Original Article

Design and Validation of Novel Evaporative Local Cooling Coatings to Prevent Adverse Health Effects of Heat Exposure

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Abstract

Background: This study aimed to design and evaluate the cooling power of local cooling coats for the head, neck, ankles, and wrists. **Methods:** Local cooling coatings were designed using Iranians workers' existing 50th anthropometric percentile data. After immersing the cooling coats in water for 5 minutes, they were placed in a chamber at 30°C, 35°C, and 40°C and 30% and 60% humidity and 0.2-0.4 m/s air velocity for 120 minutes. The amount of water evaporation was measured by weighing each coat before and after entering the chamber, and then the cooling power of each coat was calculated based on the amount of water evaporation. **Results:** The average cooling power of cooling coats with covering areas (two wrists 933.75 cm^2, two ankles 1467.37 cm^2 and head and neck 1270 cm^2) that the total area of the cover is 3671.12 cm^2, i.e., about 20% of the body at 30% relative humidity in 30°C, 35°C and 40°C was 67, 77 and 89 watts, respectively. At the mentioned temperature and in 60% relative humidity, the cooling power was 34, 40, and 55 watts. As the relative humidity increased, the cooling power of the coats decreased. **Conclusions:** Local evaporative cooling coat on the head, neck, wrists, and ankles can reasonably repel excess heat entering the body. The best performance of these coats is in hot and dry environments. Probably, if used in conjunction with cooling vests in environments with high temperatures and heavy activity, it can act as a supplement to cooling vests and have a significant effect on improving functions.

Keywords: *Heat illness, heat stress, personal protective equipment, prevention and control*

Introduction

One of the common risk factors in various activities in production, mining, agriculture, firefighting, outdoor sports, and military jobs is the heat.[1] Exposure to extreme heat can lead to an increase in body temperature and, if sustained, can lead to disorders such as heat rash, heat exhaustion, heat cramps, and heat stroke.[2] Heat stress reduces physical and mental performances and reduces productivity, and increases a person's susceptibility to accidents.[3-5]

In order to control heat stress, there are various solutions, including engineering control, administrative control and personal protective equipment. In many cases, engineering control such as thermal insulation, cooling systems and increased airflow or administrative control such as limited exposure time or education are not possible or are not sufficient to reduce the level of heat stress, so the use of personal cooling equipment can be helpful. These personal cooling devices absorb excess heat of metabolic or environmental origin and reduce the level of heat strain, improve mental and physical function[6,7]

The most common personal cooling equipment is cooling vests, covering about 35 to 40 percent of the body area. Types of cooling vests include cooling vests based on phase change materials, cooling clothes with cold liquid circulation, cooling clothes with a cold air circulation system, clothes equipped with a refrigeration cooling system and evaporative cooling vests.[8] Evaporative coolers contain special gels or crystals that swell by soaking in water and use the heat absorbed from the user's body to evaporate the water stored in these crystals.[9] In fact, by using cooling coatings, the heat gradient created between the central part of the body and the skin increases the blood flow. When the water stored in the crystals evaporates, the user's body heat is used. These coatings are made of particular hydrophilic fabrics, which, if wetted, allow sustained water evaporation, thereby cooling the garment and the underlying skin.[10]

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The use of cooling vests reduces heat strain indices such as heart rate, oral temperature, skin temperature, and sweating rate.[8,11] the study by Urša Ciuha *et al*.[11] aimed to determine the cooling power of various cooling vests, the maximum cooling power in the evaporative cooling vest was 43 watts. This amount of cooling power seems insufficient in exposure to relatively high heat.

Large and superficial blood vessels in the human body in the neck, wrist, forearm and ankle, which cover approximately 20% of the body surface, have provided good conditions for cooling the body through the bloodstream. The head, neck, arms and legs have the highest heat dissipation rate. Therefore, there are more efficient at dissipating heat per area than the trunk.[12-14] Several studies have reported the usefulness of using local cooling in the head, neck, wrists and ankles to reduce the level of heat stress.[15-17]

Study by Bright *et al*.,[18] was shown that cooling coats of the neck improve athletic performance by cooling the carotid blood vessels. A study by Desai *et al*.[15] on eight tennis men showed that the use of neck cooling coats improves the quality of training and the performance of tennis players in the competition. Ando *et al*. also reported that neck cooling leads to increased cognitive function in complex tasks after exercise-induced hyperthermia.[17]

In some workplaces, heat is produced in the body through metabolism and gained from the hot environment through, for example, solar radiation. The dissipation of this excess heat is more than the cooling power of many available cooling vests, with a coverage area of about 35 to 40% of the body area. For example, in the Ursa study, which was conducted to determine the cooling capacity of different types of cooling vests, the maximum cooling capacity of evaporative cooling vests was reported to be 43 watts per square meter. Therefore, if local cooling coats cover a larger body area on the head, neck, arms, and legs, it is expected that the body will expel excess heat more intensely. Evaporative cooling vests have less practical limitations than other cooling vests (lightweight, no need for electricity, batteries and freezers, and charging with water in a few minutes) and in hot and dry environments have acceptable performance in reducing the level of heat stress.[19] Thus, in this project, evaporative cooling coats were designed and constructed for the head, neck, wrist and ankle, inspired by the structural nature of the evaporative cooling vest localized in Iran. The cooling power of these coats was measured in the various temperatures and humidity were evaluated.

Methods

This applied study was carried out in three stages in the Faculty of Health of Isfahan University of Medical Sciences in the summer: (a) design and construct of a small chamber to regulate temperature and humidity conditions, (b) designing and sewing local cooling coats and (c) determining the cooling power of cooling coats. The following stages of this study are described.

Designing and construction of a small chamber to regulate temperature and humidity conditions

A chamber with a length of 80 cm, a width of 60 cm and a height of 80 cm was made of a transparent PVC sheet [Figure 1]. In order to control the relative humidity in the chamber, a blowing fan with a variable flow of 15 to 30 liters per minute was used. An HTC-2 temperature and humidity meter performed chamber temperature monitoring. Also, to supply the required temperature in the chamber, an electric heater with thermal power of 500 watts, model HS-860, was used. hot wire anemometer model KIMO VT110/115 was used to measure air velocity during the test. By installing two small axial fans in the central area of the chamber with 60 cfm flow, air mixing was done in the chamber.

Design of local cooling coatings

First, the data needed to design cooling coatings based on anthropometric sizes of head and neck, wrist and ankle in Iranians were collected according to Motamedzadeh, Taghizadeh, Emamgholizadeh, Mo'oudi and Bijeh studies[20-24] [Table 1]. Initial pattern was produced without a cooling layer. Subsequently, a three-layer cooling coat was designed and fabricated for the head, neck, wrists, and ankles [Figure 2]. The structure of the cooling coat consisted of three layers with different functional natures. The inner and outer layers were made of lightweight and breathable fabric with minimal water absorption and the middle layer was relatively thick with water-absorbing crystals.

In order to eliminate possible defects, the prototype of a cooling coat for the head and neck, after 5 minutes of immersion in water, was used for one hour by 12 outdoor workers who were exposed to heat. Users were then asked questions such as ease of use, size appropriateness, and comfort of coats' weights. According to users, changes

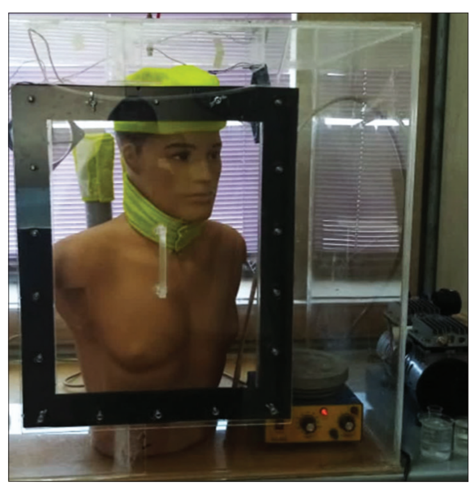

Figure 1: Temperature and humidity adjustment chamber

Table 1: Different percentiles of cooling coats design parameters

Type of cooling coat	Parameter	5th percentile	50th percentile	95th percentile	Area of cooling coat (cm^2)
Hat	Head circumference (cm)	45.2	55.5	60.95	1270
	Head length (cm)	22.1	29.5	33.9	
Neck cap	Neck diameter (cm)	39	44	59.5	
	Neck height	3	6	8	
Wristband	Wrist diameter (cm)	16.5	18	19.8	930
Ankle band	Ankle diameter (cm)	19.7	220.5	26	1470

Figure 2: Designed evaporative local cooling coats

such as using a button instead of adhesive fabric tape to adjust the neck coat and change the width of the neck cooling coat were applied. Finally, the area of the cooling coat of the head, neck, wrists and ankles was calculated. To prepare a prototype of cooling coatings, the 50th percentile of anthropometric data was used as a medium size in the design of cooling coatings.

Determining the cooling power of cooling coats

Cooling coats for the head, neck, wrist and ankle were immersed in water at room temperature for 5 minutes. Excess water was then squeezed out of the cooling coats, and the EK4100i scale weighed them with an accuracy of one-tenth of a gram. Immediately, the cooling coats of the head and neck were placed on the mannequin with a height of 75 cm, and chest circumference of 97 cm, and the coats of the wrist area were wrapped on a PVC cylinder with a diameter of 9 cm. simultaneously, the cooling coat of the ankle was placed on the cylinder with a diameter of 12.5 cm. It should be noted that the cooling coats were placed in the chamber so that they are not exposed to direct contact with the airflow. They were placed inside the chamber for 120 minutes at 30°C, 30% relative humidity and 0.2-0.4 m/s air velocity. The operator monitored the temperature, humidity, and air velocity conditions during the test. In case of temperature deviation of more than one degree and relative humidity more than 5% compared to the test conditions, the operator changed the heater power and fan flow to adjust the chamber's temperature. At the end of the test, the cooling coats were removed from the chamber and immediately weighed again. The difference in each coating's weight before and after entering the chamber was calculated and recorded as the amount of water evaporation. In order to reduce the possible errors for each specific temperature and humidity condition, the test was repeated three times in each condition and its average was recorded. All the above steps were repeated at 30, 35 and 40°C and relative humidity 60%. 18 experiments were performed in 6 different temperature and humidity modes for each cooling coat. In order to calculate the cooling power, the amount of water evaporation was used in each specific temperature and humidity condition [Table 2]. This value was multiplied by the latent heat of water evaporation in each temperature and pressure condition. Finally, the cooling power of each coat was calculated in watts [Table 3].

Results

Cooling coating surface was (two wrists 933.75 cm^2, two ankles 1467.37 cm^2 and head and neck 1270 cm^2) that the total area of the cover is 3671.12 cm^2, i.e., about 20% of the body.

The study showed that at 30% and 60% relative humidity with increasing temperature from 30°C to 40°C, water evaporation intensity increased. The intensity of water evaporation at a specific temperature, such as 30°C, was higher at the relative humidity of 30% compared to 60%.

Table 3 shows the average cooling power in different temperature and humidity conditions for different cooling coats, including hat and neck cap, wristband, ankle band and total coats. The cooling power of the hat and neck cap at temperatures between 30 and 40 degrees Celsius and 30% relative humidity is 26 to 35 watts. Under the same conditions, the cooling power of the wristband varied between 15 and 20 watts and ankle cap ranged from 25 to 33 watts. However, in the same temperature conditions and at a relative humidity of 60%, the cooling power of the coats is greatly reduced. The average cooling power of the total coats at the relative humidity of 30% and 60% is 78 watts and 42 watts, respectively.

Figure 3a shows the relationship between the cooling power of the hat and neck cap with different temperature and humidity conditions. An increase in temperature in a specific humidity condition is associated with an increase

Table 2: Average weight difference of coats before and after entering the chamber in different temperature and humidity conditions

Type of cooling coat	Mean (standard deviation) of water evaporation at 30% relative humidity (g)			Mean (standard deviation) of water evaporation at 60% relative humidity (g)		
	30	35	40	30	35	40
Head and neck cap	77.7 (18.9)	85.2 (13.6)	105.8 (26.9)	45.7 (13.6)	48.4 (12.5)	24 (67)
Wristband						
Right	22.5 (10.9)	25.7 (7.4)	30.6 (8.4)	12.9 (8.6)	13.5 (6.5)	15.9 (9.4)
Left	23.5 (13.7)	27.2 (8.5)	28.9 (14.4)	12.1 (12.5)	11.1 (6.2)	18.9 (12.5)
Ankleband						
Right	35.9 (16.1)	48.9 (6.8)	47.27 (4)	17.5 (14.1)	27.1 (8.8)	25.5 (23.3)
Left	39 (22.8)	43.9 (17.6)	51.9 (16.2)	11.5 (12.6)	18.2 (15.5)	35.9 (14.6)

Table 3: Mean of cooling power of different types of cooling coats in different temperature and humidity conditions

Type of cooling coat	Mean of cooling power at 30% relative humidity (watts)			Mean of cooling power at 60% relative humidity (watts)		
	30	35	40	30	35	40
Head and neck cap	26.2	28.6	35.4	15.4	16.3	22.4
Wristband	15.6	17.8	19.9	8.5	8.3	11.6
Ankle cap	25.3	31.2	33.2	9.8	15.2	20.5
total cooling coats	67	77	89	55	48	41

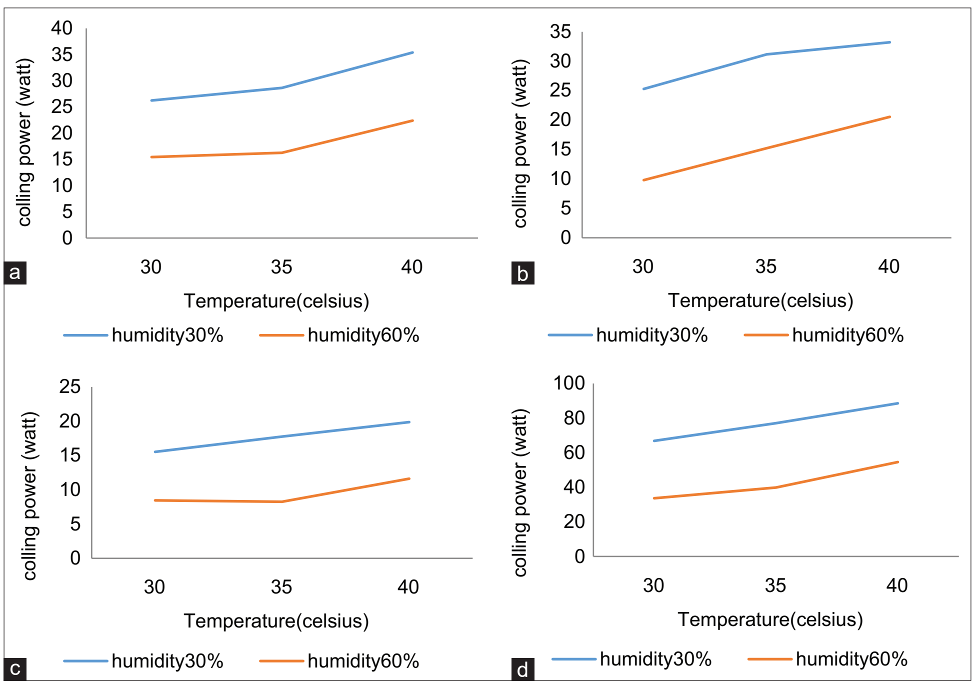

Figure 3: Relationship between the cooling power for different cooling coats with different temperature and humidity conditions. (a) Relationship between temperature and relative humidity with cooling power of hat and neck cap in different conditions. (b) Relationship between temperature and relative humiditywith the cooling power of cooling ankle cap in different conditions. (c) Relationship between temperature and relative humidity with the cooling power of cooling wristband in different conditions. (d) Relationship between temperature and relative humidity with the cooling power of total cooling coats in different conditions

in cooling power; the slope of this increase is higher at a temperature of 35 to 40 degrees Celsius.

Figure 3b. shows the relationship between the cooling power of the ankle cooling coat and the different temperature and humidity conditions. With the increasing temperature in a specific humidity condition, the cooling power shows an increasing trend. Also, the cooling power at 30% relative humidity is about twice that of 60% relative humidity.

Figure 3c shows the relationship between the cooling power of the wristband and the different temperature and humidity conditions. With the increasing temperature at

30% relative humidity, the cooling power continuously increases uniformity at 30 to 40°C. At 60% relative humidity, an irregular trend is observed at different temperatures; Cooling power remains unchanged at 30 to 35 and increases at 35 to 40.

Figure 3d shows the relationship between the cooling power of the total cooling coats and the different temperature and humidity conditions. The cooling power shows a direct relationship with the increase of temperature in a specific humidity condition, in the temperature range of 30 to 40 Celsius.

Discussion

Heat exposure from climatic conditions or industrial processes is present in many work environments or daily life. Excess body heat is removed from the body through several mechanisms, including the evaporation of sweat. If the air's relative humidity is such that the evaporation of sweat from the skin's surface is slow, excess heat is stored in the body and leads to an increase in body temperature. The prolonged onset of this condition causes symptoms of heat stress.[25]

Cooling coats are effective protective coatings to remove excess body heat in the exposure of extreme heat.[26] The present study was conducted to determine the cooling power of local cooling coats. The cooling power of the coats was calculated in the climatic chamber with different temperatures and humidity and air velocity of 0.2-0.4 m/s.

In the present study, with increasing temperature at 30% and 60% relative humidity, the cooling power of the coats increased in the temperature range of 30 to 40 Celsius. This study showed that the cooling power of the coats decreased with increasing relative humidity; The cooling power at the same temperature conditions with a relative humidity of 60% was less than 30%. This event is not unexpected because by increasing the amount of water vapor in the air at a specific temperature, the acceptance of the environment for water evaporation of cooling coats decreases. This finding is also consistent with a study by Havenith *et al*.[27] In fact, with increasing humidity, the efficiency of evaporative cooling coats decreases.

According to Table 3, the cooling power of the cooling hat and neck cap is 26 to 35 watts in the temperature range of 30 to 40 degrees Celsius. The cooling area of the head and neck was calculated to be 0.13 square meters. Considering that the head and neck area in a standard human being is 0.16 square meters (9% of the total body area), this cooling coat has covered about 80% of the head and neck area.[28] Suppose a person in heat exposure has to dissipate 200 watts of excess heat through the skin to the environment. If it is assumed that the heat dissipation is distributed evenly in different parts of the body skin, the heat dissipation from the head and neck should be 18 watts. Therefore, according to the coverage percentage of the head and neck cooling coats, cooling power of 15 watts is required. However, the head and neck coats' cooling power is more than this amount, at least 26 watts.

The cooling power of the wristband is 15 to 20 watts in the temperature range of 30 to 40 Celsius. The cooling cover area of the wrist was calculated to be 0.09 square meters. Considering that the area of the hands in a standard human being is 0.32 square meters (18% of the total body area), this cooling cover has been able to cover about 28% of the arm and hand area. Consider the mentioned assumption about the removal of 200 watts of heat from the surface of the skin.[28] Thirty-six watts of this amount must be dissipated through the arms and hands. Therefore, according to the cooling power and the percentage cover of the wristband, the cooling power required for the covered part is 10 watts. While the minimum cooling power of the cooling wristband, 15 watts, is more than the required amount.

The cooling power of the ankle is 25 to 33 watts in the temperature range of 30 to 40 Celsius. The cooling coat area of the ankle was calculated to be 0.147 square meters. Considering that the area of legs and feet in a standard human being is 0.65 square meters (36% of the total body area), this cooling covered about 23% of the area of the legs.[28] Assuming that 200 watts are expelled from the skin's entire surface, 72 watts must be expelled through the legs. Therefore, according to the cooling power and the percentage of ankle coverage, a cooling power equal to 17 watts is required for the covered area; while this coat's minimum amount of cooling power is more than 17 watts.

The cooling power of all coatings is 67-89 and 34-55 watts in the temperature range of 30-40 Celsius and the relative humidity of 30% and 60%, respectively. The cooling coats area was calculated to be 0.367 square meters, which is equivalent to 20% of the total body area. Considering the need to dissipate 200 watts through the whole body, 40 watts of heat must be dissipated through the covered area. Therefore, due to the cooling power of these coats in the temperature range of 30 to 40 Celsius and relative humidity of 30%, they will absorb the excess heat of the skin and provide a feeling of coolness for the user.

Due to the fact that the present study is the first study conducted in the country, it is not possible to compare with similar domestic studies. A non-domestic study was conducted by Urša Ciuha *et al*.[11] in 2020 to measure the evaporation resistance and heat resistance of different types of personal cooling vests at 35 Celsius and relative humidity of 35% for 8 hours. The maximum cooling power of one type of evaporative cooling vest was 43 watts per square meter. Differences in the results of studies can be due to differences in environmental conditions, the type of coats and the amount of placement time of coats in the chamber.

A study by Yi *et al*.[29] in 2017 aimed to evaluate the effect of a hybrid cooling vest designed for construction workers in reducing heat stress. This study calculated the cooling power of vests at 34 Celsius, 60% relative humidity and 1 m/s airflow. The cooling power of the newly designed vest was 67 watts and the previous vest was 56 watts. Under the mentioned environmental conditions, the total cooling power of the local cooling coats in our study was 40 watts. The difference in cooling power can be due to the difference in the body's surface coverage by the vest with local cooling coats and the type of cooling three-layer of coats media. In this study, air velocity in the climatic chamber was constant. Based on previous studies, it is expected that the cooling capacity of the coatings will increase with increasing air velocity.[29]

We wanted to design local cooling coatings to be used easily with people's work clothes and does not cause annoyance and interference in people's work during their activities. Probably, if used in conjunction with cooling vests in environments with high temperatures and heavy activity, it can act as a supplement to cooling vests and have a great effect on improving functions.

Conclusions

The results showed that the cooling power of evaporative cooling coats (three layers) in the head and neck, wrists and ankles can effectively repel heat entering the body. The best performance of these coats was in hot and dry conditions. However, because these cooling coats have been tested in terms of temperature, relative humidity and air velocity under controlled weather conditions, they are expected to act differently when used in field and under different weather conditions. For example, the personal evaporative cooling vest has better cooling power at lower relative humidity and higher air velocities due to more water evaporation. It is recommended that further studies be performed on the performance of these local cooling coats on people working in the workplace and their effect on physiological, perceptual and cognitive functions should be examined.

Authors' contribution

M.J.N and H.D contributed in draft and design, collected the data, revised the manuscript, and wrote the manuscript. Both authors read and approved the final manuscript.

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Ethical considerations

Ethical clearance was earned from the Institutional Ethics Committee of Isfahan University of Medical Sciences. Code of Ethics IR.MUI.RESEARCH.REC.1399.075 (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

Conflicts of interest

There are no conflicts of interest.

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