American Journal of Emergency Medicine 35 (2017) 881–884

Contents lists available at ScienceDirect

American Journal of Emergency Medicine

journal homepage: www.elsevier.com/locate/ajem

Original Contribution

Simple and effective method to lower body core temperatures of hyperthermic patients

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ARTICLE INFO

Article history:
Received 30 November 2016
Received in revised form 23 January 2017
Accepted 24 January 2017

Keywords:
Hyperthermia
Heat stroke
Radiation cooling

ABSTRACT

Hyperthermia is a potentially life threatening scenario that may occur in patients due to accompanying morbidities, exertion, or exposure to dry and arid environmental conditions. In particular, heat stroke may result from environmental exposure combined with a lack of thermoregulation. Key clinical findings in the diagnosis of heatstroke are (1) a history of heat stress or exposure, (2) a rectal temperature greater than 40 °C, and (3) central nervous system dysfunction (altered mental state, disorientation, stupor, seizures, or coma) (Prendergast and Erickson, 2014 [1]). In these patients, it is important to bring the body's core temperature down to acceptable levels in a short period of time to avoid tissue/organ injury or death (Yoder, 2001; Casa et al., 2007 [2,3]). A number of potential approaches, both non-invasive and invasive, may be used to lower the temperature of these individuals. Non-invasive techniques generally include: evaporative cooling, ice water immersion, whole-body ice packing, strategic ice packing, and convective cooling. Invasive approaches may include gastric lavage or peritoneal lavage (Schraga and Kates [4]). The efficacy of these methods vary and select treatment approaches may be unsuitable for specific individuals (Schraga and Kates [4]). In this work, the effectiveness of radiation cooling of individuals as a stand-alone treatment and comparisons with existing noninvasive techniques are presented.

1. Introduction

Heat illness may be classified in three categories: heat cramps, heat exhaustion, and heat stroke. The most serious is heat stroke that may be exertional or classic non-exertional with symptoms including [4]:

a. Altered mental state
b. Possible throbbing headache
c. Possible confusion, nausea, and dizziness
d. High body temperature (40.5 °C or higher)
e. Rapid and strong pulse
f. Possible unconsciousness
g. Possible hot/dry skin
h. Sweating likely if patient was involved in vigorous activity.

Exertional heat stroke generally occurs in individuals who engage in strenuous physical activity in a hot environment for extended periods. Classic non-exertional heat stroke typically impacts sedentary older individuals, people with chronic illness, and the very young. Classic heat stroke may occur during environmental heat waves. Both forms of heat stroke are associated with high morbidity and mortality (with severity impacted by delay in treatment) [2–4].

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http://dx.doi.org/10.1016/j.ajem.2017.01.053
0735-6757/

There exist two primary approaches to treat the hyperthermic patient; noninvasive external cooling, and invasive core cooling in conjunction with external cooling techniques [4].

A brief list of noninvasive external cooling techniques follows [1,5]:

1. Evaporative cooling
2. Ice water immersion
3. Whole-body ice packing,
4. Strategic ice packing, and,
5. Convective air cooling.

Invasive core cooling techniques include [1,6]:

1. Gastric lavage,
2. Peritoneal lavage,
3. Infusion of significant volumes of cooled fluids, and,
4. Use of cooling catheters.

In heatstroke patients, evaporative cooling has been demonstrated to lower core body temperature at a rate of 0.05 °C to 0.09 °C per minute [7]. Ice water immersion has been shown to be the most efficient noninvasive technique for core body temperature cooling as it achieves a reduction of approximately 0.15 °C to 0.35 °C per minute [7-10]. Whole-body ice packing and strategic ice packing are less efficient with core temperature reductions of 0.03 °C per minute [1] and 0.02 °C-0.03 °C per minute [1], respectively. Convective air cooling with healthy volunteers with exertional hyperthermia achieved approximately 0.04 °C per minute reduction in core temperature [5]. For invasive core cooling techniques, gastric lavage can achieve a reduction of approximately 0.15 °C per minute. Peritoneal lavage is also highly effective as a cooling technique because of the large surface area of the peritoneum and results in core temperature reductions of up to 0.08 °C to 0.16 °C per minute [1]. Infusion of high volume of cooled fluids or cooling catheters in an ice cold circuit may prove to be of benefit to some patients with heatstroke. However, their efficacy cannot be simply extrapolated from induce hypothermia studies. In particular, hyperthermia is high blood flow state as a result of hypothalamus-mediated cutaneous vasodilatation. This differs significantly from the low blood flow volume observed in post-cardiac arrest where fluid infusion and cooling catheters have been employed [6]. As such, these two approaches are not considered in this report.

2. Radiation cooling

Approaches to change the temperature of objects through energy transfer include conduction, convection, and radiation. A simple example depicting the three processes is shown in Fig. 1. In this schematic figure, heat from the campfire is conducted along the poker from its tip towards the gloved hand. Heated air rises through the mass motion of molecules and convectively moves heat energy toward the bare hands above the fire. Lastly, thermal energy may be transferred by electromagnetic radiation to the hands on the lower right.

Any object with a temperature above 0° Kelvin emits energy via electromagnetic radiation. The rate P_{rad} at which an objects emits energy via electromagnetic radiation depends on the surface area of the object, A, and its temperature in degrees Kelvin and follows the Stefan-Boltzmann law [12]:

$$P_{rad} = \sigma \varepsilon A T^4 \tag{1}$$

where $\sigma = 5.6704 \times 10^{-8}\ W/m^2 * K^4$ is the Stefan-Boltzmann constant and ε is the emissivity of the object's surface.

Emissivity is defined as the ratio of the energy radiated from a material's surface to that radiated from a perfect thermal energy emitter (called a blackbody radiator) at the same temperature and wavelength and under the same viewing conditions [13]. To elaborate, imagine looking into a small opening of a deep cave. In the visible wavelengths, the opening looks black because the light that enters the cave is not easily reflected back out. However, the cave glows with emitted thermal infrared (IR) energy. This energy emerges as a complete spectrum of all wavelengths of IR light. The radiance at each infrared wavelength is the maximum amount possible for a given temperature [14]. The values for emissivity range from 0 to 1 and depends upon the material

Fig. 2. Posey bed with supports mounts (left) [16] and with removable covers (right) [17] for controlled-temperature fabric surroundings.

characteristics of the object. Emissivity of human skin is 0.99 [15] so the skin acts as a true blackbody radiator, i.e., a perfect emitter.

Objects also absorb energy, P_{abs}, from the surrounding environment via thermal radiation. The environment may be taken at a uniform temperature T_{env} so that:

$$P_{abs} = \sigma \varepsilon A {T_{env}}^4 \tag{2}$$

Since an object both radiates and absorbs energy, the net energy transfer rate, P_{net}, is:

$$P_{net} = \sigma \varepsilon A \left(T^4 - {T_{env}}^4\right) \tag{3}$$

The key item to note is that if the surrounding environment of an object is at a lower temperature than the object itself, the object will radiate more energy to the environment than it absorbs, and as a result, the temperature of the object will decrease.

3. Cooling technique

The technique described herein utilizes the radiation cooling of the hyperthermic patient. In particular, the surroundings of the patient are maintained at a selected temperature that enables the patient's radiated energy to lower the body's core temperature while minimizing environmental radiation heating of the patient. An example would be to surround the hyperthermic individual's bed with a partition and/or cover, cooled to a desired temperature that is selected to optimize heat transfer from the patient. The partition may be a flexible fabric to simplify mounting and to minimize weight of the surrounding environment. One example would be to utilize the structural assembly of a Posey bed [16] for mounting the cooled fabric covers (Fig. 2). This approach would enable the partitions to surround the patient completely (except where the patient is in contact with the mattress surface) in a fully noninvasive manner. The access covers shown in the right side image of Fig. 2 may be removed and placed into refrigeration. When needed, they may be re-attached to the Posey bed to provide the cold environmental surroundings of the patient.

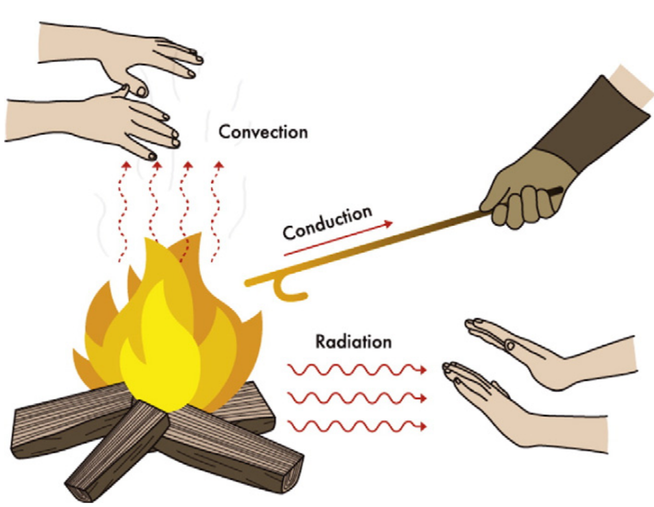

Fig. 1. Transfer of heat [11].

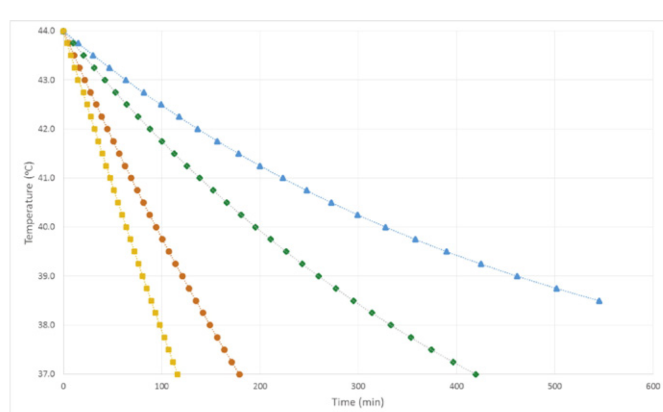

Fig. 3. Hyperthermia cooling by radiation with −18 °C (orange squares), 0 °C (red circles), 15 °C (green diamonds), and 20 °C (blue triangles) surrounding environments (metabolic processes considered intact: provides 116 W input heat continuously to patient).