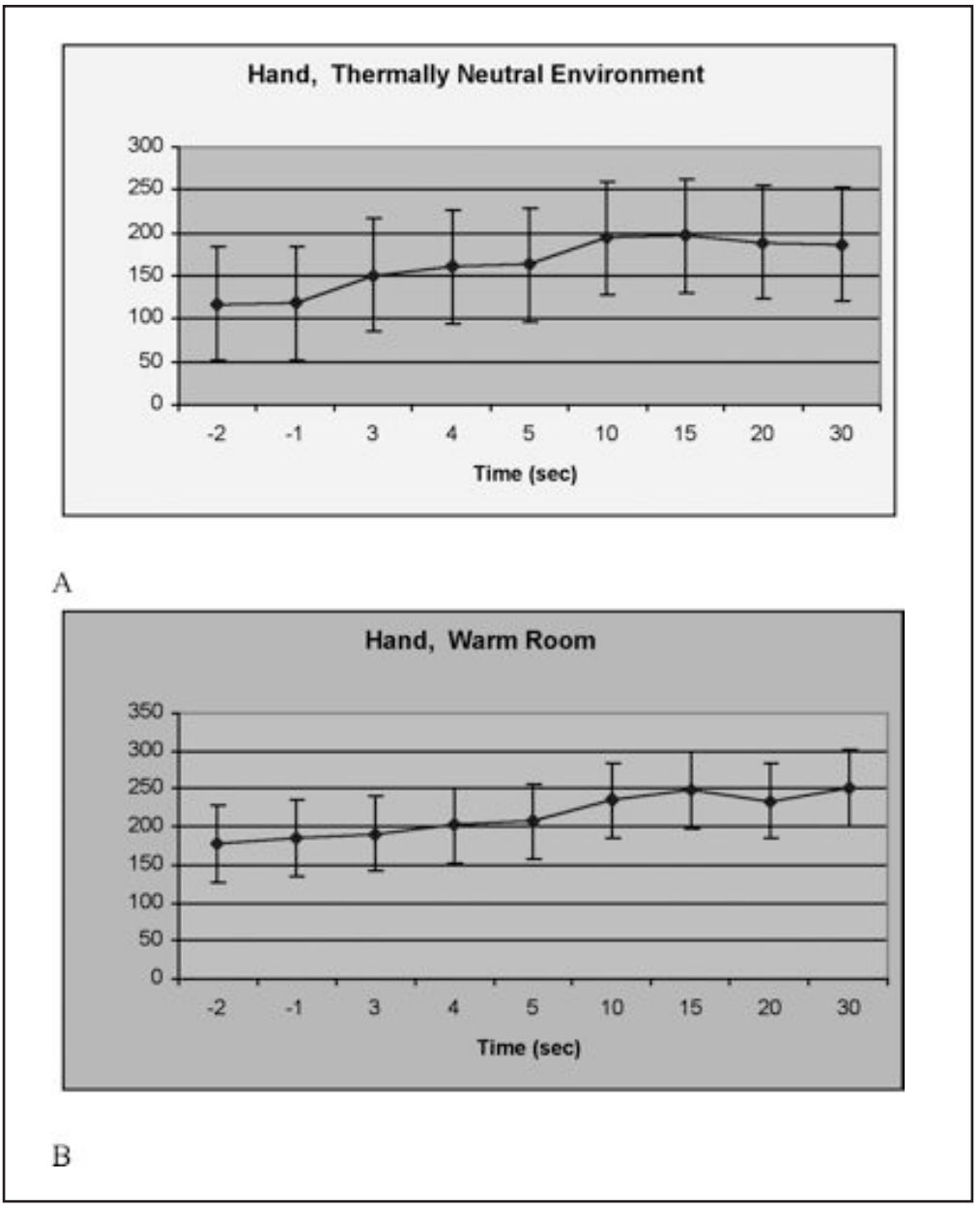


Figure 3. The blood flow (flux) measured on the hand in 10 subjects as the mean ± SD at 2 seconds before, 1 second before, and at 3, 4, 5, 10, 15, 20, and 30 seconds after the application of the brass disc; (A) shows the response of the 10 subjects in the thermally neutral room whereas (B) shows the response of the subjects in the heated room.

temperature after disc application, which was also statistically greater in the toe than in the other areas of the body in the cooler environment ($P<0.05$), was significantly less in each region of the body in the warm room ($P<0.01$). In the warm environment, the change in skin temperature was approximately one third of that of the thermally neutral environment. Thus, if the room was

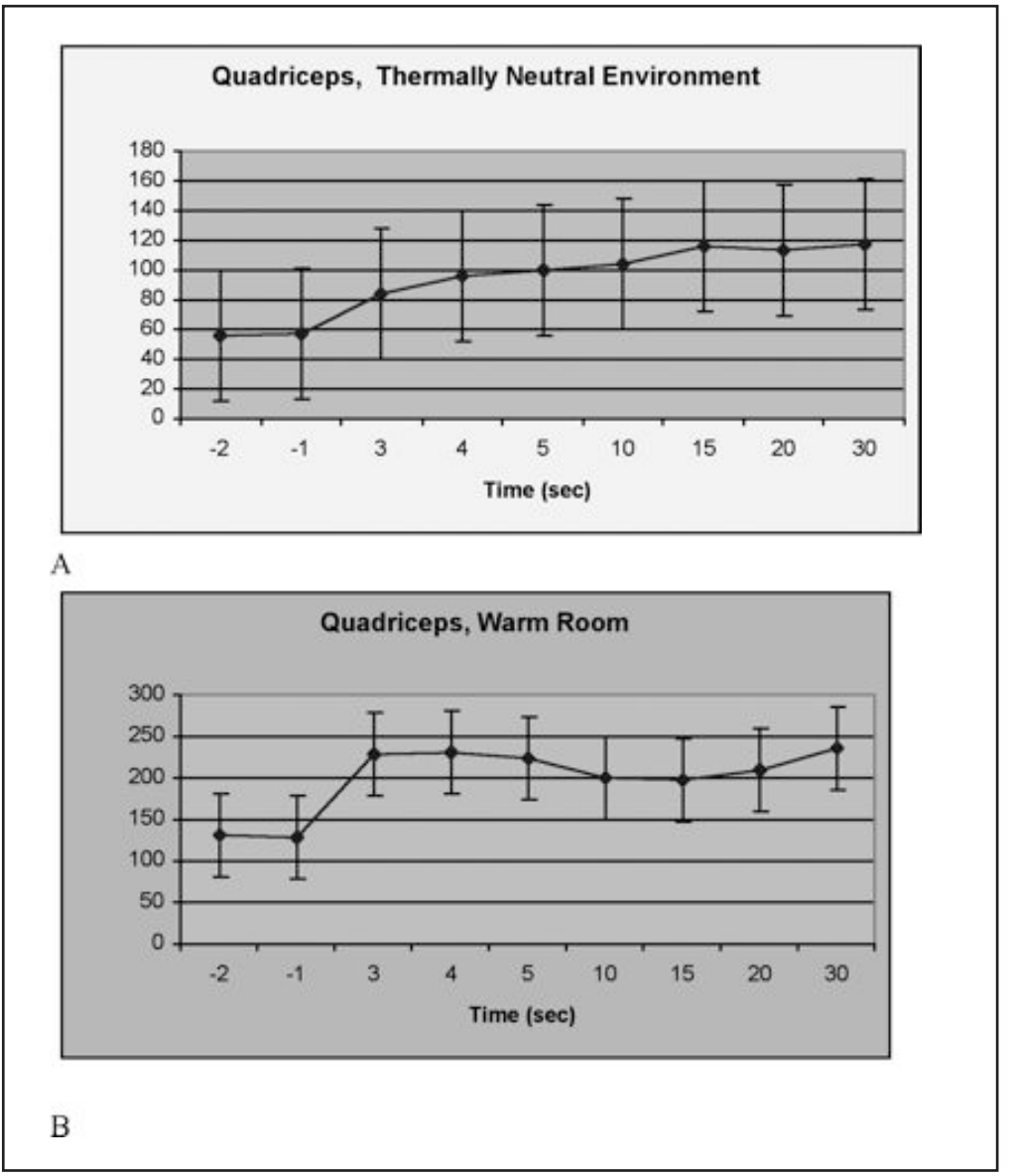


Figure 4. The blood flow (flux) measured on the quadriceps in 10 subjects as the mean ± SD at 2 seconds before, 1 second before, and at 3, 4, 5, 10, 15, 20, and 30 seconds after the application of the brass disc; (A) shows the response of the 10 subjects in the thermally neutral room whereas (B) shows the response of the subjects in the heated room.

warm, then there was little heating of the skin.

The resting blood flow 2 seconds before the application of the disc and the blood flows over a 30-second period during which the brass disc was placed on the skin are shown in Figures 1 through 4 respectively for the toe, back, hand, and quadriceps muscle. Each graph shows the mean ± SD for the group. In addition, each figure shows the resting skin blood flow and the changes in blood flow that resulted from application of the disc in the thermally neutral room and the 38ºC environment.

As can be seen in these figures and

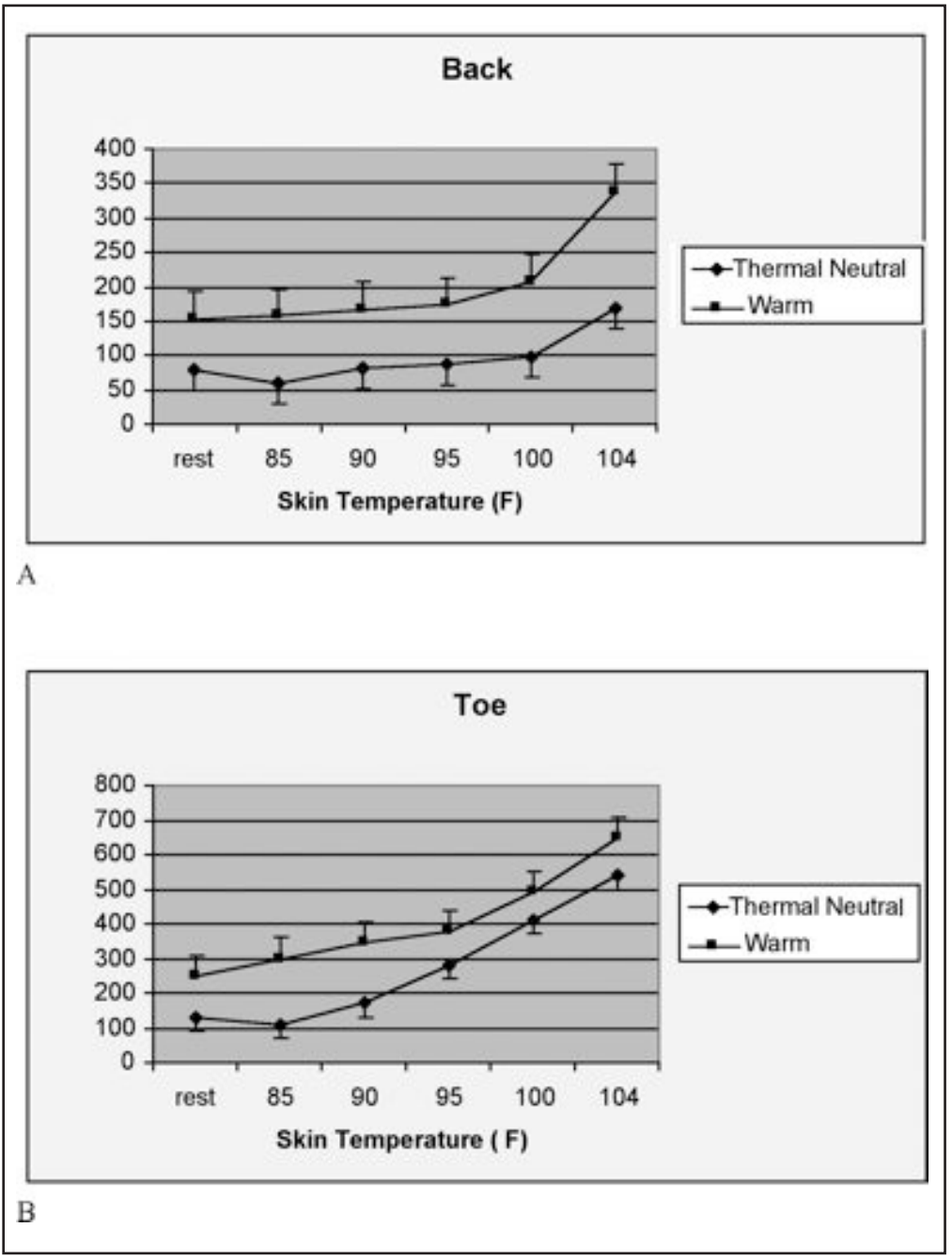


Figure 5. The skin blood flow (in flux) from the back and the toe when skin temperature was clamped at 29°, 32°, 35°, 38°, and 40oC (85°, 90°, 95°o, 100°, 104°F). Each graph shows the response of the subject in the thermally neutral and warm environments.

summarized in Table 1, for the toe, blood flow at rest was highest in any level in the body averaging 173.9 flux in the thermally neutral room and at 198.2 flux in the warm room. In contrast, for the quadriceps, blood flow was lowest averaging 57.6 flux in the thermally neutral room and 128.2 flux in the warm room.

The increase in blood flow comparing rest to after 30-second application of the brass disc was significant in the both the thermally neutral room and the warm room ($P<0.01$). However, the change in the blood flow was greatest in the warm room for each of the 4 regions of the body averaging 81.7 flux increase compared to a 60.3 flux increase in the cooler environment. The increase in blood flow after application of the brass disc was significantly greater above the quadriceps muscle and the toe in the warm room ($P<0.05$) compared with the back and hand. This can be seen in Table 1 and Figure 1 for the toe. The pattern of blood flow change for the toe was nearly identical after application of the brass disc to the toe after exposure to either of the 2 environmental temperatures, showing an immediate and then continuous increase in blood flow over the 30-second period. For the skin on the back, although blood flow varied greatly from one person to another as assessed by the SD in Figure 2, the same general trend was seen. As shown in Figure 3 for the hand, blood flow was substantially higher and also showed the same general trend; however, blood flow increased steadily throughout the 30-second period rather than showing a rapid response at the beginning as was the case for Figures 1 and 2. Finally, as shown in Figure 4, blood flow increased very rapidly on the skin above the quadriceps muscle in both the thermally neutral and warm environments after application of the brass disc.

Based on these results that showed that some areas of the body produced a greater blood flow response to local heating of the skin after global heating, an additional series of experiments was accomplished using a Peltier junction as described in the Procedures section. In this series, skin temperature was clamped at 29°, 32°, 35°, 38°, and 40°C (85°, 90°, 95°, 100°, and 104°F), and blood flow was assessed. This was accomplished in both the 38°C room and the thermally neutral room. The results from the back and toe are shown in Figure 5. As can be seen in this figure, blood flow, which, as shown in the previous figures, increased with global heating, increased further as skin temperature was elevated. However, for any given skin temperature, the blood flow response was substantially higher in the warmer environment. Thus, local heat and global heat both interacted together in producing a blood flow response to a thermal stress. For the back, the difference between the blood flows after exposure to the 2 different environmental temperatures was almost double, whereas for the toe, it was somewhat less. Repeated measured ANOVA showed that the blood flow difference was significant at any 1 skin temperature between the 2 environments ($P<0.05$).

Given the above, the thermal conductivity of the skin was calculated, and it was determined as a heat transfer index. This was accomplished by performing an additional experiment at each environmental temperature in which the disc was pulled out of the warm water bath, blotted, and then the temperature was monitored for 30 seconds. In this manner, the temperature loss of the disc alone could be calculated without touching the skin. By then using the temperature loss of the disc over a 30-second period compared with the temperature loss of the disc when laid on the skin, the actual loss of temperature from the disc into the skin could be calculated. Because the brass disc weighed 48 grams and brass has a specific heat of 0.095, the number of calories lost by the disc can be calculated by the product of the change in disc temperature after application of the disc to the skin for 30 seconds, the disc weight, and the thermal coefficient of the disc. For example, if the disc temperature were

reduced by approximately 2ºC, the disc would loose approximately 9 calories.

As shown in Table 1, in the cooler environment, for the skin of the back the thermal index was 14.4. To raise the skin temperature 1ºC, 14.4 calories of heat need to be added to the skin under the disc. This calculation pertains to a square surface area for the disc and skin of 0.00491 square meters. Therefore, the total number of calories to raise 1 square meter of skin (approximately half the body surface area) would be 29,346 calories for the back. More calories are required for a square meter of the hand, quadriceps, or toe. In the hand, 46,027 calories are required to raise 1 square meter of skin by 1ºC, while for the quadriceps the figure is 46,462 calories, and for the toe it is 46,392 calories.

In the warmer environment, also shown in Table 1, the thermal index averaged twice as high, and some specific areas of the body were substantially higher. For example, in the toe, the thermal index was 50.8 in the warmer environment compared with 20.8 in the thermally neutral environment. Therefore, it would require more than 90,000 calories to heat a square meter of skin at the toe by 1ºC. The smallest difference in thermal index was seen with the quadriceps muscle. Thermal index for the other areas of the body was still substantially higher in the warmer than the thermally neutral environment. These differences were significant ($P<0.01$).

DISCUSSION

Numerous modalities have been used to heat the skin in an effort to increase skin circulation as well as the circulation and temperature of the underlying tissue. These include diathermy, microwave, ultrasound,[4-6] and hot packs.[7] The purpose of these techniques is to develop a thermal gradient from the skin to the underlying muscle such that the muscle, soft tissue, and tendons begin to warm and thereby increase extensibility and reduce pain.[8,21] Global heating also increases tissue blood flow.[9]

In the present investigation, rather than applying a continuous hot pack or using other modalities to increase tissue temperature, heat was applied with a small piece of metal such that a limited number of calories could enter the skin. In this manner, the actual thermal conductivity the skin could be measured as the magnitude of the skin response to limited local heat exchange. It is well known that when heat overloads the skin, damage can result.[18] Using hot packs or microwave radiation, local skin temperature has been recorded as high as 42º to 43ºC.[14,22] Pennes developed a heat equation to study at what point the skin could be damaged by too much heat.[19,20] However, these models for predicting burns did not take into consideration local sympathetic outflow.

In a clinical setting, rooms are always kept cool (approximately 17ºC). This is due to the belief that bacteria can develop more readily in a hospital setting with warmer room temperatures.[5] As such, most experiments have been performed on heat conduction in the skin during treatment in these cool room temperatures. At these cooler temperatures, there is considerable vasoconstriction of the skin to protect the core temperature of the body.[23] Sympathetic vasoconstriction is often seen in a cool environment, and it can override noxious stimuli such as electrical stimulation, thereby preventing blood flow from increasing.[24] This is also true of contrast baths. When contrast baths are used, if the room is thermally neutral, the blood flow response is poor compared with the response seen if the room is warm.[25]

It is no surprise then, that in the warmer environment, skin blood flow is higher and hence, because of the higher blood flow, it takes more calories of heat

to change skin temperature. With higher blood flow, the blood, which has a very high thermal conductivity, will pull heat away from the heat source.

Thus, by just increasing the room temperature to 38ºC (102ºF), it takes twice as much heat from the disc to warm the skin to the same extent as seen in the cooler environment. Skin blood flow is strongly related to environmental stress. In a warmer environment such as a 42ºC, blood flow increases even more. As such, thermal conductivity should even be higher. Therefore, the effectiveness of a single point heat source seems to be best in a cooler environment. When using this in a cooler environment, the change in skin temperature (and presumably deep muscle temperature) would be higher than if the room was warmed or the person was in bed under the covers. If a person was warm under blankets or heavy comforters, just as with a warm room, sympathetic cholinergic vasodilator afferents should increase skin blood flow and make a single point heat source less effective.

However, it should be noted that the blood flow change was greater in the warmer environment. Thus, there seems to be 2 contradictory events occurring. The increase in skin blood flow associated with applying a single point heat source was greater with a subject who had been preheated. With a relaxation in sympathetic vasoconstrictor activity and an increase in vasodilator activity, local heat caused by the release of nitric oxide from the vascular endothelial cells causes a greater blood flow response.[23] This is the exact same phenomenon seen in previous studies with contrast baths,[23] and yet tissue temperature did not change as much. Thus, if the purpose of using a single point heat source is to increase blood flow, then keeping the subject in a warmer environment or wearing warm cloths with a single point heat source underneath should increase blood flow more effectively. However, if the object of using the single point heat source is to increase deep tissue temperature, then single point heat sources are less effective under these circumstances (because skin temperature has a reduced thermal gradient in a warm environment). This is not to say that single point heat sources are ineffective if the room is warm or if someone is wearing heavy clothing; the advantage of using this modality is simply reduced.

REFERENCES

1. Petrofsky JS, Lind AR. The insulative power of body fat on deep muscle temperature and isometric endurance. *J Appl Physiol.* 1975;39:639-642.
2. Petrofsky JS, Stuart B, Patterson C, et al. Sweat production during global heating and during isometric exercise in people with diabetes. *Med Sci Monit*. 2005;11:CR515-CR521.
3. Taguchi A, Ratnaraj J, Kabon B, et al. Effects of a circulating-water garment and forced-air warming on body heat content and core temperature. *Anesthesiology*. 2004;100:1058-1064.
4. Hayes KW. Heat and cold in the management of rheumatoid arthritis. *Arthritis Care Res*. 1993;6:156-166.
5. Hecox B, Mehreteab TA. *Physical Agents.* Appleton and Lange; 1994;103-154.
6. Michlovitz SL. *Thermal Agents in Rehabilitation.* Philadelphia, PA: FA Davis; 1996:216-243.
7. Lehmann JF, Stonebridge JB, DeLateur BJ, et al. Temperatures in human thighs after hot pack treatment followed by ultrasound. *Arch Phys Med Rehabil.* 1978;59:472-475.
8. O'dell AJ. Hot packs for morning joint stiffness. *Am J Nurs*. 1975;75:986-987.
9. Greenberg RS. The effects of hot packs and exercise on local blood flow. *Phys Ther* 1972;52:273-278.
10. Borrell RM, Parker R, Henley EJ, et al. Comparison of in vivo temperatures produced by hydrotherapy, paraffin wax treatment, and fluidotherapy. *Phys Ther.* 1980;60:1273-1276.
11. Petrofsky JS, Lind AR. The relationship of body fat content to deep muscle temperature and isometric endurance in man. *Clin Sci Mol Med.* 1975;48:405-412.

12. Webb P. Temperatures of skin, subcutaneous tissue, muscle and core in resting men in cold, comfortable and hot conditions. *Eur J Appl Physiol Occup Physiol.* 1992;64:471-476.

13. Veicsteinas A, Rennie DW. Thermal insulation and shivering threshold in Greek sponge divers. *J Appl Physiol.* 1982;52:845-850.

14. Liu J, Zhu L, Xu XL. Studies on the three-dimensional temperature transients in the canine prostate during transurethral microwave thermal therapy. *J Biomech Eng*. 2000;122:372-379.

15. Martin GT, Bowman HF, Newman WH, Cravalho EG. Thermal model with temperature dependent perfusion for the hyperthermia treatment of benign prostatic hyperplasia. *Adv Biol Heat Mass Transf ASME.* 1991;18:33-37.

16. Seip R, Ebbini ES. Studies on the three-dimensional temperature response to heating fields using diagnostic ultrasound. *IEEE Trans Biomed Eng*. 1995;42:828-839.

17. Puccini S, Bar NK, Bublat M, et al. Simulations of thermal tissue coagulation and their value for the planning and monitoring of laser-induced interstitial thermotherapy (LITT). *Magn Reson Med*. 2003;49:351-362.

18. Gowrishankar TR, Stewart DA Jr, Martin GT, Weaver JC. Transport lattice models of heat transport in skin with spatially heterogeneous, temperature-dependent perfusion. *Biomed Eng Online* [serial online]. 2004;3:42.

19. Pennes H. Analysis of tissue and arterial blood temperature in the resting human forearm. *J Appl Physiol*. 1948;1:93-122.

20. Wissler EH, Pennes' 1948 paper revisited. *J Appl Physiol.* 1998;85:35-41.

21. Lehmann JF, Warren CG, Scham SM. Therapeutic heat and cold. *Clin Orthop* 1974;99:207-245.

22. Alekseev SI, Ziskin MC. Local heating of human skin by millimeter waves: a kinetics study. *Bioelectromagnetics.* 2003;24:571-581.

23. Moseley B, Korson R, Petrofsky J, et al. The effects of contrast baths on skin blood flow in people with type 2 diabetes and age matched controls. *J Investig Med.* 2006;54(suppl 1):229.

24. Petrofsky JS, Hill J, Jorritsma R, et al. Muscle use during low impact aerobic exercise (gliding) compared to conventional weight lifting equipment. *J Appl Res.* 2005;5:136-148.