Cooling Efficiency of 4 Common Cryotherapeutic Agents

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**Context:** Cryotherapy is the application of cold as a treatment. It is widely used and accepted as beneficial in early management of soft tissue injury. However, the most efficient cryotherapeutic agent remains unknown.

**Objective:** To compare 4 common cryotherapeutic agents including crushed ice (CI), gel pack (GP), frozen peas (FP), and ice-water immersion (WI) and to determine which agent provided the greatest cooling efficiency after a 20-minute application.

**Design:** Repeated-measures design.

**Setting:** University physiology laboratory.

**Patients or Other Participants:** Nine healthy volunteers participated (5 males, 4 females; age = 24.0 ± 4.6 years, height = 1.73 ± 0.24 m, mass = 79.9 ± 24.1 kg).

**Intervention(s):** The CI, GP, FP, and WI were applied to the right ankle for 20 minutes. Participants were required to attend 1 measurement session for each agent.

**Main Outcome Measure(s):** We recorded skin surface temperature of the right ankle at a sampling rate of 1 image/min, using a thermal imaging camera during a 30-minute rewarming period.

**Results:** Application of CI produced a significantly greater reduction in skin surface temperature (19.56 ± 3.78°C) than GP (13.19 ± 5.07°C) and FP (14.59 ± 4.22°C) (P < .001). The CI and WI demonstrated significantly (P < .001) greater cooling efficiency than GP and FP.

**Conclusions:** The CI and WI had the greatest cooling efficiency and sustained decreased skin surface temperatures postapplication, indicating these agents are potentially the most clinically beneficial.

**Key Words:** thermal imaging, skin surface temperature

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**Key Points**

- Choice of modality should be an important part of clinical decision making.
- Preapplication temperature is not a good indicator of modality effectiveness or efficiency (ie, colder is not necessarily better).
- Thermal imaging is a useful tool for clinical cryotherapy research.

Cryotherapy is the lowering of tissue temperature by withdrawal of heat energy from the body to achieve a therapeutic effect.¹ Heat energy is removed via conduction² from the skin to the agent during cryotherapy. Comparing application of cryotherapeutic agents on the quadriceps muscle, investigators consistently have identified crushed ice (CI) as the most effective and gel pack (GP) as the least effective method of lowering both skin surface and intramuscular temperature.²⁻⁵ They have reported skin surface temperatures of 6.47°C and 10.2°C after application of CI. The Fourier law governs heat transfer by conduction and states: “per unit area the transfer in a given direction is proportional to the temperature gradient.” The law implies that a steeper temperature gradient provides more opportunity for heat energy transfer. Therefore, CI may have a lower preapplication temperature than GP has, but these preapplication temperatures have not been compared. Merrick et al⁴ attributed the apparent efficacy of CI to its ability to undergo phase change, which increases its capacity to absorb heat energy.

Efficacy is the capacity of the agent to produce an absolute cooling effect regardless of its preapplication temperature. Efficiency is the production of a desired effect with minimal waste. Thus, cooling efficiency is the ability of the cold agent to bring local skin surface temperature to equilibrium, and it includes the preapplication temperature of the agent. Preapplication temperature and efficiency of cooling agents have not been investigated. The skin is rarely the target tissue during cryotherapy, and Jutte et al⁶ reported no relationship between skin surface temperature and deeper tissue temperature. However, the skin is unavoidably the tissue that is cooled first because of its immediate proximity to the cooling agent. Therefore, skin surface temperature serves as a useful measure in determining the cooling efficiency of cryotherapeutic agents.

The skin effectively cools the deeper tissues by transferring the cooling. However, because of their lower thermal conductivity and diffusivity, adipose and muscle tissue are effective insulators,⁷ which indicates that the temperature gradient attenuates as tissue depth increases. Otte et al⁸ reported an increase in cooling time of deep tissue with increased adiposity.

Researchers⁶,⁹ suggested that deeper tissue cooling continues on removal of the cold agent as the superficial tissues rewarm. Optimal temperature of the target tissue has not been defined. However, authors⁶,⁹ reported that a skin surface temperature of 13.6°C reflects local analgesia and 12.5°C reflects...
a 10% reduction in nerve conduction velocity. Skin surface temperatures between 10°C and 11°C reflect a 50% reduction in cellular metabolism,9 with the onset of cell hypometabolism occurring at a skin surface temperature of 15°C.10–12 Collectively, these findings define a therapeutic skin surface temperature range from 10°C to 15°C. Therefore, an efficient agent has a preapplication temperature within this range. This temperature range potentially would increase patient comfort during cryotherapy and, in turn, increase patient compliance with treatment.

We compared the cooling efficiency of 4 commonly used cryotherapeutic agents at the ankle and investigated skin surface temperature over a region of interest (ROI) during a 30-minute rewarming period after a 20-minute application13 at the ankle.

METHODS

Participants

The university’s Faculty of Health Research Ethics Committee approved the study. The study conformed to the World Medical Association Declaration of Helsinki (1964).

Nine healthy volunteers from the staff and student populations of the University of Central Lancashire and from the staff of the Accident and Emergency Department at Royal Preston Hospital, Preston, UK, participated in this study (5 males, 4 females; age = 24.0 ± 4.6 years, height = 1.73 ± 0.24 m, mass = 79.9 ± 24.1 kg).

Criteria for exclusion from the study included referred pain to the lower limb from spinal, pelvic, or hip joints; pregnancy; increased temperature of the ankle joint; psychological problems; systemic disease; sensory deficit; cold intolerance or hypersensitivity; and skin lesions. Before participating in the study, all volunteers completed a health status questionnaire (a modified physical activity readiness questionnaire)14 and gave written consent.

All participants were required to attend 1 testing session for each of the 4 cryotherapeutic agents. Before each testing session, we administered a participant questionnaire to discover whether volunteers were still eligible for participation in the study.

Equipment

A ThermoVision A40M Thermal Imaging camera (Flir Systems, Danderyd, Sweden) was positioned 0.6 m perpendicular to the lateral malleolus of the right ankle. The validity and reliability of using noncontact, digital, infrared, thermal imaging (TI) cameras to measure skin surface temperature have been reported.15–19

Application of Cryotherapeutic Agent

Using a thermometer, we recorded ambient room temperature at the beginning of each testing session and after application of the cryotherapeutic agent to ensure that room temperature was stable. At least 24 hours was allowed between testing sessions.

Participants removed shoes and socks from both feet and sat in a semirecumbent position on a treatment couch (Doherty Medical, London, UK) with both legs extended. Participants were encouraged to adopt a relaxed and comfortable position that could be maintained for the duration of the testing session. Bare lower limbs were allowed to acclimate for 20 minutes to equilibrate to ambient room temperature, which is standard protocol when using a noncontact TI camera.15–19 Each cryotherapeutic agent was applied to the right ankle of all participants; the left ankle served as the control. Before testing, we examined both lower limbs to ensure absence of skin wounds, lesions, or rashes. To ensure participants could differentiate warm from cold, we carried out thermal sensation testing over the local area by touching the ankle with a warm test tube and a cold test tube. A dry, cotton tea towel was placed under the right foot and taped in place on the treatment couch. A baseline thermal image of the ankle was taken before application of the cryotherapeutic agent.

The 4 cryotherapeutic agents tested were 1 L of CI (Scotsman Ice Machines, Milan, Italy) in a terrycloth bag, GP (Boots Sports Hot/Cold Compress, 300 g, Boots, UK), FP (Asda Petits Pois variety, 907 g, Leeds, UK) in the plastic packaging, and WI (6 L of cold water with 1 L of crushed ice in a bucket). The temperature of each treatment was taken immediately before and after application. We took 1 thermal image each of CI, GP, and FP and analyzed the 3 images in Thermacam Researcher 2.8 software (Flir Systems). The temperature of WI was taken using a probe attached to a hydrothermometer and submerged in water.

We applied CI, GP, and FP with the participant maintained in the described position. On application, the FP were wrapped in a cold, terrycloth towel13 to prevent superficial skin burns, which participants in other studies have reported after application of the agent directly to the skin.21–23 For WI, the participant had to sit on the edge of the treatment couch with the knees flexed to 90° to place the foot into the bucket. At the end of treatment, the participant returned to the original position. All agents were applied for 20 minutes, which is a clinically relevant application time.

Immediately after removing the agent, we recorded its temperature and took a thermal image of the ankle. Thermal images of the ankle were taken at a rate of 1 image/min during a 30-minute rewarming period to monitor how long the cooling effect of each agent lasted on skin surface temperature. Previous data18 suggest that 30 minutes is a sufficient rewarming period because skin surface temperature reaches a plateau below baseline temperature within this time.

Thermal Data Analysis

We quantified thermal images using a computer linked to the TI camera and Thermacam Researcher 2.8 software. We processed the data using Excel 2003 (Microsoft Corp, Redmond, WA). Using the polygon tool within the computer software, we defined the ROI as the lateral ligament complex. The mean temperature over the ROI was taken from each image.

Statistical Analysis

Ambient room temperature between testing sessions and preapplication and postapplication was analyzed using 1-way repeated-measures analysis of variance (ANOVA). We also used 1-way repeated-measures ANOVA to determine the effect of the agent on change in skin surface temperature preapplication and postapplication. The level of significance was set at \( P < .05 \). Differences among efficiency of agents were determined with 1-way repeated-measures ANOVA at a 99%
Table 1. Overall Change in Skin Surface Temperature After Application of Cooling Agent and Efficiency of Heat Energy Transfer*

<table>
<thead>
<tr>
<th>Condition</th>
<th>Cooling Agent</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crushed Ice</td>
<td>Gel Pack</td>
</tr>
<tr>
<td>Baseline</td>
<td>28.8 ± 1.8°C</td>
<td>29.2 ± 2.5°C</td>
</tr>
<tr>
<td>Change in skin surface temperature</td>
<td>19.56 ± 3.78°C</td>
<td>13.19 ± 5.07°C</td>
</tr>
<tr>
<td>Cooling efficiency†</td>
<td>9.53 ± 1.2°C</td>
<td>31.21 ± 5.12°C</td>
</tr>
</tbody>
</table>

*Values are mean ± SD.
†Cooling efficiency = postapplication modality temperature – skin surface temperature immediately after removal of agent (00 minutes).

Figure 1. Rewarming curve over lateral aspect of ankle.

RESULTS

Ambient temperature of the laboratory did not differ significantly (P > .05) between testing sessions (20.5 ± 1.4°C) or before (20.5 ± 1.4°C) and after (20.8 ± 1.4°C) testing at each session (P > .05).

Skin Surface Temperature Reduction

The 1-way repeated-measures ANOVA (P < .05) showed that mean baseline temperature of the tested limb (29.3 ± 1.8°C) was not significantly different (P > .05) among agents (Table 1). Lowest skin surface temperatures were recorded immediately after cold application (00 minutes) for all agents (Figure 1). The CI demonstrated the greatest reduction in skin surface temperature (19.56 ± 3.78°C), followed by WI (16.99 ± 2.76°C), FP (14.59 ± 4.22°C), and GP (13.19 ± 5.07°C) (Figure 1, Table 1). Immediately after application, CI produced the lowest skin surface temperature (9.2°C), and GP produced the highest skin surface temperature (16.1°C) (Figure 2). Skin surface remained coldest for longest after application of CI (Figure 1).

One-way repeated-measures ANOVA revealed significant differences (P < .05) among agents for reduction in skin surface temperature preapplication and postapplication (Table 1). Pairwise testing with Bonferroni correction revealed that the differences were between CI and GP and between CI and FP (Table 2).

Agent Temperatures Preapplication and Postapplication

The GP had the lowest (−14.0 ± 4.5°C) and WI had the highest (10.0 ± 2.2°C) preapplication temperature (Figure 3). All agents demonstrated an increase in temperature from preapplication to postapplication. The GP changed the most (12.3 ± 5.4°C), and CI changed the least (0.2 ± 0.6°C) (Table 3). These results are not directly comparable because the WI was measured by hydroprobe; however, the analysis was performed on the overall change in temperature.

One-way repeated-measures ANOVA (P < .01) revealed significant differences (P < .01) among all agents in temperature increase from preapplication to postapplication. Post hoc tests using the Scheffé test revealed that the temperature of GP and FP increased significantly more than the temperature of CI (P < .01) and WI (P < .01). No significant differences were shown between GP and FP or between CI and WI.

Cooling Efficiency

No significant differences were noted between the efficiency of heat energy transfer for CI and GP, CI and FP, GP and WI,
or FP and WI (P < .01) (Table 4). Bonferroni correction revealed that CI and WI produced significantly more efficient cooling than both FP and GP (each P < .01). Cooling efficiency between WI and CI and between FP and GP was not significantly different (Table 4).

DISCUSSION

Cooling Efficiency

The higher initial temperature of the ankle compared with the cooling agent sets up a temperature gradient and serves as the source of heat energy for all agents. The Fourier law suggests that agents with lower preapplication temperatures offer more opportunity for heat energy transfer, resulting in lower skin surface temperatures, but we did not find supporting data. The greatest reduction in skin surface temperature (19.56°C) was recorded after application of CI. Application of WI, FP, and GP resulted in skin surface temperature reductions of 16.99°C, 14.59°C, and 13.19°C, respectively. Preapplication temperatures of both CI and WI were more than 10°C higher than those of GP and FP. Initially, therefore, it may seem paradoxical that the CI and WI produced the greatest reduction in skin surface temperature after the 20-minute application. However, CI and WI had significantly greater cooling efficiency than both FP and GP had. This result can be attributed to the ability of CI and WI to undergo phase change, allowing a consistent agent temperature throughout application. The Fourier law does not account for the energy required for phase

Table 2. Pairwise Comparison of Change in Skin Surface Temperature

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Mean Difference</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed ice and gel pack</td>
<td>6.367*</td>
<td>2.363</td>
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<tr>
<td>Crushed ice and frozen peas</td>
<td>4.967*</td>
<td>1.691</td>
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<tr>
<td>Crushed ice and water immersion</td>
<td>2.567</td>
<td>2.017</td>
</tr>
<tr>
<td>Gel pack and frozen peas</td>
<td>−1.400</td>
<td>2.087</td>
</tr>
<tr>
<td>Gel pack and water immersion</td>
<td>−3.800</td>
<td>6.470</td>
</tr>
<tr>
<td>Frozen peas and water immersion</td>
<td>−2.400</td>
<td>1.765</td>
</tr>
</tbody>
</table>

*P < .05.
Table 3. Preapplication and Postapplication Temperature of Cooling Agents*  

<table>
<thead>
<tr>
<th>Cooling Agent</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preapplication</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Crushed Ice</td>
<td>0.1 ± 0.7°C</td>
</tr>
<tr>
<td>Gel Pack</td>
<td>-14.0 ± 4.5°C</td>
</tr>
<tr>
<td>Frozen Peas</td>
<td>-10.0 ± 3.1°C</td>
</tr>
<tr>
<td>Water Immersion</td>
<td>10.0 ± 2.2°C</td>
</tr>
</tbody>
</table>

*Values are mean ± SD.

Table 4. Pairwise Comparison of Efficiency of Heat Energy Transfer for Each Modality  

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Mean Difference</th>
<th>SEM</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed ice and gel pack</td>
<td>-21.678</td>
<td>2.186</td>
<td>.001</td>
</tr>
<tr>
<td>Crushed ice and frozen peas</td>
<td>-15.489</td>
<td>1.431</td>
<td>.001</td>
</tr>
<tr>
<td>Crushed ice and water immersion</td>
<td>5.911</td>
<td>1.895</td>
<td>.086</td>
</tr>
<tr>
<td>Gel pack and frozen peas</td>
<td>6.189</td>
<td>1.895</td>
<td>.069</td>
</tr>
<tr>
<td>Gel pack and water immersion</td>
<td>27.589</td>
<td>1.935</td>
<td>.001</td>
</tr>
<tr>
<td>Frozen peas and water immersion</td>
<td>21.400</td>
<td>1.398</td>
<td>.001</td>
</tr>
</tbody>
</table>

change, which may explain why our results do not follow this law.

Heat energy abstracted from the ankle causes the phase change; the CI turns to water. As this water is absorbed by the towel, the remaining CI comes into contact with the ankle, promoting phase change of the remaining CI and maintaining a consistent agent temperature throughout application. In our study, the temperature of CI from preapplication to postapplication changed very little despite a significant decrease in skin surface temperature, indicating that most of the heat energy abstracted from the ankle was used to melt the ice and indicating that this agent is efficient.

The WI used a combination of ice and water. The heat energy transferred from the ankle to the water initially melted the ice, maintaining the temperature of the water until all the ice had melted. The cooling efficiency of this agent may be influenced by the volume of ice used. Sufficient ice is needed to promote a consistent temperature throughout application. In addition, as water close to the ankle increases in temperature, it expands and rises through convection, and cooler water replaces it. Another attribute of CI and WI is the increased contact area with the ankle, providing greater opportunity for heat energy transfer and contributing to the greater efficiency.

Despite demonstrating lower preapplication temperatures, FP (−10°C) and GP (−14°C) were less effective at reducing skin surface temperature, reaching a mean minimal temperature at the start of rewarming of 14.6°C and 16.1°C, respectively. In addition, such low preapplication temperatures may be potentially dangerous, resulting in ice burns and considerable patient discomfort. The GP does not undergo phase change. When phase change does not occur, heat energy transfer is governed by the specific heat value of a substance (in this case, the gel), which is “a measure of the amount of heat energy required to raise the temperature of that substance by one degree.” This definition suggests that, in the absence of phase change, the heat energy that the agent removes from the ankle heats the substance and, therefore, heats the agent. The gel is contained within a plastic cover, the material properties of which further influence heat energy transfer of the GP. In our study, GP also demonstrated a greater variance in preapplication temperature (−19.6°C to −7.0°C), highlighting inconsistency and a lack of reliability across applications.

Our results are consistent with the results of Merrick et al4; modalities that undergo phase change produce lower skin surface temperatures. The results highlight the modality efficiency promoted by phase change. We applied the agent for 20 minutes over the lateral aspect of the ankle, in contrast to the 30-minute application at the quadriceps of Merrick et al4 and achieved results that were similar to their results, indicating that agent efficiency may be consistent over different anatomical areas.

A small phase change does occur within FP that affects the peas themselves, which are contained within the sealed packet and are not in direct contact with the skin. Water was not released from the sealed packet. The towel that was placed between the FP and skin provided another barrier to impede heat energy transfer by conduction. The packaging of the FP limited the degree of flexibility when molding them around the ankle and created areas of poor contact over the ankle, further impeding the rate of heat energy transfer.

Therapeutic Temperature Range

Application of CI reduced skin surface temperature to just outside the defined therapeutic temperature range, suggesting that a decreased application time still produces beneficial results. The CI and WI reduced skin surface temperature enough to promote local analgesia9 and cellular hypometabolism.10-12 Application of FP caused skin surface temperature to fall just within the therapeutic range (Figure 1) and to elicit the onset of cell hypometabolism,41 but this temperature was not sustained beyond the first minute of the rewarming period. The GP failed to reduce the skin surface temperature to the therapeutic range.

Rewarming

During the 30-minute rewarming period, skin surface temperature increased with the use of all agents. Superficial tissues rewarm by drawing heat from the deeper tissues, consequently transferring cooling to the deeper tissues.2 Therefore, superficial rewarming potentially could be considered a reflection of deeper tissue cooling, which occurs on removal of the cooling agent. Our study does not provide supporting data. Jutte et al6 reported no relationship between skin surface and intramuscular temperatures during cold application and during a 30-minute rewarming period. In this study, we focused on relative change in skin surface temperature, but Jutte et al4 reported absolute temperatures. Therefore, the results are not directly comparable. Further investigation is needed to determine the relationship between skin surface and deep tissue temperatures from the point of removal of the cooling agent.
Thermal Imaging

Noncontact, digital, infrared TI cameras are a valid and reliable tool for measuring skin surface temperature; nothing radiates to or touches the body.\textsuperscript{15–19} Previous applications of noncontact TI cameras\textsuperscript{14,19,20} highlight their capacity to track dynamic changes in skin surface temperature, so the cameras are considered an ideal tool for monitoring recovery of skin surface temperature after application of cryotherapeutic agents. These TI cameras are advantageous because they enable temperature measurement over an area, and data analysis that is facilitated by computer software enables extraction of relevant temperature data from a specific ROI within the image.

Rich et al\textsuperscript{18} noted that the value of human thermographic assessment is dependent on the capacity of the underlying physiologic derangements to produce measurable and consistent alterations in overlying skin temperature. The TI provided a valuable and effective measure of changes in skin surface temperature during a 30-minute rewarming period, suggesting that application of cryotherapy produced underlying physiologic derangement.

CONCLUSIONS AND CLINICAL RELEVANCE

We found that CI and WI were the most efficient cryotherapeutic agents. Although WI was the most efficient agent and demonstrated a more favorable preapplication temperature, clinically it is not always practical to use. Twenty-minute application of CI and WI caused skin surface temperature to fall within the therapeutic temperature range. The ability of CI and WI to undergo phase change appears to enhance efficiency of heat energy transfer and enables consistent agent temperature throughout application. The preapplication temperatures of these 2 agents also may be more acceptable to the patient than the temperatures of GP and FP. Further research is needed to investigate depth of cooling and the relationship between deeper tissue temperature and skin surface temperature as measured by the noncontact TI camera.

ACKNOWLEDGMENTS

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REFERENCES