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Systematiska kunskapsöversikter; 10. Occupational Heat Stress

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Innehållsförteckning

Redaktörernas förord

Denna utgåva ingår i den serie av systematiska kunskapssammanställningar som ges ut av Göteborgs Universitet. Dessa kunskapssammanställningar hade sin bakgrund i ett behov att ange riktlinjer för hur man fastställer samband i arbetsskadeförsäkringen. Arbetet inleddes 1981 när en grupp ortopeder, yrkesmedicinare, andra arbetsmiljöforskare och läkare från LO i Läkartidningen diskuterade en modell för bedömning av vilka arbetsställningar som utgjorde skadlig inverkan för besvär i bröst och ländrygg. Gruppen pekade också på vikten av att systematiskt ställa samman kunskap inom området (Andersson 1981). Därefter publicerades flera systematiska kunskapssammanställningar med avsikt ge riktlinjer för förekomst av skadlig inverkan vid arbetsskadebedömningar (Westerholm 1995, 2002, Hansson & Westerholm 2001).

AFA Försäkring finansierar sedan 2008 ett långsiktigt projekt med avsikt att ta fram nya kunskapssammanställningar inom arbetsmiljöområdet. Arbetet samordnas av Arbets- och miljömedicin vid Göteborgs Universitet. Dessa systematiska kunskapssammanställningar har som syfte att beskriva arbetsmiljöns betydelse för uppkomst eller försämring av sjukdom eller symptom i ett bredare perspektiv. Tillämpningen av resultaten får ske inom berörda myndigheter, arbetsplatser och försäkringsbolag.

Kunskapssammanställningarna genomförs av experter inom respektive området. Deras bedömning granskas sedan av andra experter inom området. Den nya serien av systematiska kunskapssammanställningar inleddes 2008 med en förnyad översikt om psykisk arbetsskada (Westerholm 2008), som sedan följdes av sammanställningar om fukt och mögel, helkroppsvibrationer och arbetets betydelse för uppkomst av depression, stroke, Parkinsons sjukdom, ALS, Alzheimers sjukdom och prostatacancer (Torén 2010, Burström 2012, Lundberg 2013, Jakobsson 2013, Gunnarsson 2014, 2015a, 2015b, Knutsson 2017). Under 2016 presenterades ett uppmärksammat dokument om skador efter exponering för handöverförda vibrationer (Nilsson 2016). Dessutom har vi tagit fram ett mycket efterfrågat dokument om hur diabetiker klarar av olika påfrestande arbetsmiljöer (Knutsson 2013). Eftersom kunskapsläget förändras finns det ett behov av uppdateringar av gamla kunskapssammanställningar, samtidigt som det finns ett behov av kunskapssammanställningar inom nya områden.

Detta är den första systematiska kunskapssammanställningen, i en serie om två, som behandlar betydelsen av exponering för värme. Denna översikt handlar om hur man påverkas av varma miljöer och hur man kan skydda sig Den andra översikten kommer behandla hur sjuka individer klarar att arbeta i varma miljöer. Arbetet har genomförts av Kalev Kuklane och Chuansi Gao, Lunds Universitet. Externa referenter har varit Lars Barregård, Göteborg och Juhani Smolander, Helsingfors. Vi är tacksamma för författarnas gedigna arbete liksom de värdefulla och konstruktiva bidrag som referenterna har tillfört.

Göteborg, Lund och Umeå juli 2017

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Referenser

Andersson G, Bjurvall M, Bolinder E, Frykman G, Jonsson B, Kihlbom Å, Lagerlöf E, Michaëlsson G, Nyström Å, Olbe G, Roslund J, Rydell N, Sundell J, Westerholm P. Modell för bedömning av ryggskada i enlighet med arbetsskadeförsäkringen. Läkartidningen 1981;78:2765-2767.

Burström L, Nilsson T, Wahlström J. Exponering för helkroppsvibrationer och uppkomst av ländryggssjuklighet. I; Torén K, Albin M, Järvholm B (red). Systematiska kunskapsöversikter; 2. Exponering för helkroppsvibrationer och uppkomst av ländryggssjuklighet. Arbete och Hälsa 2012;46(2).

Gunnarsson LG, Bodin L. Systematiska kunskapsöversikter; 6. Epidemiologiskt påvisade samband mellan Parkinsons sjukdom och faktorer i arbetsmiljön. Arbete och Hälsa 2014;48(1).

Gunnarsson LG, Bodin L. Systematiska kunskapsöversikter; 7. Epidemiologiskt påvisade samband mellan ALS och faktorer i arbetsmiljön. Arbete och Hälsa 2015a;49(1).

Gunnarsson LG, Bodin L. Epidemiologiskt undersökta samband mellan Alzheimers sjukdom och faktorer i arbetsmiljön. Arbete och Hälsa 2015b;49(3).

Hansson T, Westerholm P. Arbete och besvär i rörelseorganen. En vetenskaplig värdering av frågor om samband. Arbete och Hälsa 2001:12.

Jakobsson K, Gustavsson P. Systematiska kunskapsöversikter; 5. Arbetsmiljöexponeringar och stroke – en kritisk granskning av evidens för samband mellan exponeringar i arbetsmiljön och stroke. Arbete och Hälsa 2013;47(4).

Knutsson A, Kempe A. Systematiska kunskapsöversikter; 4. Diabetes och arbete. Arbete och Hälsa 2013;47(3).

Knutsson A, Krstev S. Arbetsmiljö och prostatacancer. Arbete och Hälsa 2017;51(1).

Lundberg I, Allebeck P, Forsell Y, Westerholm P. Kan arbetsvillkor orsaka depressionstillstånd. En systematisk översikt över longitudinella studier i den vetenskapliga litteraturen 1998-2012. Arbete och Hälsa 2013;47(1).

Nilsson T, Wahlström J, Burström L. Systematiska kunskapsöversikter 9. Kärl och nervskador i relation till exponering för handöverförda vibrationer. Arbete och Hälsa 2016;49(4)

Torén K, Albin M, Järvholm B. Systematiska kunskapsöversikter; 1. Betydelsen av fukt och mögel i inomhusmiljön för astma hos vuxna. Arbete och Hälsa 2010;44(8).

Westerholm P. Arbetssjukdom – skadlig inverkan – samband med arbete. Ett vetenskapligt underlag för försäkringsmedicinska bedömningar (6 skadeområden). Arbete och Hälsa 1995;16.

Westerholm P. Arbetssjukdom – skadlig inverkan – samband med arbete. Ett vetenskapligt underlag för försäkringsmedicinska bedömningar (7 skadeområden). Andra, utökade och reviderade upplagan. Arbete och Hälsa 2002;15

Westerholm P. Psykisk arbetsskada. Arbete och Hälsa 2008;42:1

Abstract

The present review covers a wide scope of occupational heat stress related-issues. The problematics related to climate change have placed heat exposure on the agenda. As a result, the research on heat effects has increased in recent years and a considerable amount of new material has become available. The literature includes general and specific reviews that focus on various heat-related aspects in detail. The aim of the current review is to compile the most relevant information, both past and present, that primarily covers knowledge on how one can carry out simple evaluations of heat stress in occupational settings. Very specialised information is described in full in the specific papers. The present review covers basic information on exposure to heat, descriptions of climatic factors and how they are measured. The review takes up human thermoregulation, heat exchange with the environment, and responses to heat. Several common hot environment evaluation methods along with heat assessment and management strategies are discussed. Sample industries are described.

OCCUPATIONAL HEAT STRESS

Introduction

In recent years the problems related to heatwaves have gained actuality due to climate change. At the same time occupational exposure to workplace heat in Swedish industries has diminished. To a large extent, human work activities in heat have been taken over by automated processes. However, human work in heat has not disappeared totally. There are jobs in food processing, metallurgy, the ceramics industry, paper works, glass manufacturing, etc., where heat exposure is a part of daily routines. In some cases, unexpected events force the personnel to act in extreme heat until the normal processes are restored.

At the same time, higher daily temperatures and the more common occurrence of heatwaves affect many other jobs, such as those in the construction and agricultural sectors. Higher temperatures also affect the time it takes to recover between work periods in heat. Due to globalisation and Swedish companies acting on the international market, the extreme weather conditions affect the companies' productivity and profitability in many countries where climatic conditions have already reached the limits of human physiological tolerance.

The actualisation of the heat problematics has increased the number of research papers in the area. Reviews are available that are more or less specific in the details they provide. The overview presented here covers a wide scope of issues related to occupational heat exposure. It aims to summarise the literature of past and present material of relevance, and direct the reader to specific studies and reviews of in-depth information that can be of interest. Meanwhile, we have tried to cover all the basic aspects of occupational heat exposure, heat assessment and management, and provide examples from relevant industries.

Background

Exposure to heat

In Sweden the highest air temperature of 38 °C was recorded in Ultuna in 1933, while the daily maximal air temperatures in July commonly stay between 22 and 23 °C in the Swedish "heat pole" of Målilla (SMHI 2015). Globally, the highest measured air temperature was 56.7 °C in Death Valley, California, USA in 1913 (WMO 2015). Although several records have reached above 50 °C, it is a rare air temperature of daily exposure. Temperatures reaching 40-45 °C in arid areas and 35-40 °C in tropics are, however, common (Climate CHIP 2015). The lower air temperatures in the tropics do not necessarily mean a lower thermal load. On the contrary, the thermal load can be accentuated when the air humidity is high and the evaporative cooling from the skin is restricted compared to dry heat. Solar radiation can cause the surface temperatures to easily reach above 70 °C even at considerably lower air temperatures. Under these conditions, any activity can be considered as a challenge, and occupational exposure should be avoided. However, this may not be easy to accomplish due to the nature and time pressure of the work, like during the harvesting season in agriculture.

In industrial settings the air temperatures in extreme cases may reach several hundred degrees Celsius, such as during the repair and maintenance of ovens, or when a process is stopped e.g. due to products falling off their waggons and blocking the path in ceramic industry. Under heat radiation the air temperatures do not necessarily reach such high levels, but radiant temperatures do stand for increased risks for heat-related disorders in steel works and glass factories, for example.

Protective equipment and clothing are needed in many working conditions. Additional layers of protection interfere with the human body's ability to exchange heat with the surrounding environments and can increase heat-related risks, even at temperatures that are not commonly associated with heat stress. The protective gear that firefighters usually work in is intended for extreme fire protection, even when they are carrying out other types of rescue activities (Ilmarinen et al. 2008). Their occasional need to use impermeable, totally encapsulating gas and chemical protective garments with heavy breathing apparatus imposes a particularly demanding situation.

In work tasks that combine high levels of energy expenditure and a thermal load, the work time must be limited. If firefighters' smoke diving lasts about 30-45 minutes (limited either by heat or breathing apparatus capacity or both), then the total rescue process time may take hours (Lee et al. 2015). If the heat stress is intolerable, the exposure time needs to be limited and cooling breaks should be introduced in order to achieve acceptable strain levels. Exceeding the limits has occurred during sports events where extreme exertion in heat, such as marathon running or the combination of protective gear, high exertion and heat in American football, has led to heat-related disorders and even the death of very fit and highly motivated individuals (Howe and Boden 2007).

In addition to strenuous physical activities, heat stress can be caused by climatic factors, usually when the air temperature exceeds 25 °C with or without solar radiation. Such conditions are routinely observed at construction sites, in the forestry, agriculture, power and telecom sectors, and during recreational activities such as hiking, tourism, and sports. Additional sectors exposed to heat are mining, power plants, bakeries, kitchens and other food-related industries. Any work involving fire involves health risks related to heat. Offices and dwellings can also turn into heat traps on hot days and during heat waves, especially when power failures or the breakdown of air-conditioning systems occur (Klinger et al. 2014, Anderson and Bell 2012). The mortality in European cities has been shown to increase with increasing temperatures (Table 1). Epidemiological studies on workplace heat exposure and health show that manual workers are at increased risk for heat stress; the occupational groups include farmers, construction workers, firefighters, miners, soldiers, and manufacturing workers (Xiang et al. 2014).

Table 1. Regional meta-analytic and city-specific estimates of threshold and percent change in natural mortality associated with 1 °C increase in maximum apparent temperature above the city-specific threshold (modified from Baccini et al. 2008).

	Threshold (°C)	% Change
Region		
North-continental	23.3	1.84
Mediterranean	29.4	3.12
City		
Athens	32.7	5.54
Helsinki	23.6	3.72
London	23.9	1.54
Milan	31.8	4.29
Paris	24.1	2.44
Rome	30.3	5.25
Stockholm	21.7	1.17

In Sweden, the latest statistics on work-related disorders show that during a twelve-month period, such disorders due to heat, cold or draught in percent of the employees occurred mainly in the following sectors: 1) food, beverage and tobacco industries (2.0 %); 2) warehousing and support activities for transportation (1.4 %); 3) land transport, transport via pipelines (0.9 %); 4) building (0.8 %); 5) public services (defence, police, fire, etc., 0.8 %) (Arbetsmiljöverket 2014). However, three factors in the statistics were lumped together: heat, cold and draught. It is not clear what proportion of the disorders was attributed to heat only, but it can be seen from another source (Blom 2016) that the number of heat-related occupational injuries or illnesses resulting in sick leave that were registered at the Swedish Social Insurance Agency in recent years goes up and down (Figure 1). This seems to correlate positively with the weather data for July, for example (SMHI 2016), when higher monthly mean temperatures lead to higher numbers of workers on sick leave, and lower monthly mean temperatures to lower numbers. Of the cases reported, the major ones were related to skin trouble (23 %), unspecified hypersensitivity (14 %), problems in the airways and breathing organs (8 %), and other unspecified causes (40 %).

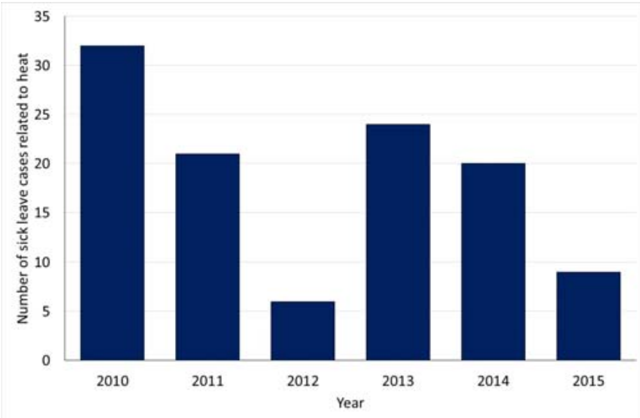

Figure 1. Number of heat related sick leave cases per year (Blom 2016).

Sources of heat stress

There are three major sources that cause heat stress as described in the introduction:

- work/exercise (i.e. metabolic heat production);
- environmental heat, and;
- clothing (i.e. restriction to body heat dissipation).

These factors are often combined in occupational settings where, for example, heavy physical work is carried out in hot workplaces that requires protection against environmental hazards. The rise in the core temperature of the workers can be controlled as long as adequate heat loss can be maintained. However, when heat cannot be dissipated either due to high environmental heat load or encapsulating clothing, a rise in core temperature of 1 °C/hour can be expected for each 100 W of workload.

Increases in either air temperature or activity are related to an increase in core temperature that stabilises at higher levels if a heat balance is achieved. If the body's heat balance cannot be maintained, the risk of various heat-related disorders (see the Heat-related disorders section) will increase depending on the level of heat stress (Davies 1979, Lind 1963, Taylor 2006).

With increasing age, the thermoregulatory system deteriorates and heat tolerance decreases. Elderly people make up the most vulnerable group in heat waves (Fouillet et al. 2006). The age-related differences in heat tolerance are observed even in occupationally active age groups (Larose et al. 1985). Significant differences between young and older firefighters occur above the age of 40 (Kenney et al. 2015). Since a physically active life-style and fitness contribute to heat acclimatisation, age-related responses to heat can also be modified by fitness.

Climate factors

The major climate factors that affect the human heat balance are air temperature, air velocity (wind), humidity, radiation and surface temperatures (Parsons 2014). Measurements and instruments for the physical environment are described in specific standards, such as ISO 7726:2002, and in the literature (Olesen and Madsen 1995, Parsons 2014). In order to cover all the major terms and definitions in one place, the reader is referred to the book entitled Human Thermal Environments by Parsons (2014) and to ISO 13731:2001 (2001).

Air temperature

Air temperature is the temperature of the air around the body and determines the convective heat exchange. It should be measured with a sensor that is protected against radiation (ISO 7726:2002). Forced air flow around the sensor increases the accuracy.

Air velocity

Air velocity is the speed of streaming air. An omnidirectional probe should be used to measure air velocity and it is represented by the mean of a 3-minute recording (ISO 7726). In hot dry conditions evaporation is enhanced by air motion and this successfully counteracts the convective heat gain (Jay et al. 2015). Air motion increases convection and evaporation from the body by blowing away warm and humid air near the body. Air speed (indoors) or wind (outdoors) has a cooling effect on the human body up to an air temperature of about 40 °C, but a warming effect when the air temperature is above 40 °C. At high air temperatures the convection effect will be negative and the body gains heat.

Air humidity

Air humidity can be expressed as absolute humidity or relative humidity. Absolute humidity occurs when the quantity of water vapour in the air is expressed as water vapour pressure or dew point (T_d). Relative humidity (RH) is expressed in percent as the relative amount of water vapour that air at a specific temperature contains in relation to the maximum possible at that temperature (saturation). Skin that is saturated at 100 % humidity can still lose a considerable amount of heat to 100 % moist air if the skin temperature is higher than the air temperature. This is because the water vapour pressure difference between the skin surface and the air drives the evaporative heat loss. The effect works in the opposite direction in a sauna when water is thrown on hot stones – the water vapour temperature is higher than the saturation temperature of the skin. The water vapour from the air condenses on the skin because it is a cooler surface. In firefighting activities, when hot steam is generated when extinguishing a fire, such an effect can cause scald burns (Kahn 2012).

Traditionally, air humidity is measured with a psychrometer that has a wet and a dry bulb thermometer. An air flow is forced over the bulbs in order to reach maximum evaporation. This has a stable cooling effect on the wet bulb and results in an accurate air temperature from the dry bulb (ASHRAE 2005, Parsons 2014). Based on the thermometer readings, humidity values can be read out from a psychrometric chart (e.g. Molliere diagram). Various instruments are currently available that utilise both traditional and modern measureing principles (Chen and Lu 2005), and often the humidity readings can be logged and/or the instant values are directly displayed on the screen.

Radiant temperature

The mean radiant temperature depends on the temperatures of the surrounding surfaces. It defines the magnitude of possible radiant heat exchange. In order to calculate it correctly for a specific location in a room, the temperatures of all the surrounding surfaces have to be weighted according to view angle in relation to that location (Olesen and Madsen 1995). A simplified method utilises a standard matt black globe temperature with correction for air temperature and air speed (Parsons 2014). Solar radiation is a special case outdoors (Clark and Cena 1978, Blazejczyk et al. 1993). In relatively homogenous conditions and low air velocity, the globe temperature represents the mean radiant temperature, but this is not the case if a directional radiation source is present. For a standard globe (150 mm diameter), the mean radiant temperature is calculated by:

$$\bar{t}_r = \left[\left(t_g + 273\right)^4 + 2.5 \times 10^8 \times v_a^{0.6} \times \left(t_g - t_a\right)\right]^{0.25} - 273$$

where:

$\bar{t}_r$ is mean radiant temperature (°C);
t_g is globe temperature (°C);
v_a is air velocity (m/s);
t_a is air temperature (°C).

Surface temperatures

The surface temperatures interact with the human body by radiation but also by direct contact. The hands and feet are usually the only body parts that come in contact with surfaces, but in some cases, larger body areas may be affected, such as the back. This can happen when working in a seated or lying position, and requires that heat exchange by means of conduction be taken into consideration.

Heat exchange between the human body and the environment

The heat exchange between the body and the environment occurs via convection, evaporation, respiration, radiation, and conduction (Parsons 2014). Various heat exchange pathways are affected or driven by different climate factors, by clothing thermal insulation and evaporative resistance, and by the body's metabolic rate.

Convection

Convective heat exchange depends on air temperature and air velocity. It is driven by the temperature difference between the skin or clothing surface and the surrounding air. Wind (forced convection) blows away the stagnant air layer around the body and thus increases the heat exchange. Convection supports heat loss up to an air temperature of around 35-36 °C. At higher air temperatures, the body will start gaining heat from the environment by convection. The thermal insulation of clothing affects the convective heat exchange by hindering the heat transfer from the skin to the environment. Clothing air permeability, especially of the outer layer, has a significant influence on thermal insulation, and thus, on the convective heat exchange.

Evaporation

Evaporation is the most powerful way to lose heat in hot environments and the major one if the air temperature is above 35 °C. Evaporation depends on air humidity and air velocity. The water vapour pressure gradient between the skin or clothing and the air is the driving force. Air movement reduces the water vapour pressure of the air around the body, and thus increases evaporation and heat loss from the body to the surrounding air. The evaporation is also influenced by the evaporative resistance of the clothing, and by the pumping effect during walking in combination with the clothing design.

Respiration

Heat exchange via respiration involves both convective and evaporative components. The inhaled air in the airways is warmed to a temperature that is near the internal body temperature, and moistened up to 100 %. Thus, both the air temperature and the ambient water vapour pressure influence the heat exchange, which is the result of the level of work intensity and the concomitant ventilation rate. Consequently, the calculations to estimate heat exchange via respiration are based on the metabolic rate (Parsons 2014).

Radiation

Heat radiation can be divided into IR (infrared, long wave) and UV (ultraviolet, short wave) radiation (Elert 2015). In nature, IR and UV radiation are components of solar radiation that involves the whole spectrum. Visible light also has its energy potential but it is just a small area between the IR and UV span (Elert 2015). The absorption of IR radiation is not affected by colour, but by reflectivity/emissivity of the surface. Absorption of UV radiation also depends on the darkness of the surface (Bröde et al. 2010, Jögård 2004, Kuklane et al. 2006) (Figure 2). Heat flux is always transferred from a warmer body to a cooler body and there needs to be a space between the surfaces for the radiation to work.

Radiation heat flux depends on the temperature gradient between the interacting surfaces (e.g. the skin and/or clothing surface temperatures) and the temperatures of the surrounding surfaces. In workplaces where specific point sources of radiant heat exist (e.g. glass factories, metallurgical works) or in the sun light, the direct radiation may be of interest, especially in relation to local heat load (e.g. head, upper chest, hands). The extra-terrestrial solar irradiance on the Earth's atmosphere is about 1361 W/m^2 (Kopp and Lean 2011), while at sea level the maximum normal surface irradiance under clear sky is approximately 900-1000 W/m^2 depending on location and properties of the atmosphere. In the case of solar load, light coloured and loose fitting clothes reduce the heat load. In the case of industrial point sources of radiation, the reflective layers reduce heat gain (Figure 2). Even an extra layer of insulation may be needed to keep the heat from reaching the skin too quickly because flames and hot surfaces may emit more than 100 kW during firefighting (Rossi 2014).

Emissivity is a surface parameter that affects heat exchange via radiation. Clothing is an example of such a surface. The emissivity of most textiles (>0.9) and the human skin (0.97) is relatively high, which supports radiant heat exchange between the body and the environment. The emissivity is very low for reflective layers, such as polished metal surfaces (<0.08), while their reflectivity is very high (Bergman et al. 2011, Parsons 2014, Wikipedia 2015). In the sun and under point radiation sources, the affected body area needs to be considered because the total load is dependent on the exposed area, which in turn depends on the angle from the heat source (Błażejczyk et al. 1993, Underwood and Ward 1966).

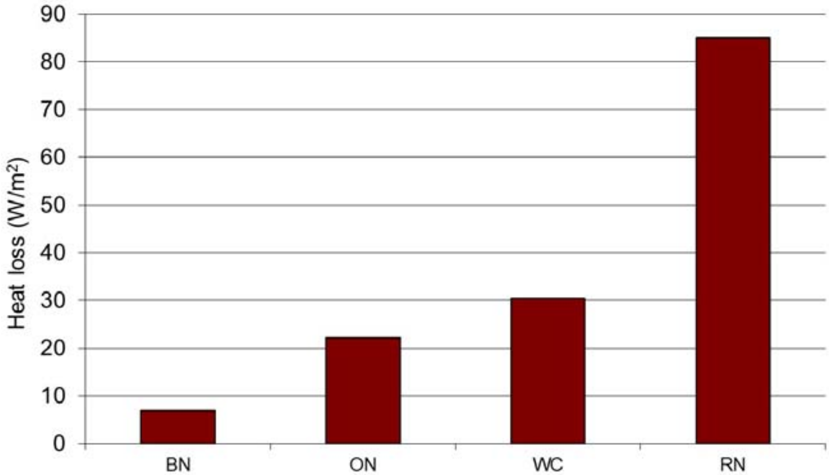

Figure 2. Effect of solar radiation (large UV component) on heat loss from a thermal manikin dressed in different coveralls: BN – black Nomex®, ON – orange Nomex®, WC – white cotton, RN – reflective (aluminised) Nomex®. High heat loss means low heat gain from solar radiation. The ensembles were of similar design, but differed in colour and fabric. The test days were selected to correspond to as similar environmental conditions as possible (clear sky, air temperature 10-15 °C, wind 0.7-0.9 m/s, time of day 12-15 o'clock) (modified from Kuklane et al. 2006a).

Conduction

Conductive heat exchange occurs when objects are in contact with each other. In many situations the heat exchange via conduction is minimal. A very strong local effect may be present when handling various materials (ISO 13732-1:2006). In some maintenance tasks, a worker may need to lie or lean on the hot surface, in which case the contact area can be quite large. Conductive heat exchange is defined by the contact area, the heat content and the heat conductivity of the material, along with the temperature gradient between the skin and the materials that are in contact. Liquids or moisture on the surfaces improves the contact and may increase the heat transfer. Contact insulation, which is insulation in a compressed state (measured, for example, by EN 511:2006 for gloves), affects the heat exchange. Any surface treatment, such as groove or coating, also affects the heat transfer.

Clothing

The elements of fashion are from the very beginning a part of the clothing design. However, the major aim of the clothing is to create a comfortable microenvironment around the body and to protect against environmental hazards. There are two major clothing properties that affect body heat exchange with the environment: insulation (thermal resistance) and evaporative resistance (Holmér 2004, Parsons 2014). Clothing insulation is measured in $m^2 \cdot K/W$ or clo (1 clo = 0.155 $m^2 \cdot K/W$); 1 clo corresponds approximately to the insulation of a full set of items comprising a business suit (Gagge et al. 1941) and the evaporative resistance unit is $m^2 \cdot Pa/W$. The thermal insulation resists dry heat loss from the body via convection and radiation. The evaporative resistance hinders evaporative heat loss from the body.

Heat exchange is also affected by body motion and wind (air velocity). The two clothing properties decrease in relation to the air permeability of the clothing material, especially the outer layer air permeability, and the pumping effect in the clothes. The latter is created by body motions that induce pressure differences in various clothing sections. The pumping effect is dependent on clothing design, size, air gaps, body position and the ability to close openings, usually at the neck, wrists, and ankles (Bouskill et al. 2002, Ueda and Havenith 2005, Havenith et al. 2015, Ismail et al. 2015).

Measurement of the thermal insulation and evaporative resistance of clothing

The thermal resistance and evaporative resistance of a textile or textile package can be measured on a hot plate (ISO 11092:2014). The thermal insulation and evaporative resistance of clothing that accounts for the 3-dimentional heat exchange of the human body are measured on thermal manikins (ASTM F1291-15, Holmér 2004, ISO 15831:2004). The effects of motion and wind on clothing have been studied extensively (Olesen and Nielsen 1983, Nielsen et al. 1985, Havenith et al. 1990a, Havenith et al. 1990b, Holmér et al. 1999, Nilsson et al. 2000, Havenith and Nilsson 2004, Lu et al. 2015b, 2015c). The correction equations for wind and motion for the individual clothing pieces and the whole ensembles are summarised in an international standard (ISO 9920:2007). The clothing tables were originally compiled by McCullough et al. (1985) and have been gradually extended with the latest input being the sets of non-western clothing (Havenith et al. 2015).

Evaporative resistance measurements on thermal manikins have been carried out over quite a long period (Meinander 1997, Fan and Chen 2002, McCullough 2002, Richards and McCullough 2005, ASTM F2370-15). The research on moisture effects in clothing expanded after the publication of the Thermprotect studies on radiation and moisture (Bröde et al. 2008a, 2008b, Bröde et al. 2010; den Hartog and Havenith 2010, Fukazawa et al. 2005, Havenith et al. 2005, 2008, 2013, 2015, Kuklane et al. 2007). Specific technologies and methods were used to more accurately determine the evaporative resistance values (Lu et al. 2015a, Ueno and Sawada 2012, Wang et al. 2010, 2011, 2012a, 2012b, 2015a, 2015b). The effects of wind and motion on evaporative resistance have also been studied (Ueno and Sawada 2012, Wang et al. 2012a). The latest findings provide a scientific basis for further revisions of the relevant standards.

Effect of clothing on heat exchange

Any clothing influences heat exchange. Higher clothing insulation is often related to a higher evaporative resistance. To improve our understanding of the thermal properties of clothing so that we can select proper ensembles from the comfort viewpoint, the ratio of the two major properties (insulation and evaporative resistance) is used and is called the vapour permeability index (i_m; dimensionless) (Woodcock 1962, ISO 9920:2007). For normal clothes, a standard value of 0.38 is used. The values above 0.38 correspond to improved permeability, and the values below to reduced permeability. For example, impermeable clothing has an i_m very close to 0, semipermeable clothing around 0.07, and a relatively tight but still permeable outer layer about 0.20 (Havenith et al. 2008, Kuklane et al. 2015b). The length of safe working times in impermeable protective clothing is drastically reduced compared with permeable coveralls, even at air temperatures just above 20 °C, while at temperatures above 40 °C, the human physiological limits are reached rapidly even in permeable clothing (Epstein et al. 2013, Holmér 2006, Kuklane et al. 1996, Kuklane et al. 2015b) (Figure 3).

A general recommendation for clothing used in warm and hot climates is to reduce the insulation and evaporative resistance, increase vapour permeability, and improve ventilation by following the habits of how traditional clothes are worn in warm countries (Havenith et al., 2015). Loose fitting clothes, however, may be difficult to combine with other industrial safety requirements. In the case of moderate radiation (e.g. solar radiation), light coloured textiles are recommended (Figure 2). They should restrict direct skin exposure to the radiation (Roy and Gies 1997). When working under extreme radiation levels, clothing needs to be well insulated (Rossi 2014) and may also contain a reflective outer layer (Figure 2) (Kuklane et al. 2006a).

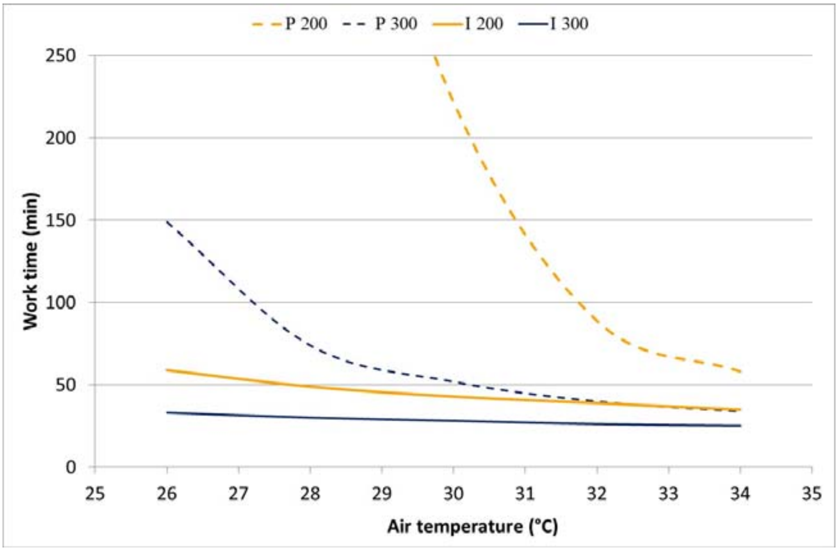

Figure 3. Prediction of work time with a modified ISO 7933 (predicted heat strain, PHS). Continuous work times for 2 work rates (200 W and 300 W) at different air temperatures before reaching a core temperature limit of 38 °C in relatively tight but still permeable (P, i_m=0.2) and impermeable (I, i_m=0.0) clothing. In the reference conditions, air velocity is 1 m/s and relative humidity is 75 %.

Metabolic heat production

During calm sleeping the body heat production is about 40 W/m^2 (basal metabolic rate); when sitting at rest, it is about 55 W/m^2 (ISO 8996:2004). Under maximal physical effort it can reach over 1000 W/m^2 for trained individuals. However, that effort can be sustained only over a short period of time. For average fit people, metabolic rates over 600, 475 and 400 W/m^2 can be maintained less than 5 minutes, 15 minutes and 2 hours, respectively, without any rest pauses (Holmér and Gavhed 2007). For normal office work the metabolic rates stay commonly between 70-100 W/m^2, while industrial work often requires considerably higher effort that involves metabolic rates above 100 and reaching even 300 W/m^2 for very heavy traditional work tasks (ISO 8996:2004). Keep in mind, though, that all metabolic energy is not always converted only into heat. In some cases, a part of the energy turns into mechanical work, such as bicycling (up to 25 % of the energy), ascending slopes and stairs. In terms of most industrial activities however, the energy used for mechanical work is approximately equal to 0. The heat produced by the body will increase the core temperature if it is not dissipated to the surrounding environments.

Body heat balance

The human body is in heat balance when the metabolic heat production and the heat loss to the environment are equal and result in no change in the body's heat content (S=0). If the heat storage is positive, the core temperature will increase; if the heat storage is negative, the core temperature will decrease. The heat balance equation is as follows:

$$S=(M-W)-(H_{res}+E+R+C+K)$$

where:

- M is metabolic energy production;
- W is external mechanical work;
- H_{res} is respiration;
- E is evaporation;
- R is radiation;
- C is convection;
- K is conduction;
- S is the body heat storage.

All the quantities above can be represented in Watts (= Joule per second; intensity), Watts/m^2 (intensity adjusted to body size/body surface area) or in kJoules (total amount of energy) (Parsons 2014). They can be calculated by specific equations that consider the influencing factors described in the previous sections (ISO 9886:2004, Parsons 2014).

Human body temperatures

Skin temperature

The principles of measuring the temperature of human skin and core are described in ISO 9886:2004. Because the skin temperature can differ in different body regions, the calculation of the mean skin temperature has to be based on several points. During heat exposure the blood vessels are dilated, and the temperature is relatively even at different skin sites. Consequently, the number of measuring points can be relatively small. At least four points are usually recommended to be used in heat, while in cold conditions where vasoconstriction may prevail, at least eight measuring points are recommended. In warm conditions, where the presence of a radiation source may create an uneven heat load on the subject, more points on the skin should be measured. One commonly used equation to calculate mean skin temperature based on four skin locations (Ramanathan et al. 1964) is given below. For other equations that are more or less complex, the user can refer to ISO 9886:2004 or Liu et al. (2011).

$$\bar{t}_{sk} = 0.3 \cdot t_{chest} + 0.3 \cdot t_{upper\ arm} + 0.2 \cdot t_{upper\ leg} + 0.2 \cdot t_{lower\ leg}$$

where:

$\bar{t}_{sk}$ is mean skin temperature (°C);
t_{chest} is temperature measured on chest (°C);
$t_{upper\ arm}$ is temperature measured on upper arm (°C);
$t_{upper\ leg}$ is temperature measured on upper leg (°C);
$t_{lower\ leg}$ is temperature measured on lower leg (°C).

Core temperature

The core temperature is used in a human thermal status evaluation to limit the exposure and to define the severity of the situation (see the sections on *Hyperthermia* and *Evaluation of heat stress and strain*). Core temperature can be represented by rectal, oesophageal, auditory canal, oral, tympanic temperatures (ISO 9886:2004). The names specify the location where the temperatures are recorded. All of them have their advantages and disadvantages related to user acceptance (e.g. rectal, oesophageal) or accuracy (e.g. oral, auditory canal). The oesophageal temperature is considered to reflect core temperature best because it allows one to relatively quick changes. A rectal probe is often used for core temperature measurement, but it is not sensitive enough for measuring quick changes. Measuring the oral, tympanic and auditory canal temperatures requires precautions to avoid influences from the environment on the measurement (e.g. by using insulating padding on the ear).

Mean body temperature

The mean body temperature is the average temperature of the human body including skin and core compartments. Changes in mean body temperature reflect the change in heat content (heat storage) of the body. In cold, the core takes up less volume due to vasoconstriction in the extremities and other skin areas. During heat exposure, the core covers about 80 % of the total body volume. Thus, the mean body temperature is calculated by:

$$t_b = 0.8 \cdot t_{core} + 0.2 \cdot \bar{t}_{sk}$$

where:

t_b is mean body temperature (°C);
t_{core} is core temperature (°C).

Human responses to heat

Thermoneutral and thermal comfort zones

The thermoneutral zone (TNZ) refers to ambient thermal conditions in which autonomic thermoregulatory responses are not yet activated. In a warm situation, the onset of sweating and simultaneously increased skin blood flow mark the upper limit of the TNZ. The thermal comfort zone is narrower than the TNZ. Both zones do vary, for example, according to changes in clothing insulation.

Within the TNZ, the stability of the core temperature is finely controlled and maintained by what is referred to as "sensible heat loss" which is caused by changes in skin vasomotor tone, i.e. skin blood flow. In TNZ, the regulation of core temperature occurs through controlled variation of skin blood flow in all skin regions, but most importantly in the distal parts of the body. Human skin contains special heat exchange organs: the arteriovenous anastomoses (AVAs) (Vanggaard et al. 2015). AVAs are thick-walled blood vessels specially designed for heat transfer, and are found abundantly in our fingers, palms, toes, feet, ears and lips (Burton 1939, Caldwell et al. 2014, Taylor et al. 2014). These areas are called non-hairy, glabrous or acral skin. Heating of the skin causes a direct sensory stimulation that raises our awareness of the potential heat load and triggers behavioural responses, such as seeking shade and opening up clothing to enhance evaporation from the skin, before the boundaries of the TNZ are reached (Kingma et al. 2014). Behavioural thermosregulation is the first line of defence against thermal stress, and often operates in a preventive fashion (feed-forward mechanism) through skin temperature e.g. dipping one's finger in a hot bath to assess the suitability of water temperature.

If any or a combination of the above responses are not sufficient to compensate heat gain, the tissue temperatures will increase, the upper limit of the TNZ will be reached, the sweat glands will activate and the blood flow to the skin will be elevated. These autonomic heat loss mechanisms operate in a feedback fashion where the hypothalamus senses and integrates the sensory information of temperatures from the different body parts (set-point), which again controls the sweating and skin blood flow responses. These responses occur outside the glabrous skin. If the heat loss mechanisms cannot compensate the heat accumulation, heat strain will ensue.

Sweating

The sweating response is an effective reaction for body cooling, where sweat glands expel water onto the skin surface to be further evaporated to ambient air. The latent heat of sweat evaporation at 32 °C is 2425 kJ/kg, and one litre per hour of sweat evaporation results in 674 W of heat loss.

Several recent research papers have examined the local and total sweat rates on human skin surfaces covering body parts, such as the hands (Machado-Moreira et al. 2008a), the feet (Smith et al. 2013, Taylor et al. 2006), the head (De Bruyne et al. 2010, Machado-Moreira et al. 2008c), the torso (Havenith et al. 2008, Machado-Moreira et al. 2008b), and the whole body and its separate regions (Smith and Havenith, 2011, 2012, Taylor and Machado-Moreira 2013), even including the effects of psychological sweating (Machado-Moreira and Taylor 2012a, 2012b).

Several studies investigated body sweat mapping with the aim of improving comfort in sports and leisure clothing (Smith and Havenith 2011, 2012). Human skin wetness perception affects comfort sensation (Filingeri and Havenith 2015). Better tactile comfort is often achieved by effective moisture transport away from the skin. Although sweat transport away from the skin is important from a comfort viewpoint (Fukazawa and Havenith 2009), it may not be the best solution from the body cooling viewpoint. The further from the skin the sweat evaporates, the less heat is taken from the body and more is taken from the environment (Havenith et al. 2013).

The sweating capacity is generally higher in men compared to women (Madeira et al. 2010, Havenith et al. 2008, Smith and Havenith 2012). To a large extent it depends on body size and physical fitness (Havenith et al. 2008). A high sweating capacity is especially beneficial in hot dry climates, while in hot wet conditions excessive sweating that drips down from the body without evaporative cooling results in a higher risk for dehydration.

Effects of heat

As discussed earlier, heat exposure is commonly connected with a rise in skin and core temperatures. At a certain level the increase is counteracted by sweating and evaporative heat losses. The skin temperature may drop when full sweating for specific conditions is reached. The temperature rise causes thermal discomfort, but also tactile discomfort due to sweating.

Effects on circulation

Heat stress imposes a considerable load on the circulatory system (Gaffin and Moran 2007, Parsons 2014). Skin and extremity blood flows increase together with heart rate. Increased skin blood flow raises the volume of blood in compliant skin veins, particularly in the upright position, and the venous return of blood is slower than in cool conditions. Cardiac filling is reduced with a reduction of central venous pressure. Stroke volume is reduced, which is compensated by the increase in heart rate.

A noticeable increase in circulatory response can be observed in the heat compared to the ordinary room temperature, where the heart rate for the same activity can be 20 or even 40 beats/min higher in the heat (Rowell 1983, Kuklane et al. 2015a) (Figure 4). If the heat stress cannot be compensated, then the heart rate will increase gradually and may reach maximal heart rate.

Increased sweat loss and the development of dehydration increase the viscosity of the blood, which in turn increases the load on the cardiovascular system. Altogether, this may lead to orthostatic intolerance. Special precautions should be taken when work is suddenly stopped. Even in hot conditions muscle contractions help the venous return (referred to as the "muscle pump"), but a sudden cessation of muscle work may cause a critical drop in cardiac filling pressures and subsequently also in arterial pressure and oxygen supply to the brain resulting in fainting (Figure 5). After exercising in hot conditions it is advisable to keep one's arms and legs moving in order to reduce the risk of fainting (heat syncope) or to sit/lay down. If fainting occurs, the treatment is to place the person in a lying (recumbent) position and raise the legs to promote venous blood return to the heart (Howe and Boden 2007).

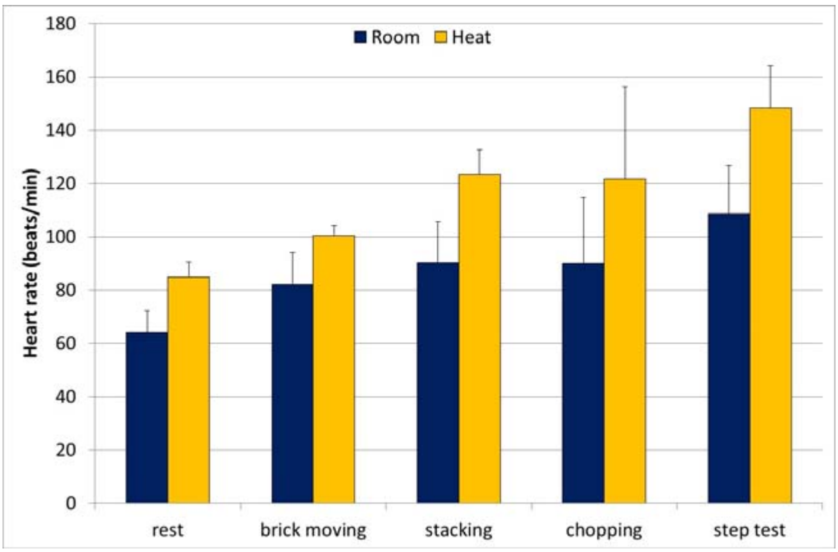

Figure 4. Heart rate under various activities at room temperature (21 °C, 52 % relative humidity) and in heat (40 °C, 30 % relative humidity) (modified from Kuklane et al. 2015a).

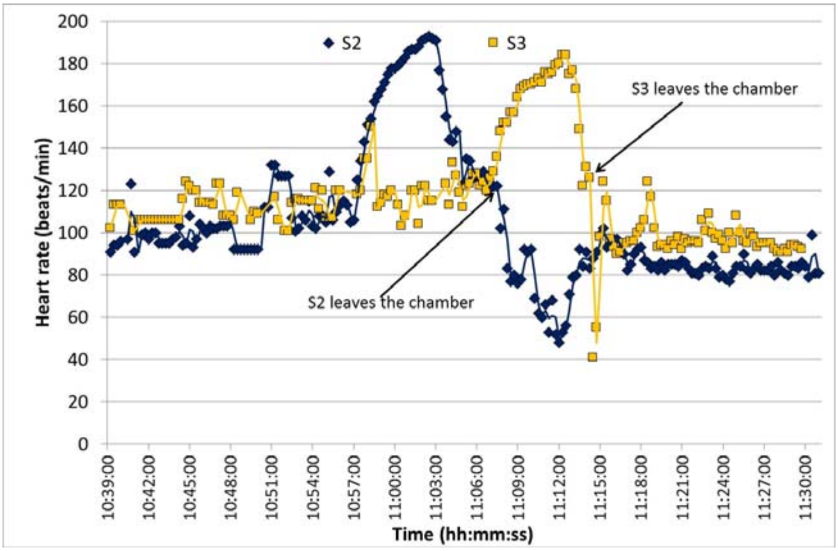

Figure 5. Heart rate during exposure to heat (50 °C, 30 % relative humidity) and heat syncope (Kuklane and Gao, 2010). S2 and S3 denote subject number. Heat exposure of the subjects started at the same time. Commonly, a low activity was maintained except for a 6-minute period where both subjects exercised on a bicycle ergometer with a load of 100 W. After their individual exercise period, the subjects stood still and started to feel dizzy. They got help to leave the chamber. S2 sat on a chair and fainted, and was laid down. S3 laid down at once after exiting the chamber.

Local effects

Air has a low specific heat and thus it contains relatively little energy even at high temperatures. Still, extreme exposures to heat require respiratory and skin protection. The following summarises the hot air effects due to convection on bare skin and on the respiratory tract (Pryor and Yuill 1966):

- nasal breathing becomes difficult at 125 °C;
- mouth breathing becomes difficult at 150 °C;
- injury to the skin occurs after 30 s at 180 °C;
- there is about 5 min tolerance at 140 °C (dry sauna);
- there is about 5 min tolerance at 110 °C (humid sauna).

The pain threshold temperature of human skin is around 43-45 °C (Parsons 2014). The stronger thermal and pain sensations are related not only to the specific temperature but also to the rate of the temperature change. Siekmann (1989) describes the maximum temperatures human skin can tolerate on contact with hot surfaces. The severity of contact skin burn depends on the contact material properties, contact area, duration, pressure, etc. (ISO 13732-1:2006).

In the 1950s, Stoll and Green (1959) carried out basic research on how energy from thermal radiation affects human tissue. Since then the methods have been developed by looking at the effects of protective clothing, air gaps and moisture on heat transfer to human skin (Barker et al. 2006, Crowe et al. 2002, Gholamreza and Song 2013, den Hartog and Havenith 2010, Song et al. 2004). The effects of energy from thermal radiation on bare skin as threshold values can be summarised as:

- 10 kW/m^2 leads to pain in 5 seconds;
- 15 kW/m^2 leads to second-degree skin burn in 5 seconds;
- 50 kW/m^2 leads to second-degree skin burn in 1 second.

Hyperthermia

The normal human core temperature is around 37 °C. It is not significantly different for males and females (Gagnon et al. 2009, McGann et al. 1993, Sund-Levander et al. 2002). Any differences can be related to body composition and eventually to fitness, and to the normal core temperature changes at different times of day (circadian rhythm) and under the follicular and luteal phases of the menstrual cycle in women.

In occupational settings (8 work hours per day) the core temperature of 38 °C is generally considered as the upper limit value for population average levels (AFS 1997:2, ISO 7243:1989, ISO 7933:2004). Individual heat sensitivity varies. If self-pacing is possible, most people behaviourally start lowering their work pace when the core temperature reaches 38 °C (Mairiaux and Malchaire 1985, Miller et al. 2011). In specific occupational settings (shorter than 8-hour continuous exposure) considerably higher core temperatures can be observed. For example, in firefighting activities the core temperatures may exceed 39 °C (Eglin 2007, Holmér et al. 2006). In such conditions, the work team is expected to support the exposed worker as he or she may not be in full control of his or her own situation: decision-making abilities deteriorate and the risk of adverse health effects is high (Svensson et al. 2009).

In endurance sports, the core temperatures of 40-40.5 °C appears to be the maximal tolerable temperature (Nielsen et al. 1993), although even higher temperatures have been recorded after the end of the exercise (Table 2). Core temperatures above 42-43 °C commonly lead to death (Shibolet et al. 1976). The tissue damage is also dependent on exposure time, and the damage rate steepens at temperatures above 43 °C (Dewhirst et al. 2003). The highest recovered human core temperature elevation reported without permanent injury was 46.5 °C (Slovic et al. 1982).

Table 2. Human responses to heat (modified from Bohgard et al. 2009).

Change in body heat storage, kJ	Core temperature, °C	Medical/physiological reactions	Psychological reactions
>1120	>41	Risk for heat stroke, increased risk of irreversible tissue damage	
860	40	Failing temperature regulation	Intolerable
590	39	Temperature during heavy work in heat	Approaching exhaustion
290	38	Vasodilatation, sweating	Growing discomfort
0	37	Normal body temperature	Thermal comfort

Heat-related disorders

One should avoid working alone in hot conditions. Some unexplained accidental deaths in warm confined spaces, like cleaning of tanks, have raised the possibility of heat syncope (see the section *Effects on circulation*) being a contributory or even a causative factor. Heat syncope is a major risk in unacclimatised persons, and adaptation to hot conditions greatly diminishes the number of casualties. Sufficient fluid intake helps in part to prevent fainting but does not replace acclimatisation.

Heat stroke is a serious heat disorder with high mortality, and thus requires immediate emergency care when suspected (Gaffin and Moran 2007, Howe and Boden 2007). In heat stroke patients the core temperature is extremely high (over 40 °C). The body thermal regulation mechanisms collapse. Sweating stops and the skin is dry. This is often preceded by changed and/or impaired mental functions like aggressiveness, confusion, and disorientation followed by sudden coma or convulsions. Rapid cooling (high cooling rate) is needed for treatment, for example by using prompt, vigorous cold water immersion with a cold water temperature of approximately 10 °C and by maximising the body surface contact by using whole-body immersion whenever possible (Zhang et al. 2015).

Heat exhaustion includes circulatory overload, fatigue, and physical exhaustion. It is sometimes considered as a pre-stage of heat stroke, and the separation is based on the level of core temperature. Heat cramp consists of involuntary muscle contractions caused by an uncompensated loss of salt (Schwellnus 2009). The treatment is to provide water with salt. Heat rash (miliaria rubra) is a skin disorder that results from the malfunction of the sweat glands (Hölzle and Kligman 1978).

The increase of fatal chronic kidney disease (CKD) is observed in heavy agricultural activities (e.g. sugar cane harvesting) in hot and humid areas, and may be associated with heat exposure and dehydration (Wesseling et al. 2014).

Other contributing factors can be exposure to agricultural chemicals (e.g. herbicides, insecticides, combustion products) and the quality of the available drinking water, or combinations of some or all of these factors. According to Moran and Gaffin (2007) with reference to Knochel (1974) and Knochel and Reed (1987), heatstroke results in a 25 % higher risk of kidney failure. This evidence supports it as being a cause of heat-related CKD. If heatstroke does indeed increase the risk of kidney failure, then long-term exposure that is close to heat tolerance limits may do so as well. The very recent studies have confirmed that heavy work in heat together with excess dehydration is the major cause of CKD development (Roncal-Jiménez et al. 2016, Wesseling et al. 2016).

In a similar way, if people with cardiovascular diseases are at risk of increased heat-related incidents (Fouillet et al. 2006), then exposure to heat elevates the load on the cardiovascular system and may in the long run result in chronic health effects. Wallace et al. (2007) studied the effect of prior heat illness on early death risk among military personnel indicating there are chronic effects of heat on heart, kidneys and liver. There are several other long-term effects related to heat exposure, such as increased vulnerability to heat-related illness, and effects on the reproductive system (Bogerd and Daanen 2011, Liu et al. 2015).

Dehydration

Dehydration corresponding up to 2 % of the body weight is considered to be reasonable. Physical performance decreases by 10 % per each percent of body weight loss. Water losses reaching 6 % and more may be life threatening and require medical treatment (Gopinathan et al. 1988, Montain et al. 1995). The treatment is to hydrate and to rest in a cool place.

Both increases in core temperature and body water loss are considered as critical responses in heat strain assessment. They are used to limit exposure time in international standards on heat exposure assessment (e.g. the predicted heat strain model) (PHS, ISO 7933). The standard evaluates and recommends scheduling work, rest and recovery to reduce the risks of heat-related disorders.

Mental and physical performance

The effects of heat on mental performance, vigilance and arousal already occur before core or skin temperatures reach any limit values. The moment of entering hot environments may trigger reactions that disturb performance of the set tasks. On the other hand, air temperatures up to 32 °C in combination with low activity levels (e.g. seated office work) have not been associated with much cognitive performance degradation for acclimatised persons while the effect could be seen on physical performance (Caldwell et al. 2012). At these temperatures the cognitive performance reduction was related to dehydration.

Heavy workloads and environments with conditions close to human thermos-regulation limits will degrade productivity (Kjellström 2009, Kjellström et al. 2009, Lin and Chan 2009, Sahu et al. 2013, Spector and Sheffield 2014), reaching the levels where survival prevails (Horowitz et al. 2015).

The above effects have a negative effect on work capacity. The relative workload at the same activity increases (Figure 4) while endurance drops. Excessive heat strain may lead to heat disorders and injuries, such as heat stroke, heat syncope, heat exhaustion, heat cramps, heat rashes (Binkley et al. 2002, Gaffin and Moran 2007, Parsons 2014). Several publications examine heat illnesses in relation to specific occupations, including Hunt et al. (2013) in connection with mining and Crowe et al. (2015) with sugarcane harvesting. Various emergency medical treatment strategies are described by Binkley et al. 2002, and Moran and Gaffin (2007), and occupational heat management strategies by Parsons (2014). Some of these are described in the section *Management of heat stress*.

Evaluation of heat stress and strain

The methods for prediction of thermal stress and strain include empirical methods (epidemiology), regression models, heat exchange models and physiological models. There are many thermal indices available to evaluate the thermal environment and comfort, and heat stress (de Freitas and Grigorieva 2015, Epstein and Moran 2006). A critical review of some indices is also provided by d'Ambrosio Alfano et al. (2011).

A few of the thermal indices have become international standards (Parsons 2013). A selection of the indices is described in the following sections. The work with the standards is ongoing; for example, several standards related to heat are under revision, and a risk assessment and management standard for hot workplaces similar to ISO 15743:2008 is under development.

Wet Bulb Globe Temperature (WBGT)

The Wet Bulb Globe Temperature (WBGT, Yaglou and Minard 1957) is the most widely used occupational heat stress index across the world. The WBGT index functions as a simple screening tool for the assessment of heat stress (Epstein and Moran 2006, Parsons 2013). The WBGT applies to hot environments with and without solar radiation. Equipment for measurements should meet standard specifications (ISO 7243:1989).

Limitations of the WBGT have been summarised by Budd (2008) and d'Ambrosio Alfano et al. (2014). The major criticism has been related to underestimating the effect of air velocity, and neglecting metabolic rate and clothing effect. The WBGT has limited use in high humidity or low air movement environments. The WBGT index only considers the increase of core temperature, but does not consider the risk of dehydration. The clothing factor has not been integrated into the WBGT. As standard instruments may be expensive, the use of non-standard ones is widespread, which leads to variance in exposure evaluations.

The latest research has focused on the possibility of using weather station data in the heat stress evaluation of outdoor work or in the corrections for non-standard instruments (Bernard and Barrow 2013, Lemke and Kjellstrom 2012). The use of weather station data should be treated with care because it commonly does not reflect the actual thermal conditions at the workplace. Improvement of the WBGT interpretation method has been attempted by taking into consideration clothing, metabolic rate and gender, thus, aiming to meet the most common criticisms (Ashley et al. 2008, Bernard et al. 2007).

Inside buildings and outside buildings without solar radiation:

$$\text{WGBT} = 0.7 \cdot t_{nw} + 0.3 \cdot t_g$$

While outside buildings with solar radiation:

$$\text{WBGT} = 0.7 \cdot t_{nw} + 0.2 \cdot t_g + 0.1 \cdot t_a$$

where:

t_{nw} is the natural wet bulb temperature, °C;

t_g is the temperature of a 150 mm diameter black globe, °C;

t_a is the air temperature shielded from radiation, but not restricted for air circulation around the sensor, °C.

The recommended maximum WBGT exposure levels (°C) at different work intensities and rest/work ratios for an average acclimatised worker wearing light clothing are available in section *Management of heat stress* and Table 3.

Predicted Heat Strain model (PHS)

ISO 7933:2004 should be used for a detailed assessment of occupational heat stress (Parsons 2013). In contrast to the WBGT, the PHS describes a method based on a human body heat balance equation for predicting both sweat rate and core temperature. The heat transfer between the body and the environment is calculated from all the important parameters such as the four thermal climate factors, physical work intensity (metabolic rate) and clothing thermal properties (Havenith et al. 1999; Malchaire et al. 2000, 2001; Malchaire 2006; Parsons et al. 1999). Currently the PHS method is one of the most developed methods for predicting potential heat strain due to work in the heat (Parsons 2013).

The PHS has been considered to be complicated for users in occupational settings, while it has been used for the evaluation and planning of work in heat (Rowlinson and Jia 2013). With the present development of digital aids, it should not be a problem to create an easy-to-use mobile application that would allow an even broader use of the PHS model. Several such standard-based tools are already available on the Internet, for example, the PHS simulation at www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS1/PHS.html.

One should keep in mind that the algorithms may not fully follow the standard as each application creator may have included his or her own interpretation, or the algorithms may contain errors. The PHS has been criticized as well (d'Ambrosio Alfano et al. 2007, Wang et al. 2013). However, during any change or planned improvement, one has to consider how the updating of a single equation can affect the entire estimation of heat exposure (d'Ambrosio Alfano et al. 2015).

Heat Index (HI)

In 1979, Steadman proposed the Heat Index (HI) that accounted for all relevant climatic, physiological and clothing factors. Based on a regression analysis of all the factors, a simplified equation was derived that utilises only air temperature and humidity (Rothfusz 1990), although doing so resulted in the loss of precision. Although, the simplified HI is a handy screening tool that does not require expensive equipment, a proper assessment of the hot environments should be based on standard methods that include the WBGT and the PHS (Bernard and Iheanacho 2015). The major drawbacks of the HI are that it does not account for radiant heat, nor does it consider air speed. It is also insensitive to clothing. When evaluating the heat exposure of construction workers, Yi and Chan (2015b) showed that the WBGT functioned better than the HI.

Individual heat strain monitoring

A relatively quick and simple way to evaluate how workers respond to heat is to use checklists like ILO 2010, or subjective assessment scales like ISO 10551:1995. However, to monitor in detail the individual thermophysiological responses in the heat, actual measurements should be taken of the core temperature (usually rectal), body mass loss (dehydration) due to sweating, heart rate and skin temperature (ISO 9886:2004). In some cases, the medical supervision of individuals exposed to extreme heat is required (ISO 12894:2001).

Medical supervision methods related to dehydration include, for example, analysis of urine osmolality, urine specific gravity, etc. (Armstrong 2005). The changes in urine parameters are reflected in urine colour. Beside weight measurements, comparison of urine colour to special colour charts is a simple indicator of dehydration status. However, the method should be used with care because urine colour can also be affected by other factors such as illness, medicine, diet, etc. (NIOSH 2016).

Thermal Work Limit (TWL)

The Thermal Work Limit (TWL) is defined as the limiting (or maximum) sustainable metabolic rate that fully hydrated, acclimatised individuals can maintain in a specific thermal environment within a safe core temperature (<38.2 °C) and sweat rate (<1.2 kg/h, Brake and Bates 2002). The TWL utilises five environmental parameters: dry bulb temperature, wet bulb temperature, globe temperature, wind speed and barometric pressure. Clothing is also taken into account in the estimation of a safe metabolic rate (W/m^2). The higher the TWL, the lower the limits for work in this thermal environment. The lower the TWL, the higher the risk for body overheating. The TWL can be used to schedule work and rest, or to recommend work cessation if the TWL reaches very low values (Miller and Bates 2007). Examples of specific cases are given in Brake and Bates (2002).

Universal Thermal Climate Index (UTCI)

A Universal Thermal Climate Index (UTCI, utci.org) has recently been proposed based on a model of human thermoregulation and is believed to be a step in the link between meteorological data and predicting the impact of climate on health (Bröde et al. 2012a, 2012b, Fiala et al. 2012, Havenith et al. 2012, Jendritzky et al. 2012, Kampmann et al. 2012, Parsons 2013). The UTCI provides a simple, one-dimensional characteristic of complex thermal environments as determined by air temperature, heat radiation, humidity and wind speed. The UTCI equivalent temperature for a given combination of wind, radiation, humidity and air temperature is then defined as the air temperature of the reference environment, which produces the same heat strain index value. A reference environment is defined as an environment with 50 % relative humidity (but vapour pressure not exceeding 2 kPa), still air (v_a = 0.5 m/s) and mean radiant temperature equal to the air temperature (Bröde et al. 2012a). Since the mean radiant temperature is usually not measured at weather stations, the application of the UTCI to the assessment of body heat strain is apparently limited by the lack of data on solar radiation. In addition, the assessment of heat strain using the UTCI does not consider local workplace conditions. Thus, it needs a standard to deal with meteorological data for occupational heat stress assessment. Some research has been carried out that compares the UTCI to other thermal indices and applies it in work environment and heat stress evaluations (Błażejczyk et al. 2012, Krüger et al. 2015, Vatani et al. 2015).

Advanced physiological models

Today many advanced thermal physiological models provide enough accurate and detailed predictions that also combine the environmental and clothing parameters into the calculations (Curran et al. 2014, Fiala and Havenith 2015, Rida et al. 2014, Kobayashi and Tanabe 2013). The physiological models are connected to clothing models and are prepared to be coupled with physical manikins to evaluate complex human-clothing-environment systems (Psikuta et al. 2015). Future heat exposure evaluation is expected to move in this direction.

Management of heat stress

Currently, the official recommendations on indoor environments in Sweden are issued by the Public Health Agency (Folkhälsomyndigheten, FoHMFS-2014-17). For practical guidelines, including heat-related recommendations, one can still refer to the National Board of Health and Welfare document (Socialstyrelsen 2005) or to the report by Gavhed and Holmér on thermal climate at the workplaces (2006). In United States the National Institute of Occupational Safety and Health (NIOSH) compiled lately a new criteria document on occupational exposure to heat and hot environments (NIOSH 2016). A review on firefighters' exposure is provided by Barr et al. (2010).

When it comes to more specific advice and situations, several textbooks are available (Auerbach 2007, Parsons 2014) where heat management strategies are covered in various sections. Several overviews are also available on heat illness management from the perspectives of public health (Glazer 2005) and sports (Binkley et al. 2002).

Organisational measures

If an organization intends to rely on its employees to make their own behavioural adaptations to heat, then the workers should be allowed to carry out self-pacing in extreme heat work situations (Miller et al. 2011). As the core temperature approaches 38 °C, people tend to slow down their work rate in order to cope with the growing heat stress (Nag et al. 2013a). During paced work in emergency situations, and for highly motivated individuals, the risks for heat overload are higher and need to be compensated by organisational and other measures, such as shifting between heavy and light work, and the selection of time of day for work. A rest/work schedule in relation to WGBT values is given in Table 3. These WBGT values are taken from a graph in the international standard, ISO 7243,) and are approximate (Kjellstrom et al. 2009).

Table 3. Recommended maximum WBGT exposure levels (°C) at different work intensities and rest/work ratios for an average acclimatised worker wearing light clothing (adapted from Kjellstrom et al. 2009).

	1 (light work) WBGT (°C)	2 (medium work) WBGT (°C)	3 (heavy work) WBGT (°C)	4 (very heavy work) WBGT (°C)
Continuous work, 0 % rest/hour	31	28	27	25.5
25 % rest/hour	31.5	29	27.5	26.5
50 % rest/hour	32	30.5	29.5	28
75 % rest/hour	32.5	32	31.5	31

Acclimatisation to heat

Systematic studies on acclimatisation started in the 1960s in connection with work-related exposures in South African mines (Williams et al. 1967, Wyndham 1973, Wyndham et al. 1960, 1973). Full acclimatisation is considered to take about 10 days. During that period, the workers should not be exposed to a full workload, but instead should have reduced work time in heat along with prolonged recovery breaks. This process should also be supervised by experienced and acclimated colleagues. Keep in mind that different WBGT limit values apply to them as well (ISO 7243:1989).

Acclimatisation procedures require 2-4 hours of heat exposure per day in order to have the most effective result. Physical training is also a type of heat acclimatisation – during exercise the core temperature rises and the body starts to deal with the excess heat in the same way as during environmental heat load. Thus, it will be less strenuous for people who regularly train and are physically fit to be exposed to heat (Tipton et al. 2008).

The most difficult period for heat exposure is the first 3-4 days (Pandolf 1998, Spitz et al. 2012) during which most of the adaptive changes occur. The onset of sweating is quicker, the sweat rate is higher, the plasma volume increases, the sweat has a lower salt content, the core temperature and heart rate are lower at a given work level, the risk of fainting is reduced, and the person experiences less discomfort. Acclimatisation to heat also contributes to a higher sustainable sweating capacity (important for tolerance times), a redistribution of sweating from trunk to limbs, and an increase in the total body water content. An effective acclimatisation process requires adequate fluid intake during the heat exposures. Acclimatisation to heat is considered to be the most dramatic physiological adaptive response in humans.

In connection with heat waves, heat incidents increase a few days after the first day of the heat wave for the most part (Fouillet et al. 2006). This may be related to the thermal inertia of the buildings where the temperature change of construction materials takes time, and allows only a gradual increase of thermal stress. If one only considers physiology and acclimatisation, then the first two exposure days entail the highest risk (Spitz et al. 2012). On the other hand, if people are commonly exposed to air-conditioned premises and the actual exposure to heat consists of very short periods of building-to-car type of exposures, then acclimatisation may not develop, and any power failure could easily contribute to a high risk of heat exposure.

Acclimatisation effects are considered to be lost if the heat load has not been experienced for over two weeks (Pandolf 1998). However, if the work in the heat is resumed within less than 30 days, it takes less than 10 days to achieve full acclimatisation again (Tipton et al. 2008). Ashley et al. (2015) suggest increasing the number of acclimatisation days depending on how many weeks one has been away from the heat. Two weeks away would require four days of re-acclimatisation, four weeks would require five days, and six weeks away would require the full acclimatisation process to be followed again.

Water balance

Each percent of body water loss corresponds to 10 % of loss in maximal work capacity. Access to drinking water is an easy way to keep hydrated. Plain water is often sufficient, since salts will be available from food if meals are taken regularly. Sport drinks are often too sweet and sugars impair water absorption mainly in the stomach. During heavy work in hot weather with high sweating rate, salt loss also needs to be replaced. In this case mineral water or adding some salt to plain water is a solution (Ladell 1955, Moran et al. 2007, Spitz et al. 2012). However, Meyer et al. (1995) showed that adding electrolytes was not an advantage. Some natural drinks, such as coconut water, are not too sweet and contain all the important ingredients for recovery (Saat et al. 2002). The temperature of the drink is not so important from a heat loss viewpoint (Price et al. 2011) as the liquid quantities required would be too large to make a difference. However, the temperature of the drink may affect the instant comfort sensation.

One should consider that the body can take in about 300-400 ml of water at a time. Thus, drinking 3-4 times per hour á 200-400 ml of water compensates a water loss of about 1 litre per hour during heavy work in the heat (Montain et al. 1999, Moran et al. 2007, Spitz et al. 2012). Sweat rates much above 1 l/h over longer periods of time need to be compensated by recovery periods. Even though hot workplaces may have good routines for water replacement, it needs to be considered that off-job drinking habits may also affect the development of heat strain (Peiffer and Abbiss 2013).

Auxiliary cooling

There are different principles available to improve or regulate heat loss from the body. Examples include the use of phase change materials (PCM) (Gao et al. 2010, 2011, 2012a, House et al. 2013) and ice (Smolander et al. 2004) in protective clothing; decreasing and increasing clothing insulation according to user needs by utilising smart textiles (Park et al. 2012); applying a liquid cooling garment or device (McCullough and Eckels 2009, Xu et al. 2006); using air cooling systems (McCullough and Eckels 2009, Kuklane et al. 2000); and increasing ventilation of the garments (Gao et al. 2012b, Kuklane et al. 2006b, Xu and Gonzalez 2011, Zhao et al. 2012, Zhao et al. 2015). Kuklane et al. (2012) have summarised the approaches that apply various ventilation solutions. A recent study has shown that the use of electric fans is a simple and low cost method that could have helped to alleviate heat strain in most of the recent heat waves (Jay et al. 2015). Combinations of the above cooling methods can also be used to achieve the maximal cooling effect under a variety of conditions, an example being the incorporation of a personal cooling system (PCS) with phase change materials (PCMs) and ventilation fans (Lu et al. 2015d, Song and Wang 2015).

Elson and Eckels (2015) proposed a method for the evaluation and selection of a PCS that incorporates the PCS, subject, and equipment weights; PCS run time; user task time; PCS cooling power; and average metabolic rate. Evaluation methods for cooling systems are also described by Bogerd et al. (2010). Chan et al. (2015) carried out a meta-analysis of the effects of microclimate cooling systems on human performance in thermally stressful environments. The results showed that cold air garments, liquid cooling garments and hybrid cooling garments that combine air and liquid cooling are applicable for work where workers do not move frequently. Ambient air-cooled garments and PCM garments are more applicable for the majority of occupational workers.

Making use of the AVA-rich skin areas (see section *Thermoneutral and thermal comfort zones*) in human extremities for cooling during work may have a limited effect. However, cooling the hands and arms, and feet and legs for recovery or in the case of heat disorders may be effective (Caldwell et al. 2014, House et al. 1997, Taylor et al. 2013). Even moderately cool water (about 26 °C) would be enough for reaching reasonable cooling rates while generated cold discomfort is much less than in cold water (Taylor et al. 2008). Special applications have been developed that allow one to maximise the effect of extremity cooling (Grahn et al. 2009). When electing the cooling solution one needs to consider the specific prerequisites and not only the cooling power. Thermal comfort in occupational settings is an important factor. For example, a liquid cooling device for the head (a hood) provided the best core cooling with circulated media at 10 °C; it provided reasonably good core cooling but considerably better thermal comfort at 15 °C (most preferred by users); and it resulted in poor cooling and high discomfort from heat with cooling media at 20 °C (Shin et al. 2015).

First aid principles for acute heat-related disorders

- Move away from the heat, at least into shade, and if possible into an air-conditioned location.
- Open or remove clothing.
- Lay the person on his or her side (lying down position) if unconscious, or has fainted.
- Put the person’s legs in a higher position to allow blood flow to the heart and brain.
- Cooling by the use of moist towels, water, electric fans, etc.
- Cold water (<26 °C) immersion of the extremities or the whole body in case of heat stroke (Taylor et al. 2008, Zhang et al. 2015).
- Drink water or water with salt if necessary.

Care at the scene in the case of burns

- **Flame burns:** Put out the flame with a fire blanket by smothering or rolling. If possible, remove clothing but be aware that synthetic material may have melted to the skin and should be dealt with very carefully or left for medical personnel.
- **Scalds and grease burns:** Remove the heat, remove wet clothes.
- **Airway**: Keep airway clean.
- **Cold application**: Apply cool water to the affected areas.
- **Swelling**: Remove constricting clothing, jewellery.
- **Electrical burns**: Most dangerous as damage cannot be seen; medical treatment is needed.
- **Chemical burns:** Wash with running water 5-10 minutes.

Estimate the burned surface area using the rule of nines (Mann and Heimbach 2007). The rule of nines is used to estimate the total body surface area that is affected by a burn. The rule divides the body (100 %) into sections that have surface areas related to 9: the lower leg, the thigh, the entire arm and the head each account for 9 %; the front and back torso each account for 18 %, and the groin for 1 %. If the burn area is smaller, the entire palm of the hand (from wrist to fingertips) is used to represent 1 % of the body area (Mann and Heimbach 2007). First degree burn (superficial burn that leads only to reddening of the skin) should not be counted into burn area calculation (Kearns 2013).

Occupational exposure cases

The following sections cover some specific occupations where heat is an acknowledged stress factor. Based on these examples the generalisation of the solutions may be applicable to many other workplaces where heat stress is an issue. Several of the examples are related to warm countries. However, with the global warming of the climate and expected increase in the number and severity of extreme weather events such as heat waves, the methods and solutions will be useful for temperate climate areas. Although air conditioning may be an option in office spaces and some industries, during heat waves the load on the central power systems may cause power failure, and local and/or simpler cooling strategies need to be available and known to the workers (Gao et al. 2012a, 2012b, Jay et al. 2015, Lundgren and Kjellstrom 2013). Work organisational solutions include planning rest-work schedules and alternately shifting work tasks that are carried out in hot and cool areas or during cooler time periods. It is important to plan these solutions for sustained productivity during normal conditions (Yi and Chan 2013, 2015a). The availability of drinking water and proper routines of water replacement are essential in order to avoid heat strain and heat-related illnesses. Sustainable work activity can be supported by the selection of optimal clothing and protective equipment or means of auxiliary cooling (Barr et al. 2010, Bernard et al. 2010, Kuklane et al. 2014, Kuklane et al. 2015b, Lundgren et al. 2014, Potter et al. 2015), but there is a limit beyond which heat exposure results in the cessation of work.

Agriculture

Agricultural activities are largely dependent on weather and the season. Although modern agricultural techniques utilise air conditioning in operators' cabs, much of the work is still carried out in an outdoor environment. Even in tractor cabins one may need to keep the windows open for improved vision, and the vehicle climate is known for its complexity related to the inhomogeneity of temperatures due to the positioning of air inlets and solar radiation through the glazing, for example (Bohm et al. 1990, Bohm et al. 2002). ISO standards are available for the evaluation and improvement of vehicle climate (ISO/TS 14505-1:2007, ISO 14505-2:2006, ISO 14505-3:2006).

The major heat issues in agriculture are related to the warm countries where daily temperatures are high and are expected to rise even more with increasing global temperatures, which will have a negative influence on productivity (Cecchini et al. 2010, Crowe et al. 2013, Culp et al. 2011, Nag et al. 2007, Sahu et al. 2013). The heat stress on the workers is considerably increased if they have to use protection against reactive agents in fertilizers, herbicides, pesticides, etc. (Schenker et al. 2002). Impermeable protective layers can cause heat strain even at moderate temperatures (Bohm et al. 1990, Bohm et al. 2002). In temperate climates the work in greenhouses also involves higher risks of heat stress due to high temperature and humidity (Callejón-Ferre et al. 2011, Marucci et al. 2012).

As previously discussed, self-pacing may be an option to cope with heat stress (Mairiaux and Malchaire 1985, Nag et al. 2013a). If this is not possible and/or not sufficient, then tighter organisational rules are the option and include the planning of work-rest schedules, drinking pauses, provision of drinking water, and shading the rest areas from solar radiation (Callejón-Ferre et al. 2011, Cecchini et al. 2010, Crowe et al. 2015). The work rates in agricultural activities may remain at around 60 % of the workers' maximal capacity (Davies et al. 1976). This corresponds to up to 2 hours of continuous work until exhaustion (Bohgard et al. 2009). Avoiding work, especially heavy work during the hottest work hours is suggested (Cecchini et al. 2010). That, of course, may affect the workers' daily lives, especially if the transport to fields is long. In some cases, working during late evenings and night allows for relief from the heat (Xiang et al. 2014), but in that case the solutions for lighting (projectors, powerful head lamps) need to be provided. A choice for auxiliary cooling may be an option, especially, if protective layers have to be worn (Gao et al. 2011, Smolander et al. 2004, Zhao et al. 2012). Autonomous auxiliary cooling devices should be of interest since agricultural activities are often mobile (Song and Wang 2015). Evaporative cooling options are not effective in hot humid climates, and they will not help under impermeable protective layers, while the use of contact cooling solutions, like PCM, that cover large body areas and restrict evaporation may not be the best under hot dry exposures (Zhao et al. 2013).

In addition to human performance and well-being, the environmental conditions in agriculture need to consider the well-being of the crops for the best yield, otherwise the whole season's efforts may be lost (Siebert and Ewert 2014). The same is valid for livestock (Kadzere et al. 2002).

Construction industry

Like agriculture, the largest sources of heat stress in the construction industry are the weather in combination with hard physical work, and in some cases, with personal protective equipment and clothing (Nag et al. 2013a, Rowlinson and Jia 2013). While it is possible in housing construction to work indoors or in the shade, it is not the case in road construction where outdoor workers are often more exposed (Nag et al. 2013b). Thus, one step in reducing heat stress is to offer shade from the solar radiation and to create cool areas for resting. Yi and Chan (2013, 2015a) suggest optimisation of working hours and resting breaks with a longer lunch break during the hottest time of the day. Coherent continuous work periods in the afternoon when the temperature is higher should be shorter between the breaks. Regular fluid intake should be promoted, and fluids should be available in large quantities close to the work and rest areas. The workloads at the construction sites commonly range between moderate and heavy intensity (Farshad et al. 2014, Lundgren et al. 2014). Clothing used in the heat should preferably be in light colours and should allow ventilation; under strong solar radiation it should cover the skin (Roy and Gies 1997). At the same time, it may be difficult for well-ventilated clothing to comply with safety issues related to the possibility of getting caught in objects. Rowlinson et al. (2014) summarises what is known and reports on the future perspectives of construction work management in heat, including useful tables for the mitigation of risks.

Process industries: Ceramics and metal industry, glassworks, food processing

In many industrial settings the processes define the work routines and the thermal environment. The ceramics, glass, metal and other industries are traditionally recognised as being hot working places due to their industrial processes (Bernard and Cross 1999, Mairiaux and Malchaire 1985, Oliveira et al. 2015, Vangelova et al. 2008). A study comparing the work conditions in the Portuguese ceramic industry in 1994 and 18 years later showed that in spite of a reduction in temperature extremes, the heat stress is still at a similarly high level (Oliveira et al. 2015). Occupational heat stress is even accentuated when industrial processes are combined with hot weather (Nag et al. 2013a, Vatani et al. 2015). Hot weather does not support recovery because heat stress is maintained even outside the process areas. Chaudhary et al. (2012) and Parikh et al. (1978) have suggested breaks to counteract body heating, but as productivity drops, so will the workers' income. Chaudhary et al. (2012) strongly advocate for organisational measures by alternating work in hot and cool areas in order to avoid a large drop in productivity. The availability of drinking water is essential. Examples of evaluation procedures, reporting and recommendations in hot work conditions at a glass bottle factory can be found in a NIOSH health hazard report (Dowell and Tapp 2007).

Clothing should allow for ventilation while in some work areas it may need to have high insulation to protect from excessive heat. Clothing insulation is commonly around 0.6 clo and depends on the work area (Oliveira et al. 2015).

If specific protection is required, then insulation layers will be added. When exposed to strong heat radiation sources, the reflective clothing layers need to be used to protect exposed body parts. The workload ranges between 180 and 400 W (Oliveira et al. 2015). The authors also show a general trend that if thermal conditions are milder, breaks are shorter and work rates tend to be higher. A similar trend is observed by Sett and Sahu (2013) where the brick carriers and moulders work until exhaustion and then only take a rest in the shade. Based on their heart rates it can be estimated that even these women work at approximately 60 % of their maximal capacity, similar to the agricultural workers studied by Davies et al. (1976). Often the only way to reduce heat stress is to lower the work pace. This in turn will affect the workers' productivity and income (Sett and Sahu 2013).

Food processing is traditionally an activity where exposure to heat and heat-related risks are high (Lundgren et al. 2014, Matsuzuki et al. 2011). The estimated physical workloads in food processing usually remain below the ones estimated for agricultural tasks and tasks in construction-related industries (Davies et al. 1976, Lundgren et al. 2014, Sett and Sahu 2013). Cooking and baking do not only increase the risks for radiation heat, contact with hot surfaces and steam burns, but also increase the temperature of the work environment above the exterior environment values. The cooking environment also commonly involves higher air humidity because cooking processes involve evaporation.

Firefighting

Firefighting involves a high risk of skin burns (Kahn et al. 2012), very heavy activities (Eglin 2007, Holmér and Gavhed 2007), and requires protection against flames, flashfires, high air temperatures, and chemicals. (Barr et al. 2010, McQuerry et al. 2015, Mäkinen 2010). However, over 90 % of the time, firefighters are involved in tasks that are not related to fire but to various rescue activities (e.g. during traffic accidents) (Ilmarinen et al. 2008). As firefighters have to always be prepared to move to the scene of a fire, they often use the same turnout gear when carrying out other tasks. This exposes them to heat stress due to excess protection and adds to the workload (Dorman and Havenith 2009). From this viewpoint, improving and optimising firefighter clothing and gear is a high priority. Different fire scenes also require different types of protection, such as when dealing with wildland fires (Alexander et al. 2007) and fires on ships (Bilzon et al. 2001). The tactical approaches differ from scene to scene as well (Svensson et al. 2009).

Radiant heat tests for fabrics or fabric combinations are carried out according to ISO 6942:2002. The effects of flames (i.e. convective heat) (EN 367:1992) are tested similarly but with a propane flame. Requirements for firefighter clothing are available in EN 469:2005. Fire tests of firefighter clothing ensembles have been carried out on a fire manikin with a propane flame at 80 kW/m^2 for 8 seconds (ISO 13506:2008, Rossi et al. 2014, Song et al. 2004). Sensors on the manikin's surface detect the heat flux and temperature, and allow the evaluation of degrees of skin burn.

Hot water tank diving

An international standard (EN 14225-3:2005) sets the requirements for cooling systems and exposure times when considering the exposure to water, for example during occupational diving in hot tanks. During the tests the subjects should be able to stay 60±5 minutes at a depth of 3±0.5 m in the water of 30±1 °C. The mean skin temperature during the dive should always stay under 40 °C in warm water and the body core temperature should not increase more than 1 °C when using auxiliary cooling solutions.

Conclusions

In spite of industrial developments and the automation of processes, occupational heat exposure remains a challenge in the globalised world. Heat stress levels are in fact increasing internationally due to climate change. Because of this, knowledge about the human capacity to tolerate heat stress and about heat stress assessment and management methods is needed more than ever. Recent and past research on human thermal physiology, climatic factors, protective clothing and support technologies has been reviewed in this article in order to effectively meet heat-related challenges in work environments. The human body is limited in its ability to tolerate heat stress. Consequently, the prevention of heat stress – including the selection of proper work routines and strategies, and personal protective equipment – is essential in order to maintain productivity, thermal comfort and health.

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References

AFS 1997:2 Arbete i stark värme, Arbetsmiljöverket, Sweden

Alexander ME, Mutch RW, Davis KM (2007) Wildland fires: dangers and survival. Chapter 12 in Auerbach PS (ed.) Wilderness Medicine, p. 286-335. Fifth edition, Mosby Elsevier

American Society of Testing and Materials International (ASTM) (2015): Standard test method for measuring the evaporative resistance of clothing using a sweating manikin (ASTM F2370-15). [Standard] Philadelphia, Pa.: ASTM

American Society of Testing and Materials International (ASTM) (2015): Standard test method for measuring the thermal insulation of clothing using a heated manikin (ASTM F1291-15). [Standard] Philadelphia, Pa.: ASTM

Anderson GB, Bell ML (2012) Lights out: Impact of the August 2003 power outage on mortality in New York, NY. Epidemiology (Cambridge, Mass.), 23 (2), p. 189-193 doi.org/10.1097/EDE.0b013e318245c61c

Arbetsmiljöverket (2014) Arbetsorsakade besvär 2014 (Work-Related Disorders 2014). ISSN 1652-1110

Armstrong LE (2005) Hydration assessment techniques. Nutrition Reviews, 63 (6), p. S40-S54, DOI: dx.doi.org/10.1111/j.1753-4887.2005.tb00153.x

Ashley CD, Ferron J, Bernard TE (2015) Loss of heat acclimation and time to re-establish acclimation. Journal of Occupational and Environmental Hygiene 12 (5), p. 302-308, DOI: 10.1080/15459624.2014.987387

Ashley CD, Luecke CL, Schwartz SS, Islam MZ, Bernard TE (2008) Heat strain at the critical WBGT and the roles of clothing, metabolic rate and gender. International Journal of Industrial Ergonomics, 38, 640-644, doi:10.1016/j.ergon.2008.01.017

ASHRAE Handbook (2005) Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, USA

Auerbach PS (2007) Wilderness Medicine. Fifth edition, Mosby Elsevier

Baccini,M, Biggeri A, Accetta G, Kosatsky T, Katsouyanni K, Analitis A, Anderson HR, Bisanti L, D'Ippoliti D, Danova J, Forsberg B, Medina S, Paldy A, Rabczenko D, Schindler C, Michelozzi P (2008) Heat Effects on Mortality in 15 European Cities. Epidemiology, 19 (5), p. 711-719, doi: 10.1097/EDE.0b013e318176bfcd

Barker RL, Guerth-Schacher C, Grimes RV, Hamouda. H. (2006) Effects of moisture on the thermal protective performance of firefighter protective clothing in low-level radiant heat exposures. Text Res J 76 (1), p. 27-31.

Barr D, Gregson W, Reilly T (2010) The thermal ergonomics of firefighting reviewed. Applied Ergonomics, 41 (1), p. 161-172, doi:10.1016/j.apergo.2009.07.001

Bergman TL, Lavine AS, Incropera FP, DeWitt DP (2011) Fundamentals of Heat and Mass Transfer. Seventh edition. John Wiley & Sons, USA

Bernard T, Ashley C, Trentacosta J, Kapur V, Tew S (2010) Critical heat stress evaluation of clothing ensembles with different levels of porosity. Ergonomics, 53 (8), p. 1048-1058, DOI: 10.1080/00140139.2010.494736

Bernard TE, Barrow CA (2013) Empirical approach to outdoor WBGT from meteorological data and performance of two different instrument designs. Industrial Health 51, p. 79-85

Bernard TE, Caravello V, Schwartz SW, Ashley CD (2007) WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. Journal of Environmental and Occupational Hygiene, 5 (1), p. 1-5, DOI: 10.1080/15459620701732355

Bernard TE, Cross RR (1999) Heat stress management: case study in an aluminum smelter. Int J Ind Ergonom, 23 (5-6), p. 609-620, doi: 10.1016/S0169-8141(97)00075-9

Bernard TE, Iheanacho I (2015) Heat Index and Adjusted Temperature as Surrogates for Wet Bulb Globe Temperature to Screen for Occupational Heat Stress, Journal of Occupational and Environmental Hygiene, 12 (5), p. 323-333, DOI: 10.1080/15459624.2014.989365

Bilzon JL, Scarpello EG, Smith CV, Ravenhill NA, Rayson MP (2001) Characterization of the metabolic demands of simulated shipboard Royal Navy fire-fighting tasks. Ergonomics, 44 (8), p. 766-780, DOI:10.1080/00140130118253

Binkley HM, Beckett J, Casa DJ, Kleiner DM, Plummer PE (2002) National Athletic Trainers' Association position statement: Exertional heat illnesses. J. Athl. Train. 37 (3), p. 329-343

Błażejczyk K, Epstein Y, Jendritzky G, Staiger H, Tinz B (2012) Comparison of UTCI to selected thermal indices. International Journal of Biometeorology 56 (3), p. 515-535

Błażejczyk K, Nilsson H, Holmér I (1993) Solar heat load on man (Review of different methods of estimation). International Journal of Biometeorology, 37(3), p. 125-132

Blom K. (2016) Personal communication, 2016.03.10. Swedish Work Environment Authority.

Bogerd N, Daanen HAM (2011) Physiological effects after exposure to heat: a brief literature review. Annales Kinesiologiae, 2 (1) p. 14-23

Bogerd N, Psikuta A, Daanen HAM, Rossi RM (2010) How to measure thermal effects of personal cooling systems: human, thermal manikin and human simulator study. Physiological Measurement 31 (9), p. 1161-1168 doi:10.1088/0967-3334/31/9/007

Bohgard M, Akselsson R, Holmér I, Johansson G, Rassner F, Swensson L-G (2009) Physical factors. In: Eds. Bohgard M, Karlsson S, Lovén E, Mikaelsson L-Å, Mårtensson L, Osvalder A-L, Rose L, Ulfvengren L. Work and technology on human terms. Prevent, Stockholm, Sweden

Bohm M, Browen B, Noren O, Holmer I, Nilsson H (1990) Evaluation of the thermal environment in tractor cabs. Proceedings of Agricultural Engineering Conference, Berlin, Germany

Bohm M, Holmer I, Nilsson H, Noren O (2002) Thermal effect of glazing in driver's cabs: Evaluation of the impact of different types of glazing on the thermal comfort. JTI-rapport, Lantbruk & Industri 305, www.jti.se/uploads/jti/R-305MB.pdf

Bouskill LM, Havenith G. Kuklane K, Parsons KC, Withey WR (2002) Relationship between clothing ventilation and thermal insulation. Am. Ind. Hyg. Assoc. J., 63(3), p. 262-268

Brake DJ, Bates GP (2002) Limiting metabolic rate (thermal work limit) as an index of thermal stress. Appl Occup Environ Hyg, 17 (3), p. 176-186, DOI: 10.1080/104732202753438261

Bröde P, Fiala D, Błażejczyk K, Holmér I, Jendritzky G, Kampmann B, Tinz B, Havenith G (2012a) Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). International Journal of Biometeorology 56 (3), p. 481-494

Bröde P, Havenith G, Wang X, Candas V, den Hartog E, Griefahn B, Holmér I, Kuklane K, Meinander H, Nocker W, Richards M (2008a) Nonevaporative effects of a wet mid layer on heat transfer through protective clothing. Eur J Appl Physiol 104(2), p. 341-349

Bröde P, Krüger E, Rossi FA, Fiala D (2012b) Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI - a case study in Southern Brazil. International Journal of Biometeorology 56 (3), p. 471-480

Bröde P, Kuklane K, Candas V, den Hartog E, Griefahn B, Holmér I, Meinander H, Nocker W, Richards M, Havenith G (2008b) Heat transfer through protective clothing under symmetric and asymmetric long wave thermal radiation. Z Arb Wiss 62 (4), p. 267-276

Bröde P, Kuklane K, Candas V, den Hartog E, Griefahn B, Holmér I, Meinander H, Nocker W, Richards M, Havenith G (2010) Heat Gain From Thermal Radiation Through Protective Clothing With Different Insulation, Reflectivity and Vapour Permeability. International Journal of Occupational Safety and Ergonomics (JOSE) 16 (2), p. 231-244

Budd GM (2008) Wet-bulb globe temperature (WBGT)——its history and its limitations Journal of Science and Medicine in Sport 11 (1), p. 20—32Burton AC (1939) The range and variability of the blood flow in the human fingers and the vasomotor regulation of body temperature. Am J Physiol, 127: 437-453

Caldwell JN, Matsuda‑Nakamura M, Taylor NAS (2014) Three‑dimensional interactions of mean body and local skin temperatures in the control of hand and foot blood flows. Eur J Appl Physiol 114 (8), p. 1679-1689, DOI 10.1007/s00421-014-2894-x

Caldwell JN, Patterson MJ, Taylor NAS (2012) Exertional thermal strain, protective clothing and auxiliary cooling in dry heat: evidence for physiological but not cognitive impairment. European Journal of Applied Physiology 112 (10), p. 3597-3606

Callejón-Ferre AJ, Manzano-Agugliaro F, Díaz-Pérez M, Carreno-Sánchez J (2011) Improving the climate safety of workers in Almería-type greenhouses in Spain by predicting the periods when they are most likely to suffer thermal stress. Applied Ergonomics 42 (2), p. 391-396, doi:10.1016/j.apergo.2010.08.014

Cecchini M, Colantoni A, Massantini R, Monarca D (2010) Estimation of the risks of thermal stress due to the microclimate for manual fruit and vegetable harvesters in central Italy. J. Agric. Saf. Health 16 (3), p. 141-159

Chan APC, Song W, Yang Y (2015) Meta-analysis of the effects of microclimate cooling systems on human performance under thermal stressful environments: Potential applications to occupational workers. Journal of Thermal Biology, 49-50, p. 16-32, doi:10.1016/j.jtherbio.2015.01.007

Chaudhary R, Ajit, Verma M, Srivastava RK (2012) Reduction of occupational health hazards of firer in brick kiln industry using artificial neural network and genetic algorithm. International Journal of Computer Science and Communication Engineering, Special issue on "Emerging Trends in Engineering" ICETIE 2012, p. 51-55

Chen Z, Lu, C (2005) Humidity Sensors: A Review of Materials and Mechanisms. Sensor Letters, 3 (4), 274-295

Cheuvront SN, Kenefick RW, Montain SJ, Sawka MN (2010) Mechanisms of aerobic performance impairment with heat stress and dehydration. Journal of Applied Physiology 109 (6), p. 1989-1995, DOI: 10.1152/japplphysiol.00367.2010

Clark JA, Cena K (1978) Net radiation and heat transfer through clothing: the effects of insulation and colour. Ergonomics 21: 691-696

Climate CHIP (2015) www.climatechip.org/your-area-climate-data, accessed 2015.11.30

Crowe J, Nilsson M, Kjellstrom T, Wesseling C (2015) Heat exposure in sugarcane harvesters in Costa Rica. Am J Ind Med 58, p. 541-548. DOI: 10.1002/ajim.22450

Crowe J, Wesseling C, Solano BR, UmañaMP, Ramírez AR, Kjellstrom T, Morales D, Nilsson M (2013) Heat-Related Symptoms in Sugarcane Harvesters. Am J Ind Med 56 (10), p. 1157-1164, doi: 10.1002/ajim.22204

Crown EM, Dale JD. Bitner E (2002) A Comparative analysis of protocols for measuring heat transmission through flame-resistant materials: capturing the effects of thermal shrinkage, Fire and Materials 26, p. 207-213

Culp K, Tonelli S, Ramey SL, Donham K, Fuortes L (2011) Preventing Heat-Related Illness among Hispanic Farmworkers. Workplace Health Saf. 59 (1) p. 23-32, doi: 10.1177/216507991105900104

Curran AR, Peck SD, Hepokoski MA, Burke RA (2014) Physiological model control of a sweating thermal manikin. Ambience`14&10i3m, 7-9 Sept 2014 Tampere, Finland

d'Ambrosio Alfano FR, Malchaire J, Palella BI, Riccio G (2014) The WBGT index revisited after 60 years of use. Ann Occup Hyg, 58 (8), p. 955-970, doi: 10.1093/annhyg/meu050

d'Ambrosio Alfano FR, Palella BI, Riccio G (2007) The role of measurement accuracy on the heat stress assessment according to ISO 7933:2004. WIT Transactions on Biomedicine and Health 11, p. 115-124

d'Ambrosio Alfano FR, Palella BI, Riccio G (2011). Thermal environment assessment reliability using temperature–humidity indices. Industrial Health 49 (1), p. 95-106.

d'Ambrosio Alfano FR, Palella BI, Riccio G, Malchaire J (2015) On the effect of thermophysical properties of clothing on the heat strain predicted by PHS model. Annals of Occupational Hygiene, p. 1-21, doi:10.1093/annhyg/mev070

Davies CT (1979) Influence of skin temperature on sweating and aerobic performance during severe work. Journal of Applied Physiology 47 (4), p. 770-777

Davies CTM, Brotherhood JR, Collins KJ, Dore C, Imms F, Musgrove J, Weiner JS, Amin MA, Ismail HM, El Karim M, Omer AHS, Sukkar MY (1976) Energy expenditure and physiological performance of Sudanese cane cutters. British Journal of Industrial Medicine, 33, p. 181-186, doi:10.1136/oem.33.3.181

De Bruyne G, Aerts J-M, Sloten Vander J, Goffin J, Verpoest I, Berckmans D (2010) Transient sweat response of the human head during cycling. Int. J. Ind. Ergon. 40 (4), p. 406-413, dx.doi.org/10.1016/j.ergon.2010.02.005

de Freitas CR, Grigorieva EA (2015) A comprehensive catalogue and classification of human thermal climate indices. Int J Biometeorol, 59 (1), p. 109-120 den Hartog EA, Havenith G (2010) Analytical study of the heat loss attenuation by clothing on thermal manikins under radiative heat loads. International Journal of Occupational Safety and Ergonomics (JOSE) 16 (2), p. 245-261

Dewhirst MW, Viglianti BL, Lora-Michiels M, Hanson M, Hoopes P (2003) Basic principles of thermal dosimetry and thermal thresholds for tissue damage from hyperthermia. International Journal of Hyperthermia, 19 (3), p. 267-294, doi: 10.1080/0265673031000119006

Dorman LE, Havenith G (2009) The effects of protective clothing on energy consumption during different activities. Eur J Appl Physiol 105 (3), p. 463-470, DOI: 10.1007/s00421-008-0924-2

Dowell CH, Tapp LC (2007) Evaluation of Heat Stress at a Glass Bottle Manufacturer. Health Hazard Evaluation Report, HETA 2003-0311-3052, National Institute for Occupational Safety and Health, Lapel, Indiana, USA

Eglin CM (2007) Physiological Responses to Fire-fighting: Thermal and Metabolic Considerations. Journal of the Human-Environment System, 10 (1) p. 7-18, doi: 10.1618/jhes.10.7

Elert G (2015) The Electromagnetic Spectrum, The Physics Hypertextbook. physics.info/em-spectrum/, accessed 2015-11-22

Elson J, Eckels S (2015) An objective method for screening and selecting personal cooling systems based on cooling properties. Applied Ergonomics, 48, p. 33-41.

EN 14225-3:2005 Diving suits – Part 3: Actively heated or cooled suit (systems) – Requirements and test methods. European Committee for Standardisation, Brussels

EN 367:1992 (1992) Protective clothing – Protection against heat and flames – Test method: Determination of the heat transmission on exposure to flame. European Committee for Standardisation, Brussels

EN 469:2005 (2006) Protective clothing for firefighters – Performance requirements for protective clothing for firefighting. European Committee for Standardisation, Brussels

EN 511:2006 (2006) Protective gloves against cold. European Committee for Standardisation, Brussels

Epstein Y, Heled Y, Ketko I, Muginshtein J, Yanovich R, Druyan A, Moran DS (2013) The Effect of Air Permeability Characteristics of Protective Garments on the Induced Physiological Strain under Exercise-Heat Stress. Ann Occup Hyg 57 (7), p. 866-874, doi: 10.1093/annhyg/met003

Epstein Y, Moran DS (2006) Thermal Comfort and the Heat Stress Indices. Industrial Health, 44 (3), p. 388-398

Fan J, Chen YS (2002) Measurement of clothing thermal insulation and moisture vapour resistance using a novel perspiring fabric thermal manikin. Meas. Sci. Technol. 13(7), p. 1115-1123

Farshad A, Montazer S, Monazzam MR, Eyvazlou M, Mirkazemi R (2014) Heat Stress Level among Construction Workers. Iranian Journal of Public Health, 43 (4), p. 492-498

Fiala D, Havenith G (2015) Modelling Human Heat Transfer and Temperature Regulation. In Gefen A (ed.) Studies in Mechanobiology, Tissue Engineering and Biomaterials. Springer. p. 1-38

Fiala D, Havenith G, Bröde P, Kampmann B, Jendritzky G (2012) UTCI-Fiala multi-node model of human heat transfer and temperature regulation. International Journal of Biometeorology 56 (3), p. 429-441

Filingeri D, Havenith G (2015) Human skin wetness perception: psychophysical and neurophysiological bases. Temperature 2 (1), p. 86-104, DOI: 10.1080/23328940.2015.1008878

Folkhälsomyndigheten (2014) Allmänna råd om temperatur inomhus. FoHMFS-2014-17, www.folkhalsomyndigheten.se/documents/publicerat-material/foreskrifter1/fohmfs-2014-17.pdf, accessed 2015-11-24

Fouillet A, Rey G, Laurent F, Pavillon G, Bellec S, Guihenneuc-Jouyaux C, Clavel J, Jougla E, Hémon D (2006) Excess mortality related to the August 2003 heat wave in France. International Archives of Occupational and Environmental Health, 80 (1), p.16-24, doi:10.1007/s00420-006-0089-4

Fukazawa T, den Hartog EA, Daanen HAM, Tochihara Y, Havenith G (2005) Water vapour transfer in the simulated protective clothing system with exposure to intensive solar radiation. In: Proceedings of the 3rd International Conference on Human-Environment System ICHES' 05, Tokyo, Japan, 2005, p. 202-205.

Fukazawa T, Havenith G (2009) Differences in comfort perception in relation to local and whole body skin wettedness. Eur J Appl Physiol; 106 (1), p. 15-24, dx.doi.org/10.1007/s00421-009-0983-z

Gaffin SL, Moran DS (2007) Pathophysiology of Heat-Related Illnesses. Chapter 10 in Auerbach PS (ed.) Wilderness Medicine, p. 228-268. Fifth edition, Mosby Elsevier

Gagge AP, Burton AC, Bazett HC (1941) A practical system of units for the description of heat exchange of man with his environment. Science; 94: 428-30

Gagnon D, Dorman LE, Jay O, Hardcastle S, Kenny GP (2009) Core temperature differences between males and females during intermittent exercise: physical considerations. Eur J Appl Physiol, 105(3):453-61, doi: 10.1007/s00421-008-0923-3

Gao C, Kuklane K, Holmér I (2010) Cooling vests with phase change material packs: the effects of temperature gradient, mass, and covering area. Ergonomics, 53(5): p. 716-723

Gao C, Kuklane K, Holmér I (2011) Cooling vests with phase change materials: the effects of melting temperature on heat strain alleviation in an extremely hot environment. European Journal of Applied Physiology, 111 (6): p. 1207-1216

Gao C, Kuklane, K, Wang F, Holmér I (2012) Personal cooling with phase change materials to improve thermal comfort from a heat wave perspective. Indoor Air, 22 (6), p. 523-530

Gao C, Wang F, Sakoi T (2012) Ventilated evaporative cooling as a preventive strategy when confronted with heat waves In: Eds. Muñoz R, Martínez M, Jordá N. The 5th European Conference on Protective Clothing (ECPC) and NOKOBETEF 10, Valencia, Spain: Aitex, Spain and ESPC

Gavhed D, Holmér I (2006) Det termiska klimatet på arbetsplatsen. Arbetslivsrapport 2006:2, Arbetslivsinstitutet

Gholamreza F, Song G (2013) Laboratory evaluation of thermal protective clothing performance upon hot liquid splash. Ann Occup Hyg 57 (6), p. 805-822, doi: 10.1093/annhyg/met028

Glazer JL (2005) Management of heatstroke and heat exhaustion. Am. Fam. Physician. 71 (11), p. 2133-2140

Gopinathan PM, Pichan G, Sharma VM (1988) Role of dehydration in heat stress-induced variations in mental performance. Arch Environ Health 43 (1), p. 15-17

Grahn, DA, Dillon JL, Heller HC (2009) Heat loss through the glabrous skin surfaces of heavily insulated, heat-stressed individuals. J Biomech Eng, 131:071005, DOI: 10.1115/1.3156812

Havenith G, Bröde P, den Hartog E, Kuklane K, Holmer I, Rossi RM, Richards M, Farnworth B, Wang X (2013) Evaporative cooling: effective latent heat of evaporation in relation to evaporation distance from the skin. J Appl Physiol 114 (6), p. 778-785, dx.doi.org/10.1152/japplphysiol.01271.2012

Havenith G, Fiala D, Błażejczyk K, Richards M, Bröde P, Holmér I, Rintamaki H, Benshabat Y, Jendritzky G (2012) The UTCI-clothing model. International Journal of Biometeorology 56 (3), p. 461-470

Havenith G, Fogarty A, Bartlett R, Smith CJ, Ventenat V (2008) Male and female upper body sweat distribution during running measured with technical absorbents. Eur J Appl Physiol, 104 (2), p. 245-255

Havenith G, Holmér I, den Hartog EA, Parsons KC (1999) Clothing evaporative heat resistance-proposal for improved representation in standards and models. Ann Occup Hyg 43 (5), p. 339-346, doi: 10.1093/annhyg/43.5.339

Havenith G, Nilsson HO (2004) Correction of clothing insulation for movement and wind effects, a meta-analysis. Eur J Appl Physiol, 92 (6), p. 636-640

Havenith G. Heus R, Lotens WA (1990a) Clothing ventilation, vapour resistance, and permeability index: changes due to posture, movement, and wind. Ergonomics; 33 (8), p. 989-1005

Havenith G. Heus R, Lotens WA (1990b) Resultant clothing insulation: a function of body movement, posture, wind, clothing fit, and ensemble thickness. Ergonomics;33 (1), p. 67-84.

Havenith, G.; Kuklane, K.; Fan, J.; Hodder, S.; Ouzzahra, Y.; Lundgren, K.; Au, Y. and Loveday, D (2015) A Database of Static Clothing Thermal Insulation and Vapor Permeability Values of Non-Western Ensembles for Use in ASHRAE Standard 55, ISO 7730, and ISO 9920, ASHRAE Transactions, Volume 121, Part 1, pp 197-215

Holmér I (2004) Thermal manikin history and applications. Eur J Appl Physiol 92 (6), p. 614-618, DOI 10.1007/s00421-004-1135-0

Holmer I (2006) Protective clothing in hot environments. Ind Health 44 (3), p. 404-413

Holmér I, Gavhed D (2007) Classification of metabolic and respiratory demands in fire fighting activity with extreme workloads. Applied Ergonomics, 38(1), p. 45-52

Holmér I, Kuklane K, Gao C (2006) Test of firefighter's turnout gear in hot and humid air exposure. International Journal of Occupational Safety and Ergonomics 12 (3), p. 297-305

Holmér I, Nilsson H, Havenith G, Parsons K (1999) Clothing convective heat exchange – proposal for improved prediction in standards and models. Ann Occup Hyg 43, p. 329-337.

Hölzle E, Kligman AM (1978) The pathogenesis of miliaria rubra. Role of the resident microflora. Br J Dermatol 99 (2), p. 117-137

Horowitz M, Kenny GP, McAllen RM, van Marken Lichtenbelt WD (2015) Thermal physiology in a changing thermal world. Temperature 2 (1), p. 22-26, DOI: 10.1080/23328940.2015.1017088

House JR, Holmes C, Allsopp AJ (1997) Prevention of heat strain by immersing the hands and forearms in water. J Royal Navy Med Serv 83:26-30

House JR, Lunt HC, Taylor R, Milligan G, Lyons J, House C (2013) The impact of a phase-change cooling vest on heat strain and the effect of different cooling pack melting temperatures. European Journal of Applied Physiology, 113 (5), p. 1223-1231.

Howe AS and Boden BP (2007) Heat-Related Illness in Athletes. The American Journal of Sports Medicine, 35 (8) p. 1384-1395, doi: 10.1177/0363546507305013

Hunt AP, Parker AW, Stewart IB (2013) Symptoms of heat illness in surface mine workers. Int Arch Occup Environ Health 86 (5), p. 519-527

Ilmarinen R, Mäkinen H, Lindholm H, Punakallio A, Kervinen H (2008) Thermal Strain in Fire Fighters While Wearing Task-Fitted Versus EN 469:2005 Protective Clothing During a Prolonged Rescue Drill. International Journal of Occupational Safety and Ergonomics, 14 (1), p. 7-18, DOI: 10.1080/10803548.2008.11076744

ILO (2010) Ergonomics checkpoints: practical and easy-to-implement solutions for improving safety, health and working conditions. Second edition. International Labour Office, Geneva

Ismail N, Ghaddar N, Ghali K (2015) Effect of inter-segmental air exchanges on local and overall clothing ventilation. Textile Research Journal (online), p. 1-17, DOI: 10.1177/0040517515591775

ISO 10551:1995 (2002) Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales. International Organisation for Standardisation, Geneva

ISO 11092:2014 (2014) Textiles – Physiological effects – Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test). International Organisation for Standardisation, Geneva

ISO 12894:2001 Ergonomics of the thermal environment – Medical supervision of individuals exposed to extreme hot or cold environments. International Organisation for Standardisation, Geneva

ISO 13506:2008 (2008) Protective clothing against heat and flame – test method for complete garments – prediction of burn injury using an instrumented manikin. International Organisation for Standardisation, Geneva

ISO 13731:2001 (2001) Ergonomics of the thermal environment – Vocabulary and symbols. International Organisation for Standardisation, Geneva

ISO 13732-1:2006 (2006) Ergonomics of the thermal environment – Methods for the assessment of human responses to contact with surfaces – Part 1: Hot surfaces. International Organisation for Standardisation, Geneva

ISO 14505-2:2006 (2006) Ergonomics of the thermal environment – Evaluation of thermal environments in vehicles - Part 2: Determination of equivalent temperature. International Organisation for Standardisation, Geneva

ISO 14505-3:2006 (2006) Ergonomics of the thermal environment – Evaluation of thermal environments in vehicles - Part 3: Evaluation of thermal comfort using human subjects. International Organisation for Standardisation, Geneva

ISO 15743:2008 (2008) Ergonomics of the thermal environment – Cold workplaces – Risk assessment and management. International Organisation for Standardisation, Geneva

ISO 15831:2004 (2004) Clothing – Physiological effects – Measurement of thermal insulation by means of a thermal manikin. International Organisation for Standardisation, Geneva

ISO 6942:2002 (2002) Protective clothing – Protection against heat and fire – Method of test: Evaluation of materials and material assemblies when exposed to a source of radiant heat. International Organization for Standardization, Geneva

ISO 7243:1989 (1989) Hot Environments – Estimation of the heat stress on working man, based on the WBGT index (wet-bulb globe temperature). International Organization for Standardization, Geneva

ISO 7726:1998 (1998) Ergonomics of the thermal environment - Instruments for measuring physical quantities. International Organisation for Standardisation, Geneva

ISO 7933:2004 (2004) Ergonomics of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. International Organisation for Standardisation, Geneva

ISO 8996:2004 (2004) Ergonomics of the thermal environment – Determination of metabolic rate. International Organisation for Standardisation, Geneva

ISO 9886:2004 (2004) Ergonomics – Evaluation of thermal strain by physiological measurements. International Organisation for Standardisation, Geneva

ISO 9920:2007 (2007) Ergonomics of the thermal environment – Estimation of thermal insulation and water vapour resistance of a clothing ensemble. International Organisation for Standardisation, Geneva

ISO/TS 14505-1:2007 (2007) Ergonomics of the thermal environment – Evaluation of thermal environments in vehicles – Part 1: Principles and methods for assessment of thermal stress. International Organisation for Standardisation, Geneva

Jay O, Cramer MN, Ravanelli NM, Hodder SG (2015) Should electric fans be used during a heat wave? Applied Ergonomics, 46, p. 137-143.

Jendritzky G, de Dear R, Havenith G (2012) UTCI – Why another thermal index? International Journal of Biometeorology 56 (3), p. 421-428

Jögård H (2004) Solenergitransmission i textila material (Solar energy transmission in textile materials. In Swedish). Kandidatexamen vid institutionen Textilhögskolan, Högskolan i Borås, 2004:2:1

Kadzere CT, Murphy MR, Silanikove N, Maltz E (2002) Heat stress in lactating dairy cows - a review. Livestock Production Science, 77 (1), p. 59-91, doi:10.1016/S0301-6226(01)00330-X

Kahn SA, Patel JH, Lentz CW, Bell DE (2012) Firefighter Burn Injuries: Predictable Patterns Influenced by Turnout Gear. Journal of Burn Care & Research 33(1) p. 152-156, doi: 10.1097/BCR.0b013e318234d8d9

Kampmann B, Bröde P, Fiala D (2012) Physiological responses to temperature and humidity compared to the assessment by UTCI, WGBT and PHS International Journal of Biometeorology 56 (3), p. 505-513, DOI 10.1007/s00484-011-0410-0.

Kearns RD, Cairns CB, Holmes JH, Rich PB, Cairns BA (2013) Thermal burn care: A review of best practices. EMS World 42 (1), p. 43-51

Kenny GP, Larose J, Wright-Beatty HE, Boulay P, Sigal RJ, Flouris AD (2015) Older firefighters are susceptible to age-related impairments in heat dissipation. Med. Sci. Sports Exerc., Vol. 47, No. 6, p. 1281-1290, DOI: 10.1249/MSS.0000000000000537

Kingma BRM, Frijns AJH, Schellen L, van Marken Lichtenbelt WD (2014) Beyond the classic thermoneutral zone. Temperature 1 (2), p. 142-149, DOI: 10.4161/temp.29702

Kjellstrom T (2009) The direct impact of climate change on regional labour productivity. Arch Environ Occup Health 64, p. 217-227

Kjellstrom T, Holmer I, Lemke B (2009) Workplace heat stress, health and productivity – an increasing challenge for low-and middle income countries during climate change. Glob Health Action 2, dx.doi.org/10.3402/gha.v2i0.2047

Klinger C, Landeg O, Murray V (2014) Power outages, extreme events and health: a systematic review of the literature from 2011-2012. PLoS Currents 6, ecurrents.dis.04eb1dc5e73dd1377e05a10e9edde673, doi: 10.1371/currents.dis.04eb1dc5e73dd1377e05a10e9edde673

Knochel JP (1974) Environmental heat illness: An eclectic review. Arch Intern Med, 133, p. 841-864

Knochel JP, Reed G (1987) Disorders of heat regulation. In: Kleeman CR, Maxwell MH, Narin RG (eds.). Clinical Disorders of Fluid and Electrolyte Metabolism. New York, McGraw-Hill, p. 1197-1232

Kobayashi Y, Tanabe S-i (2013) Development of JOS-2 human thermoregulation model with detailed vascular system. Building and Environment, 66, p. 1-10, doi: 10.1016/j.buildenv.2013.04.013

Kopp G, Lean JL (2011) A new, lower value of total solar irradiance: Evidence and climate significance. Geophysical Research Letters, 38, L01706, doi:10.1029/2010GL045777

Krüger E, Drach P, Bröde P (2015) Implications of air-conditioning use on thermal perception in open spaces: A field study in downtown Rio de Janeiro. Building and Environment 94 (1), p. 417-425, doi:10.1016/j.buildenv.2015.07.024

Kuklane and Gao, 2010. Report on an incident under laboratory exercise. Lund University

Kuklane K, Dahlqvist C, Lundgren K, Lucas R, Halder A, Gao C, Jakobsson K, Hansson G-Å (2015a) Assessment of workload in heat: an approach with accelerometers. International Symposium on fire Fighters and Heat Strain, p. 62-67

Kuklane K, Gao C, Holmér I (2012) Ventilation solutions in clothing. The 10th Joint International Scientific Conference CLOTECH 2012: Innovations in textile materials & protective clothing, p. 205-212

Kuklane K, Gao C, Holmér I, Giedraityte L, Bröde P, Candas V, den Hartog E, Meinander H, Richards M, Havenith G (2007) Calculation of clothing insulation by serial and parallel methods: Effects on clothing choice by IREQ and thermal responses in the cold. International Journal of Occupational Safety and Ergonomics 13(2), p. 103-116

Kuklane K, Gao C, Holmér I, Thermprotect study group (2006a) Effects of natural solar radiation on manikin heat exchange. In: 3rd European Conference on Protective Clothing (ECPC) and NOKOBETEF 8. Protective Clothing Towards Balanced Protection [CD-ROM]. Warszawa, Poland: Central Institute for Labour Protection – National Research Institute, p. 1-6

Kuklane K, Heidmets S, Johansson T (2006b) Improving thermal comfort in an orthopaedic aid: Better Boston Brace for scoliosis patients. In: Ed. Fan J. The 6th International Meeting on Manikins and Modelling (6I3M), Hong Kong: The Hong Kong Polytechnic University

Kuklane K, Lundgren K, Gao C, Löndahl J, Hornyanszky ED, Östergren PO, Becker P, Samuels MC, Gooch P, Sternudd C, Albin M, Taj T, Malmqvist E, Swietlicki E, Olsson L, Persson K, Alkan Olsson J, Kjellstrom T (2015b). Ebola: Improving the design of protective clothing for emergency workers allows them to better cope with heat stress and help to contain the epidemic. Ann Occup Hyg, 59(2), 258-261

Kuklane K, Lundgren K, Kjellstrom T, Venugopal V, Fan F, Havenith G (2014) Insulation of traditional Indian clothing: estimation of climate change impact on productivity from PHS (predicted heat strain) model. In Aulin R, Ek Å (eds) CIB W099 International Conference on Achieving Sustainable Construction Health and Safety, Lund University, Lund, Sweden, 2-3 June 2014, lup.lub.lu.se/record/8030454/file/8030501.pdf

Kuklane K, Ohlsson G, Nilsson H, Holmér I (1996) Värmebelastning vid arbete i Ringhals reaktorinneslutning. Arbetslivsrapport 1996:14, Arbetslivsinstitutet

Kuklane K, Ohlsson G, Nilsson H, Holmér I (2000) Heat stress in ventilated airtight coverall. In: Eds. Werner J, Hexamer M. Environmental ergonomics IX, Dortmund: Shaker Verlag

Ladell WS (1955) The effects of water and salt intake upon the performance of men working in hot and humid environments. J Physiol 127 (1), p. 11-46

Larose J, Boulay P, Wright-Beatty HE, Sigal RJ, Hardcastle S, Kenny GP (2014) Age-related differences in heat loss capacity occur under both dry and humid heat stress conditions. Journal of Applied Physiology 117 (1), p. 69-79, DOI: 10.1152/japplphysiol.00123.2014

Lee J-Y, Park J, Park H, Coca A, Kim J-H, Taylor NAS, Son S-Y, Tochihara Y (2015) What do firefighters desire from the next generation of personal protective equipment? Outcomes from an international survey. Industrial Health 53 (5), p. 434-444, doi.org/10.2486/indhealth.2015-0033

Lemke B, Kjellstrom T (2012) Calculating workplace WBGT from meteorological data: a tool for climate change assessment. Ind Health, 50 (4), p. 267-78, doi.org/10.2486/indhealth.MS1352

Lin R-T, Chan C-C (2009) Effects of heat on workers' health and productivity in Taiwan. Global Health Action 2, doi.org/10.3402/gha.v2i0.2024

Lin R-T, Chan CC (2009). Effects of heat on workers' health and productivity in Taiwan. Global Health Action, 2, doi.org/10.3402/gha.v2i0.2024

Lind AR (1963) A physiological criterion for setting thermal environmental limits for everyday work. J Appl Physiol 18, p. 51-56.

Liu W, Lian Z, Deng Q, Liu Y (2011) Evaluation of calculation methods of mean skin temperature for use in thermal comfort study. Build. Environ., 46 (2), p. 478-488, dx.doi.org/10.1016/j.buildenv.2010.08.011

Liu C, Yavar Z, Sun Q (2015) Cardiovascular response to thermoregulatory challenges. Am J Physiol Heart Circ Physiol, 309 (11), p. H1793-H1812

Lu Y, Wang F, Peng H (2015a) Effect of two sweating simulation methods on clothing evaporative resistance in a so-called isothermal condition. Int J Biometeorol, p. 1-9, DOI 10.1007/s00484-015-1095-6

Lu Y, Wang F, Wan X, Song G, Shi W, Zhang C (2015b) Clothing resultant thermal insulation determined on a movable thermal manikin. Part I: effects of wind and body movement on total insulation. Int J Biometeorol 59 (10), p. 1475-1486, DOI:10.1007/s00484-015-0958-1

Lu Y, Wang F, Wan X, Song G, Shi W, Zhang C (2015c) Clothing resultant thermal insulation determined on a movable thermal manikin. Part II: effects of wind and body movement on local insulation. Int J Biometeorol 59 (10), p. 1487-1498, DOI 10.1007/s00484-015-0959-0

Lu Y, Wei F, Lai D, Shi W, Wang F, Gao C, Song G (2015d) A novel personal cooling system (PCS) incorporated with phase change materials (PCMs) and ventilation fans: An investigation on its cooling efficiency. Journal of Thermal Biology, 52, p. 137-146

Lundgren K, Kjellstrom T (2013) Sustainability challenges from climate change and air conditioning use in urban areas. Sustainability, 5, p. 3116-3128; doi:10.3390/su5073116

Lundgren K, Kuklane K, Venugopal V (2014) Occupational heat stress and associated productivity loss estimation using the PHS model (ISO 7933): a case study from workplaces in Chennai, India. Glob Health Action, 7, dx.doi.org/10.3402/gha.v7.25283

Machado-Moreira CA, Caldwell JN, Mekjavic IB, Taylor NAS (2008a) Sweat secretion from palmar and dorsal surfaces of the hands during passive and active heating. Aviat Space Environ Med 79 (11), p. 1034-1040

Machado-Moreira CA, Smith FM, van den Heuvel AMJ, Mekjavic IB, Taylor NAS (2008c) Sweat secretion from the torso during passively induced and exercise-related hyperthermia. Eur J Appl Physiol 104 (2) p. 265-70.

Machado-Moreira CA, Taylor NAS (2012a) Psychological sweating from glabrous and non-glabrous skin surfaces under thermoneutral conditions. Psychophysiol 49, p. 369-374, DOI: 10.1111/j.1469-8986.2011.01309.x

Machado-Moreira CA, Taylor NAS (2012b) Sudomotor responses from glabrous and non-glabrous skin during cognitive and painful stimulations following passive heating. Acta Physiol 204, p. 571-581, doi: 10.1111/j.1748-1716.2011.02362.x

Machado-Moreira CA, Wilmink F, Meijer A, Mekjavic IB, Taylor NAS (2008b) Local differences in sweat secretion from the head during rest and exercise in the heat . Eur J Appl Physiol 104 (2), p. 257-64.

Madeira LG, da Fonseca MA, Fonseca IA, de Oliveira KP, Passos RL, Machado-Moreira CA, Rodrigues LO (2010) Sex-related differences in sweat gland cholinergic sensitivity exist irrespective of differences in aerobic capacity. Eur J Appl Physiol 109 (1), p. 93-100

Mairiaux Ph, Malchaire J (1985) Workers self-pacing in hot conditions: A case study. Applied ergonomics 16 (2), p. 85-90

Malchaire J, Kampmann B, Havenith G, Mehnert P, Gebhardt HJ (2000) Criteria for estimating acceptable exposure times in hot work environment, a review. Int Arch Occup Environ Health 73, p. 215-220

Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, den Hartog E, Holmér I, Parsons K, Alfano G, Griefahn B (2001) Development and validation of the predicted heat strain model. Ann Occup Hyg 45, p. 1231-1235

Malchaire JB (2006) Occupational heat stress assessment by the predicted heat strain model. Industrial Health, 44 (3), p. 380-387, doi: 10.2486/indhealth.44.380

Mann R, Heimbach DM (2007) Emergency care of the burned victim. Chapter 13 in Auerbach PS (ed.) Wilderness Medicine, p. 335-351. Fifth edition, Mosby Elsevier

Marucci A, Pagniello B, Monarca D, Cecchini M, Colantoni A, Biondi P (2012) Heat stress suffered by workers employed in vegetable grafting in greenhouses. Journal of Food, Agriculture & Environment, Vol.10 (2), p. 1117-1121

Matsuzuki H, Ito A, Ayabe M, Haruyama Y, Tomita S, Katamoto S, Muto T (2011) The effects of work environments on thermal strain on workers in commercial kitchens. Ind. Health, 49 (5), p. 605-613, doi.org/10.2486/indhealth.MS1219

McCullough EA (2002) An Interlaboratory Study of Manikins Used to Measure the Thermal and Evaporative Resistance of Clothing. Institute for Environmental Research (IER) Technical Report #02-04, Kansas State University, MA, January 2002.

McCullough EA, Eckels S (2009) Evaluation of personal cooling systems for soldiers. In: Eds. Endrusick TL, Castellani JW. The 13th International Conference on Environmental Ergonomics, Boston, USA: University of Wollongong, Australia: published on behalf of the organisers

McCullough EA, Jones BW, Huck J. 1985. A comprehensive data base for estimating clothing insulation. ASHRAE Transactions 91, 29-47

McGann KP, Marion GS, Camp L, Spangler JG (1993) The influence of gender and race on mean body temperature in a population of healthy older adults. Arch Fam Med, 2(12), p. 1265-7

McQuerry M, den Hartog E, Barker R, Ross K (2015) A review of garment ventilation strategies for structural firefighter protective clothing. Textile Research Journal, online, doi: 10.1177/0040517515595029

Meinander H (1997) Experience with a sweating thermal manikin – Ready for standard use? In: Nilsson H, Holmér I (eds) Proceedings of a European seminar on thermal manikin testing. National Institute for Working Life, Stockholm, Sweden, p. 38-42

Meyer LG, Horrigan DJ, Lotz WG (1995) Effects of three hydration beverages on exercise performance during 60 hours of heat exposure. Aviation, Space, and Environmental Medicine, 66 (11), p. 1052-1057

Miller V, Bates G, Schneider JD, Thomsen J (2011) Self-pacing as a protective mechanism against the effects of heat stress. Annals of Occupational Hygiene, 55(5), p. 548-555

Miller VS, Bates GP (2007) The thermal work limit is a simple reliable heat index for the protection of workers in thermally stressful environments. Ann Occup Hyg, 51 (6), p. 553-561, doi: 10.1093/annhyg/mem035

Montain SJ, Latzka WA, Sawka MN (1995) Control of thermoregulatory sweating is altered by hydration level and exercise intensity. Journal of Applied Physiology 79 (5), p. 1434-1439

Montain SJ, Latzka WA, Sawka. MN (1999) Fluid Replacement Recommendations for Training in Hot Weather. Military Medicine 164, p. 502-508.

Moran DS, Gaffin SL (2007). Clinical Management of Heat-Related Illnesses. Chapter 11 in Auerbach PS (ed.) Wilderness Medicine, p. 268-283. Fifth edition, Mosby Elsevier

Moran DS, Mendel L, Gaffin SL (2007) Dehydration, rehydration, and hyperhydration. Chapter 64 in Auerbach PS (ed.) Wilderness Medicine, p. 1464-1476. Fifth edition, Mosby Elsevier

Mäkinen H (2010) Firefighter's protective clothing. In Scott RA (ed.) Textiles for protection. Woodhead Publishing Ltd., Cambridge, UK, p. 622-647

Nag P, Dutta P, Nag A (2013a) Critical body temperature profile as indicator of heat stress vulnerability. Ind Health 51 (1) p. 113-122

Nag PK, Dutta P, Nag A, Kjellstrom T (2013b) Extreme heat events: perceived thermal response of indoor and outdoor workers. International Journal of Current Research and Review, 5 (17), p. 65-78

Nag PK, Nag A, Ashtekar SP (2007) Thermal limits of men in moderate to heavy work in tropical farming. Ind Health 45 (1), p. 107-117

Nielsen R, Olesen BW, Fanger PO (1985) Effect of physical activities and air velocity on the thermal insulation of clothing. Ergonomics 28, p. 1617-1631

Nilsson HO, Anttonen H, Holmér I (2000) New algorithms for prediction of wind effects on cold protective clothing. Ergonomics of Protective Clothing: NOKOBETEF 6 and the 1st European Conference on Protective Clothing (ECPC 1). In Kuklane K, Holmér I (eds.) Arbete och hälsa 2000:08 p.17-20

NIOSH (2016). NIOSH criteria for a recommended standard: occupational exposure to heat and hot environments. By Jacklitsch B, Williams WJ, Musolin K, Coca A, Kim J-H, Turner N. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication 2016-106.

Olesen BW, Madsen TL (1995) Measurements of the physical parameters of the thermal environment. Ergonomics 38 (1), p. 138-153

Olesen BW, Nielsen R (1983) Thermal insulation of clothing measured on a movable thermal manikin and on human subjects. Research n:o 7206/00/914, IIIrd ECSC Programme in ergonomics.

Oliveira AV, Gaspar AR, Raimundo AM, Quintela DA (2015) Assessment of thermal environments: Working conditions in the Portuguese ceramic industry in 1994 and 2012. Work, 51 (3), p. 457-470, DOI: 10.3233/WOR-141938

Pandolf KB (1998) Time course of heat acclimation and its decay. Int J Sports Med 19 (Suppl 2), p. S157-160

Parikh DJ, Ghodasara NB, Ramanathan NL (1978) A special thermal stress problem in ceramic industry. Eur J Appl Physiol Occup Physiol 40 (1), p. 63–72, DOI 10.1007/BF00420990

Park G, Chae Y, Kim E (2012) Thermal protective performance of fire fighter’s turnout gear embedded with shape memory alloy thermal liner. In: Eds. Muñoz R, Martínez M, Jordá N. The 5th European Conference on Protective Clothing (ECPC) and NOKOBETEF 10, Valencia, Spain: Aitex, Spain and ESPC

Parsons K (2013) Occupational health impacts of climate change: current and future ISO standards for the assessment of heat stress. Industrial Health, 51 (1), p. 86 - 100

Parsons K (2014) Human thermal environments. Taylor and Francis

Parsons K.C, Havenith G, Holmér I, Nilsson H, Malchaire J (1999) The effects of wind and human movement on the heat and vapour transfer properties of clothing. Ann Occup Hyg 43 (5), p. 347-52, doi: 10.1093/annhyg/43.5.347

Peiffer JJ, Abbiss CR (2013) Thermal stress in North Western Australian iron ore mining staff. Ann Occup Hyg 57 (4), p. 519-527.

PHS simulation. Program at www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS1/PHS.html, accessed on 2015-11-29

Potter AW, Gonzalez JA, Xu X (2015) Ebola Response: Modeling the Risk of Heat Stress from Personal Protective Clothing. PLoS ONE 10 (11), doi:10.1371/journal.pone.0143461

Price M, Brownlee T, Goodman H, Priest M, Trotter S, Woollard C (2011) A comparison of ice vest pre-cooling and cold water ingestion on thermoregulatory responses to exercise in the heat wearing a bomb disposal suit. In Kounalakis S, Koskolou M (eds) XIV International Conference on Environmental Ergonomics, Nafplio, Greece

Pryor AJ, Yuill CH (1966) Mass fire life hazard. Final report for Office of Civil Defense Department of the Army. Southwest Research Institute, Department of Structural Research, Fire Research Section, San Antonio, Texas

Psikuta A, Kuklane K, Bogdan A, Havenith G, Annaheim S, Rossi RM (2015) Opportunities and constraints of presently used thermal manikins for thermo-physiological simulation of the human body. International Journal of Biometeorology, first online, p. 1-12

Ramanathan NL (1964) A new weighting system for mean surface temperature of the human body. J Appl Physiol 19, p. 531–533

Richards MGM, McCullough EA (2005) Revised Interlaboratory Study of Sweating Thermal Manikins Including Results from the Sweating Agile Thermal Manikin. Journal of ASTM International 2 (4), p. 1-13, Paper ID JAI12109, available online at www.astm.org

Rida M, Ghaddar N, Ghali K, Hoballah Y (2014) Elderly bioheat modeling: changes in physiology, thermoregulation, and blood flow circulation. Int J Biometeorol 58 (9), p. 1825-1843, DOI: 10.1007/s00484-013-0785-1

Roncal-Jiménez C, García-Trabanino R, Barregard L, Lanaspa MA, Wesseling C, Harra T, Aragón A, Grases F, Jarquin ER, González M, Weiss I, Glaser J, Sánchez-Lozada LG, Johnson RJ (2016) Heat stress nephropathy from exercise-induced uric acid crystalluria: a perspective on mesoamerican nephropathy. American Journal of Kidney Disease 67 (1), p. 20-30, dx.doi.org/10.1053/j.ajkd.2015.08.021

Rossi R (2014) Clothing for protection against heat and flames. In Wang F, Gao C (eds) Protective Clothing: managing thermal stress. Woodhead Publishing Limited. p. 70-89

Rossi RM, Schmid M and Camenzind MA (2014) Thermal energy transfer through heat protective clothing during a flame engulfment test. Text Res J 84 (13), p. 1451–1460, doi: 10.1177/0040517514521115

Rothfusz LP (1990) The heat index "equation" or more than you ever wanted to know about heat index. National Weather Service Southern Region technical attachment SR/SSD 90-23, Fort Worth: National Weather Service; p. 1-2

Rowell LB. 1983. Cardiovascular aspects of human thermoregulation. Circulation Research. 52:367-79

Rowlinson S, Jia YA, Li B, Ju CC (2013) Management of climatic heat stress risk in construction: a review of practices, methodologies, and future research. Accident Analysis and Prevention 66, p. 187–198, doi: 10.1016/j.aap.2013.08.011

Rowlinsson S, Jia YA (2013) Application of the predicted heat strain model in development of localized, threshold-based heat stress management guidelines for the construction industry. Ann Occup Hyg 58 (3), p. 326-339, doi: 10.1093/annhyg/met070

Roy C, Gies H (1997) Protective measures against solar UV exposures. Radiat. Prot. Dosim. 72 (3-4), p. 231-240

Saat M, Singh R, Sirisinghe RG, Nawawi M (2002) Rehydration after exercise with fresh young coconut water, carbohydrate-electrolyte beverage and plain water. Journal of Physiological Anthropology and Applied Human Science, 21(2): 93-104

Sahu S, Sett M, Kjellstrom T (2013) Heat Exposure, Cardiovascular Stress and Work Productivity in Rice Harvesters in India: Implications for a Climate Change Future. Ind Health, 51 (4) p. 424-431

Schenker MB, Orenstein MR, Samuels SJ (2002) Use of protective equipment among California farmers. Am J Ind Med 42 (5), p. 455-464

Schwellnus MP (2009) Cause of exercise associated muscle cramps (EAMC)—altered neuromuscular control, dehydration or electrolyte depletion? Br J Sport Med 43 (6), p. 401-408

Sett M, Sahu S (2014) Effects of occupational heat exposure on female brick workers in West Bengal, India. Global Health Action, 7, 10.3402/gha.v7.21923. doi.org/10.3402/gha.v7.21923

Shibolet S, Lancaster MC, Danon Y (1976) Heat stroke: a review. Aviat Space Environ Med; 47: 280-301

Shin S, Park J, Lee J-Y (2015) Does the hair influence heat extraction from the head during head cooling under heat stress? Industrial Health, 53 (6), p. 533-541

Siebert S, Ewert F (2014) Future crop production threatened by extreme heat Environmental Research Letters, 9, doi:10.1088/1748-9326/9/4/041001

Siekmann H (1989) Determination of maximum temperatures that can be tolerated on contact with hot surfaces. Applied Ergonomics 20 (4), p. 313-317, doi:10.1016/0003-6870(89)90197-X

Slovic CM, Anderson GF, Casolaro A (1982) Survival in a heat stroke victim with a core temperature in excess of 46.5 °C. Ann Emerg Med, 11(5), 269-271

SMHI 2015. www.smhi.se/kunskapsbanken/meteorologi/svenska-temperaturrekord-1.5792, accessed 2015.11.30

SMHI (2016) www.smhi.se/klimatdata/meteorologi/kartor/monYrTable.php?par=tmp&month=7, accessed 2016.03.17

Smith CJ, Havenith G (2011) Body mapping of sweating patterns in males athletes in mild exercise-induced hyperthermia. Eur J Appl Physiol, 111 (7), p. 1391-1404

Smith CJ, Havenith G (2012) Body mapping of sweating patterns in athletes: a sex comparison. Medicine & Science in Sports & Exercise, 44 (12), p. 2350-2361, DOI: 10.1249/MSS.0b013e318267b0c4

Smith CJ, Machado-Moreira CA, Plant G, Hodder S, Havenith G, Taylor NAS (2013) Design data for footwear - sweating distribution on the human foot. Int J Cloth Sci Tech 25 (1), p. 43-58

Smolander J, Kuklane K, Gavhed D, Nilsson H, Holmér I (2004) Effectiveness of a light-weight ice-vest for body cooling while wearing fire fighter's protective clothing in the heat. International Journal of Occupational Safety and Ergonomics 10 (2), p. 111-117

Socialstyrelsen (2005) Temperatur inomhus. Handböcker om handläggning. www.folkhalsomyndigheten.se/pagefiles/12940/temperatur-inomhus.pdf, accessed 2015-11-24

Song G, Barker RL, Hamouda H, Kuznetsov AV, Chitrphiromsri P, Grimes RV (2004) Modeling the thermal protective performance of heat resistant garments in flash fire exposures. Text Res J 74 (12), p. 1033-1040, doi: 10.1177/004051750407401201

Song W, Wang F (2015): The hybrid personal cooling system (PCS) could effectively reduce the heat strain while exercising in a hot and moderate humid environment, Ergonomics, DOI: 10.1080/00140139.2015.1105305

Spector JT, Sheffield PE (2014) Re-evaluating Occupational Heat Stress in a Changing Climate. Ann Occup Hyg 58 (8), p. 936-942, doi: 10.1093/annhyg/meu073

Spitz MG, Castellani JW, Freund BJ, Sawka MN (2012) Management of heat and cold stress – guidance to NATO medical personnel. USARIEM Technical Report T13-3, Thermal and Mountain Medicine Division, U.S. Army Research Institute of Environmental Medicine, Natick, MA, USA, December 2012

Steadman RG (1979) The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. J Appl Meteor, 18 (7), p. 861-873, dx.doi.org/10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2

Stoll AM, Greene LC (1959) Relationship between pain and tissue damage due to thermal radiation. Journal of Applied Physiology 14 (3) p. 373-382

Sund-Levander M, Forsberg C, Wahren LK (2002) Normal oral, rectal, tympanic and axillary body temperature in adult men and women: a systematic literature review. Scand J Caring Sci 16 (2), p. 122-128. doi:10.1046/j.1471-6712.2002.00069.x

Svensson S, Cedergårdh E, Mårtensson O, Winnberg T (2009) Taktik, ledning, ledarskap. MSB (Myndigheten för samhällsskydd och beredskap)

Taylor NAS (2006) Challenges to temperature regulation when working in hot environments. Industrial Health 44 (3), p. 331-344

Taylor NAS, Caldwell JN, Mekjavic IB (2006) The sweating foot: local differences in sweat secretion during exercise-induced hyperthermia. Aviat Space Environ Med 77 (10), p. 1020-1027.

Taylor NAS, Caldwell JN, van den Heuvel AMJ, Patterson MJ (2008) To cool, but not too cool: that is the question — immersion cooling for hyperthermia. Med. Sci. Sports Exerc. 40 (11), p. 1962-1969

Taylor NAS, Machado-Moreira CA (2013) Regional variations in transepidermal water loss, eccrine sweat gland density, sweat secretion rates and electrolyte composition in resting and exercising humans. Extreme Physiology & Medicine, 2(4), www.extremephysiolmed.com/content/2/1/4 1

Taylor NAS, Machado-Moreira CA, van den Heuvel AMJ, Caldwell JN. 2014. Hands and feet: physiological insulators, radiators and evaporators. Eur J Appl Physiol, 114:2037-2060, DOI 10.1007/s00421-014-2940-8

Tipton M, Pandolf K, Sawka M, Werner J, Taylor NAS (2008) Physiological adaptation to hot and cold environments. In Taylor NAS, Groeller H, McLennan P (eds) Physiological bases of human performance during work and exercise. Churchill Livingstone Elsevier, p. 379-400

Ueda H, Havenith G (2005) The effect of fabric air permeability on clothing ventilation. In Tochihara Y, Ohnaka T (eds.) Environmental Ergonomics — The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment. Elsevier Ergonomics Book Series. Volume 3, p. 343-346

Ueno S, Sawada S (2012) Correction of the evaporative resistance of clothing by the temperature of skin fabric on a sweating and walking thermal manikin. Text. Res. J., 82 (11), p. 1143-1156, DOI: 10.1177/0040517511427966

Underwood CR, Ward EJ (1966) The solar radiation area of man. Ergonomics 9, 155-168

Vanggaard L, Kuklane K, Halder A (2015) The “AVA - organ”. Extreme Physiology & Medicine, 4 (Suppl 1): A95, p. 1-2, doi:10.1186/2046-7648-4-S1-A95

Vangelova K, Deyanov C, Velkova D, Ivanova M, Stanchev V (2008) Heat stress in two manufacturing units. Acta Medica Bulgarica, 35 (2), p. 40-46

Vatani J, Golbabaei F, Farhang Dehghan S, Yousefi A (2015) Applicability of Universal Thermal Climate Index (UTCI) in occupational heat stress assessment – a case study in Brick industries. Industrial Health, advance publication

Wallace RF, Kriebel D, Punnett L, Wegman DH, Amoroso PJ (2007) Prior heat illness hospitalization and risk of early death. Environmental Research, 104 (2), p. 290-295, doi: 10.1016/j.envres.2007.01.003

Wang F, del Ferraro S, Lin L-Y, Mayor TS, Molinaro V, Ribeiro M, Gao C, Kuklane K, Holmér I (2012a) Localised boundary air layer and clothing evaporative resistances for individual body segments, Ergonomics, 55 (7), p. 799-812, dx.doi.org/10.1080/00140139.2012.668948

Wang F, Gao C, Kuklane K, Holmér I (2011) Determination of clothing evaporative resistance on a sweating thermal manikin in an isothermal condition: heat loss method or mass loss method? Ann. Occup. Hyg 55 (7), p. 775-783

Wang F, Gao C, Kuklane K, Holmér I (2013) Effects of various protective clothing and thermal environments on heat strain of unacclimated men: the PHS (predicted heat strain) model revisited. Industrial Health 51 (3), p. 266-274

Wang F, Kuklane K, Gao C, Holmér I (2010) Development and validity of a universal empirical equation to predict skin surface temperature on thermal manikins. J Ther Biol 35 (4), p. 197-203.

Wang F, Kuklane K, Gao C, Holmér I (2012b). Effect of temperature difference between manikin and wet fabric skin surfaces on clothing evaporative resistance: how much error is there? Int. J. Biometeorol. 56 (1), p. 177-182

Wang F, Shi W, Lu Y, Song G, Rossi RM, Annaheim S (2015a) Effects of moisture content and clothing fit on clothing apparent 'wet' thermal insulation: a thermal manikin study. Text. Res. J. dx.doi.org/10.1177/0040517515580527

Wang F, Zhang C, Lu Y (2015b) Correction of the heat loss method for calculating clothing real evaporative resistance. J Therm Biol 52, p. 45-51, doi:10.1016/j.jtherbio.2015.05.004

Wesseling C, Aragón A, González M, Weiss I, Glaser J, Bobadilla NA, Roncal-Jiménez C, Correa-Rotter R, Johnson RJ, Barregard L (2016) Kidney function in sugarcane cutters in Nicaragua - A longitudinal study of workers at risk of Mesoamerican nephropathy. Environmental Research, 147, p. 125-132, dx.doi.org/10.1016/j.envres.2016.02.002

Wesseling C, Crowe J, Hogstedt C, Jakobsson K, Lucas R, Wegman DH (2014) Resolving the enigma of the mesoamerican nephropathy: a research workshop summary. American Journal of Kidney Diseases, 63 (3), p. 396-404

Wikipedia (2015) en.wikipedia.org/wiki/Emissivity, accessed 20/11/2015

Williams CG, Wyndham CH, Morrison JF (1967) Rate of loss of acclimatization in summer and winter. Journal of Applied Physiology, 22(1), 21-26

WMO 2015. wmo.asu.edu/world-highest-temperature, accessed 2015.11.30

Woodcock AH (1962) Moisture Transfer in Textile Systems, Part I. Textile Research Journal 32 (8), p. 628-633, doi: 10.1177/004051756203200802

Wyndham CH (1973) The physiology of exercise under heat stress. Ann. Rev. Physiol. 1973. 35: 193-220

Wyndham CH, Strydom NB, Benade AJ, van Rensburg AJ (1973) Limiting rates of work for acclimatization at high wet bulb temperatures. Journal of Applied Physiology, 35(4), p. 454-458

Wyndham CH, Strydom NB, Cooke HM, Maritz JS (1960) The temperature responses of men after two methods of acclimatization. Internationale Zeitschrift für angewandte Physiologie einschließlich Arbeitsphysiologie, 18(2), 112-122

Xiang J, Bi P, Pisaniello D, Hansen A (2014) Health impacts of workplace heat exposure: an epidemiological review. Industrial Health, 52 (2), p. 91-101, doi.org/10.2486/indhealth.2012-0145

Xu X, Endrusick T, Laprise B, Santee W, Kolka M (2006) Efficiency of liquid cooling garments: prediction and manikin measurement. Aviation, Space and Environmental Medicine, 77, p. 644-648

Xu X, Gonzalez J (2011) Determination of the cooling capacity for body ventilation system. European Journal of Applied Physiology, 111 (12), p. 3155-3160.

Yaglou CP, Minard D (1957) Control of heat casualties at military training centers. Am Med Ass Arch Ind Hlth 16, p. 302-316

Yi W, Chan APC (2013) Optimizing work–rest schedule for construction rebar workers in hot and humid environment. Building and Environment 61, p. 104-113, dx.doi.org/10.1016/j.buildenv.2012.12.012

Yi W, Chan APC (2015a) Optimal work pattern for construction workers in hot weather – A case study in Hong Kong. Journal of Computing in Civil Engineering 29 (5), p. 1-11, doi: 10.1061/(ASCE)CP.1943-5487.0000419

Yi W, Chan APC (2015b) Which Environmental Indicator Is Better Able to Predict the Effects of Heat Stress on Construction Workers? J Manage Eng, 31 (4), p. 1-9, doi: 10.1061/(ASCE)ME.1943-5479.0000284, 04014063

Zhang Y, Davis J-K, Casa DJ, Bishop PA (2015) Optimizing cold water immersion for exercise-induced hyperthermia: a meta-analysis. Medicine & Science in Sports & Exercise 47 (11), p. 2464-2472, DOI: 10.1249/MSS.0000000000000693

Zhao M, Gao C, Wang F, Kuklane K, Holmér I, Li J (2012) A study on local cooling of garments with ventilation fans and openings placed at different torso sites. International Journal of Industrial Ergonomics, 43 (3), p. 232-237

Zhao M, Gao C, Wang F, Kuklane K, Holmér I, Li J (2013) The torso cooling of vests incorporated with phase change materials: a sweat evaporation perspective. Textile Research Journal, 83 (4), p. 418-425

Zhao M, Kuklane K, Lundgren K, Gao C, Wang F (2015) A ventilation cooling shirt worn during office work in a hot climate: cool or not? International Journal of Occupational Safety and Ergonomics, 21 (4), p. 457-463, DOI: 10.1080/10803548.2015.1087730

Redaktörernas sammanfattning och slutord

Det finns en betydande kunskap om hur påfrestningen på den mänskliga organismen vid arbete i varma miljöer kan begränsas och kontrolleras, vars huvuddrag redovisas i denna översikt. Det inkluderar kroppens egen anpassningsprocess (acklimatisering), skydd mot värmestrålning, arbetets organisering, skyddskläder, vätskeintag, med mera. Den som är äldre, har till exempel hjärt-kärlsjukdom eller tar mediciner som påverkar kroppens förmåga att avge överskottsvärme, har en nedsatt tolerans mot värmebelastning. Detta är en problematik som blir mer aktuell då fler arbetar högre upp i åldern och då fler kan återvända till arbetslivet efter allvarlig sjukdom tack vare bättre behandling. Denna problematik diskuteras i en separat översikt (Kjellström 2017). Denna översikt är skriven på engelska och nedan finns en sammanfattning av texten på svenska och referenserna till figurer och artiklar finns i den engelska texten.

Exponering för hetta

De viktiga källorna till värmebelastning i arbetslivet är:

1. Klimatfaktorer (omgivningstemperatur, med mera)
2. Fysisk arbetstyngd (kroppens egen värmeproduktion)
3. Klädsel (hindrar kroppens värmeavgivning)

De högsta utomhustemperaturerna varierar kraftigt från plats till plats. Studier av dödlighet i relation till höga temperaturer visar att den temperatur där dödligheten börjar öka varierar på motsvarande sätt (till exempel 22 °C i Stockholm och 33 °C i Aten), det vill säga, det är snarast avvikelsen från den normala än den absoluta temperaturen som är avgörande. Detta innebär att den temperaturtröskel då speciella försiktighetsåtgärder behöver vidtas för att skydda den allmänna befolkningen (särskilt de äldre) varierar från land till land. Detta har både med samhällsbyggnad, beteende och acklimatisering att göra.

Vid tungt fysiskt arbete kan kroppstemperaturen hållas normal så länge kroppen kan avge extravärmen till omgivningen. Om det inte är möjligt, till exempel på grund av skyddskläder, kommer kroppstemperaturen att höjas med 1 °C för varje 100W ökning av belastningen.

Kroppens förmåga att hantera värmestress är åldersberoende (mindre vid högre ålder) och märkbar även i yrkesverksam ålder. Detta kommer att ha en ökande betydelse då utträdesåldern från arbetslivet höjs.

Flera industriella processer genererar höga temperaturer. Skyddskläder kommer att bidra till att öka värmestressen. Om arbetet dessutom är fysiskt krävande ökar det värmestressen ytterligare, till exempel hos rökdykare.

Klimatfaktorer

De klimatfaktorer som huvudsakligen påverkar kroppens värmebalans är lufttemperatur, lufthastighet (vind), luftfuktighet, strålningsvärme och yttemperatur (Parsons 2014). Definitioner och mätmetodik är väl utarbetade i ISO-standarder och läroböcker (ISO 7726:2002, Parsons 2014). Kläder ger en isolerande effekt och särskilt genomsläppligheten i det yttre lagret har stor betydelse.

Luftrörelser minskar värmestressen genom att transportera bort varm och fuktig luft från kroppen om lufttemperaturen är högst 35-36 °C. Vid temperaturer därutöver kommer effekten att bli den motsatta.

En hög luftfuktighet minskar kroppens förmåga att hålla nere kroppstemperaturen genom svettavdunstning, som är det effektivaste sättet att bli av med värme och den huvudsakliga mekanismen vid lufttemperaturer över 35 °C. Men även hud med 100 % fuktighetsmättnad kan avge väsentliga värmemängder till luft med 100 % fuktighet så länge hudens temperature är högre än den omgivande luftens, på grund av ångtrycksskillnaden mellan hud och luft. Klädselns fuktgenomsläpplighet påverkar, liksom klädernas utformning (om luften rör sig kring kroppen till exempel vid gång).

Strålningsvärme kan väsentligen indelas i infraröd (till exempel från ugnar) respektive ultraviolett (en viktig komponent av solljus) strålning. Absorptionen av infraröd strålning påverkas inte av färg men av ytans reflektion, medan absorptionen av ultraviolett strålning påverkas också av hur mörk ytan är (Figur 2, sida 13).

Yttemperatur är en del av strålningsvärmen, men kan också bidra till värmestress genom direkt kontakt vanligen med händer och fötter, men ibland med större kroppsytor (till exempel rygg) om man måste luta sig/ligga mot den varma ytan.

Fysisk arbetstyngd

Ämnesomsättningen i kroppen bildar värme (40 W/m^2 kroppsyta i sömn, basal metabolism). Värmen ökar snabbt vid fysisk ansträngning. Vid normalt kontorsarbete bildas 70-100 W/m^2, medan manuellt arbete oftast producerar över 100 W/m^2 (upp till 300 för mycket tunga arbetsuppgifter, ISO 8996:2004). Om inte denna värme kan avges till omgivningen kommer kroppens kärntemperatur att öka. Kärntemperaturen är det mått som används för att definiera hur allvarlig värmebelastningen är. Den mäts oftast i ändtarmen. Den kan också mätas i matstrupe (speglar snabba förändringar), hörselgång och munhåla (ISO 9886:2004).

Klädsel

All klädsel påverkar värmeutbyte med omgivningen genom att isolera och begränsa avdunstning från kroppen. Den tid under vilken man kan arbeta säkert är drastiskt reducerad i impermeabla jämfört med permeabla skyddskläder, även vid temperaturer kring 20 °C, medan den fysiologiskt säkra gränsen nås snabbt vid temperaturer över 40 °C även i permeabla kläder (Figur 3, sida 16). I varma klimat med UV-strålning (solstrålning) som en väsentlig värmekälla rekommenderas generellt ljusa löst sittande kläder med låg termisk resistens och avdunstningsresistens och som också tillåter luftcirkulation kring kroppen, men löst sittande kläder kan vara svårt att kombinera med andra säkerhetsaspekter i till exempel industriella miljöer. I arbete med extrem värmestrålning behövs välisolerade kläder som också kan innehålla ett reflekterande yttre lager (Figur 2, sida 13).

Bedömning av värmestress och värmebelastning

Flera olika metoder kan användas för att bedöma värmestress och värmebelastning. Ett arbete pågår med revidering av flera standarder (bland annat ISO 7243 och ISO 7933).

Wet Bulb Globe Temperature (WBGT) är det globalt mest använda indexet på yrkesmässig värmestress, det fungerar som ett screeningverktyg (Epstein and Moran 2006, Parsons 2013) som kan användas för varma miljöer både med och utan solstrålning. Användningen begränsas av flera saker. En praktisk sådan är att den utrustning som möter kraven i standarden (ISO 7243:1989) är dyr i inköp. Metoden beaktar dessutom bara ökning av kärntemperatur men inte risk för uttorkning och tar inte hänsyn till klädsel. Den har begränsad användning vid hög luftfuktighet eller låg lufthastighet. Rekommenderade maximala WBGT exponeringsnivåer (°C) vid olika arbetsbelastning och förhållande mellan arbete/vila för en arbetare som är acklimatiserad till värmen och bär lätt klädsel finns i Tabell 3 (sida 31).

Beräknad värmebelastning (*Predicted Heat Strain*, PHS, ISO 7933:2004) är en av de mest utvecklade metoderna för att beräkna yrkesmässig värmebelastning (Parsons 2013). I denna beräknas både påverkan på kärntemperatur och vätskeförlust på grund av svettning, den inkluderar förutom klimatfaktorer också fysisk belastning, ämnesomsättning (metabolic rate) och klädselns termiska egenskaper. Den har tidigare ansetts vara för komplicerad för användning på enskilda arbetsplatser, men simuleringsverktyg finns nu tillgängliga på Internet, exempelvis:

www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS1/PHS.html

Tillgängligheten skulle kunna ökas ytterligare genom till exempel mobilapplikationer.

Värmeindex (Heat Index) utvecklades från en matematisk modell som inkluderade klimatfaktorer, fysiologiska faktorer och kläder till en förenklad ekvation som bara använder luftens temperatur och fuktighet. Fördelen är att ingen dyr utrustning krävs men den tar inte hänsyn till strålningsvärme eller lufthastighet och är okänslig för klädsel. Den anses därför inte vara en metod som kan ersätta WBGT eller PHS.

En annan möjlighet är att direkt mäta *hur individen reagerar* på värmen genom checklistor, så som ILO 2010, eller subjektiva skattningsskalor, så som ISO 10551:1995. Men för en mer detaljerad bedömning krävs mätningar av kärntemperatur (vanligen i ändtarmen), viktförlust (dehydrering), puls och hudtemperatur (ISO 9886:2004). I vissa fall krävs en medicinsk övervakning av de individer som utsätts för extrem hetta vad gäller till exempel individens förutsättningar att klara belastningen (ISO 12894:2001).

Termiskt arbetsgräns (thermal work limit) är den maximala ämnesomsättning (fysiska belastning) som en individ, vid god vätskebalans och som är acklimatiserad till värmen, kan upprätthålla i en given termisk miljö med säker (<38,2 °C) kärntemperatur och svettning (<1,2 kg/tim). Beräkningar av den termiska arbetsgränsen kan användas för att schemalägga arbete och vila, eller för att ge riktlinjer för när arbetet skall stoppas (Miller and Bates 2007).

Ett universellt termiskt klimatindex (universal thermal climate index, UTCI, www.utci.org) har utvecklats relativt nyligen och föreslås kunna fungera som ett steg mellan meteorologiska data och att förutspå hälsoeffekter. UTCI ger en ekvivalenttemperatur för en given kombination av lufttemperatur, fuktighet, värmestrålning och vindhastighet. En begränsning är att det inte beaktar lokala förhållanden på arbetsplatsen. Utvärdering pågår i relation till andra sätt att förutsäga värmestress på arbetsplatser.

Effekter på den friska människan

Det finns en fin reglering av kroppens kärntemperatur som utnyttjar specifika organ i huden (arteriovenösa anastomoser). De finns särskilt på ickehårbeklädda ytor på våra fingrar, handflator, tår, fötter, öron och läppar. Om inte detta räcker för att hålla kärntemperaturen konstant kommer blodflödet i huden att ökas ytterligare och svettningen ökar. Svetten på hudytan ger en avkylning genom avdunstning (svettning på 1 l/timme motsvarar 674 W). Kläder som transporterar bort fukt från hudytan upplevs oftast ha bäst komfort, men samtidigt minskar avkylningseffekten. Män har i allmänhet en högre förmåga att svettas än kvinnor. Förmågan beror också på kroppsstorlek och kondition. En god förmåga att svettas är särskilt värdefull i en varm och torr miljö, medan det inte ger samma fördel i en varm miljö med hög luftfuktighet. Svetten har då svårt att avdunsta. Vid kraftig svettning behöver vätskeförlusten ersättas.

Värmestress belastar kroppens cirkulationsorgan. För måttligt till tungt fysiskt arbete kan skillnaden i pulsfrekvens, mellan 20 °C och 40 °C, vara 20-40 slag/minut (Figur 4, sida 21). Vätskeförlusten genom svettning kan ge en ökad risk för blodtrycksfall. Det kan uppträda då en fysisk ansträngning plötsligt upphör.

Extremt het luft kan ge lokala effekter på hud och andningsorgan. Vid 125 °C försvåras näsandning, vid 150 °C är det svårt att andas genom munnen, huden skadas efter 30 sekunder vid 180 °C.

Den mentala prestationsförmågan, vaksamhet och reaktionstid, påverkas av hetta redan innan kroppens temperatur når några gränsvärden. Lufttemperaturer upp till 32 °C har vid arbete som endast kräver låg fysisk aktivitet (sittande kontorsarbete) inte visats ge någon betydande kognitiv prestationsnedsättning för acklimatiserade personer, medan däremot den fysiska prestationsförmågan minskade. Om förlusten vid svettning inte ersätts så påverkas snabbt den kognitiva förmågan.

En vätskeförlust som motsvarar upp till 2 % av kroppsvikten betraktas som acceptabel. Den fysiska prestationsförmågan minskar med 10 % för varje procents förlust av kroppsvikt. Vätskeförlust på 6 % och mer kan vara livshotande och kräver medicinsk behandling. Behandlingen är vätsketillförsel och vila i sval miljö.

Den normala kärntemperaturen i kroppen är 37 °C för både män och kvinnor. För yrkesmässig exponering (8 timmar per dag) betraktas generellt en kärntemperatur på 38 °C som övre genomsnittlig gräns för acceptabel värmebelastning (AFS 1997:2, ISO 7243:1989; ISO 7933:2004). Den individuella känsligheten varierar. Om det finns möjlighet att själv styra arbetstakten kommer de flesta att börja sänka takten då kärntemperaturen i kroppen når 38 °C. I uthållighetssporter förefaller den maximala tolerabla kärntemperaturer vara 40,0-40,5 °C. En kärntemperatur på 42-43 °C leder ofta till döden.

Man bör undvika ensamarbete i hetta. Svimning på grund av hettan har framförts som en bidragande eller till och med utlösande orsak av dödsfall i heta slutna utrymmen, som tankrengöring. Svimning på grund av hetta är en avsevärd risk framför allt hos icke-acklimatiserade personer.

Värmeslag är en allvarlig följd av värmestress, med hög dödlighet och misstänkta fall måste därför behandlas skyndsamt. Hos patienter med värmeslag är kärntemperaturen extremt hög (över 40 °C) och kroppens egna regleringsmekanismer fungerar inte längre, svettningen upphör och huden är torr. Ofta har detta föregåtts av ett förvirringstillstånd.

Värmeutmattning inkluderar överbelastning av hjärtkärlsystemet, mental och fysisk utmattning. Det räknas ibland som ett förstadium till värmeslag. Värmekramper orsakas av okompenserad förlust av salt och behandlas med saltat vatten. Värmeutslag (miliaria rubra) är en hudsjukdom som orsakas av funktionsstörning i svettkörtlarna.

En ökning av kronisk njursjukdom med dödligt förlopp har observerats i tungt lantbruksarbete i varmt och fuktigt klimat och föreslagits beror på värmestress och vätskebrist (Wesseling et al 2016).

Att förebygga värmestress

Organisatoriska åtgärder, acklimatisering, vätskebalans och kylning, är viktiga komponenter för att förebygga värmestress. Riktlinjer vad gäller temperaturer inomhus har utfärdats av Folkhälsomyndigheten (2014). En mer omfattande genomgång av det termiska klimatet på arbetsplatsen har gjorts av Gavhed och Holmér (2006). Det amerikanska arbetslivsinstitutet NIOSH har nyligen sammanställt ett kriteriedokument om yrkesmässig exponering för hetta (2016).

För att den enskilde medarbetaren själv skall kunna göra anpassningar vid exponering för hetta, krävs det att arbetsgivaren tillåter att arbetstakten minskar vid höga temperaturnivåer (Miller et al 2011). Det finns en ökad risk för överbelastning av värmen om arbetstakten är styrd och för högmotiverade individer, särskilt i utryckningssituationer. Då ökar kravet på organisatoriska åtgärder, till exempel växling mellan tungt och lätt arbete eller att arbetet anpassas efter tidpunkt på dagen. Ett schema för arbete och vila i relation till WGBT-värden (ungefärliga värden från ISO 7243, Kjellström et al 2009) ges i Tabell 3 (sida 31) i denna översikt.

Acklimatisering till hetta är en viktig skyddande faktor. Systematiska studier visar att det tar cirka 10 dagar att bli fullt acklimatiserad. Under den perioden skall arbetsbördan vara lägre, med längre vilopauser mellan arbetspassen i hetta (2-4 tim/dag för full effekt). Erfarna och acklimatiserade arbetskamrater bör finnas på plats. Fysisk träning är också en sorts acklimatisering – under träning stiger kärntemperaturen i kroppen och kroppen börjar hantera överskottsvärmen på samma sätt som värmebelastning från omgivningen. Därför är den fysiska påfrestningen vid exponering för hetta mindre för den som är vältränad (Tipton et al 2008).

Kroppens anpassning till hetta anses vara en av de mest dramatiska fysiologiska anpassningarna hos människan. Den mest påfrestande perioden under acklimatiseringen är de första 3-4 dagarna, då huvuddelen av den fysiologiska anpassningen sker[1]. Anpassningen innebär att svettningen kommer tidigare, är rikligare (med en omfördelning från kroppen till armar och ben) och innehåller mindre salt, en ökning av vätskeinnehållet i kroppen med ökad plasmavolym, kärntemperatur och pulsfrekvens är lägre vid en given arbetsbelastning, risken för svimning minskar och personen känner mindre obehag. För att acklimatiseringen skall vara effektiv krävs ett tillräckligt vätskeintag.

Acklimatiseringseffektern försvinner efter två veckor om man inte utsätts för värmebelastning. Om man återigen utsätts för värmestress inom en månad

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[1] Det kan mot bakgrund av den beskrivna acklimatiseringen tyckas motsägelsefullt att ökningen av insjuknanden relaterad till hetta i samband med en värmebölja vanligen kommer först efter några dagar och sedan tilltar under hela värmeböljans varaktighet. Detta beror sannolikt på att det finns en tröghet i temperaturförändringen i byggnader, med mera, som gör att befolkningens exponering för värme gradvis ökar under ett sådant förlopp.

är acklimatiseringstiden kortare än 10 dagar och ett schema för den tid som behövs efter olika uppehåll har föreslagits.

Varje procents förlust av kroppsvätska motsvarar 10 % förlust av den fysiska arbetskapaciteten. Tillgång till dricksvatten är viktigt för att bibehålla vätskebalansen. Äter man regelbundet räcker ofta vanligt vatten eftersom det finns salt i maten. Sportdrycker är ofta för söta och socker försämrar vattenupptaget i magen. Vid tungt arbete i hetta med hög svettning, behöver saltförlusten ersättas. Då är mineralvatten eller vanligt vatten med salttillsats en lösning.

Det finns flera olika sätt att öka kroppens värmeavgivning. Exempel på detta är värmereglerande material i skyddskläder, skyddskläder med varierande isoleringsfaktor, luftkylande system, ökad ventilation i kläderna. Elektriska fläktar kan också ge effektiv kylning (Jay 2015). Dessa metoder kan kombineras för att öka effekten (Lu et al 2015d, Song och Wang 2015). Metodvalet måste ta hänsyn till både arbetets art och ge rimlig komfort. En personlig kylningsmetod som fungerar vid rörligt arbete är exempelvis en kylande huva. Den sänkte kärntemperaturen bäst om mediet höll 10 °C, men komforten upplevdes som mycket bättre och det gav fortfarande god effekt på kärntemperaturen om mediet höll 15 °C (Shin et al 2015).

Värmebelastning och åtgärder i några branscher

Hanteringen av värmestress i några olika branscher kan visa på möjligheter att handskas med problemet också i andra typer av verksamhet. Även om flera av exemplen kommer från länder med varmt klimat, kan de med tanke på klimatförändringen med återkommande, längre och svårare värmeböljor också vara relevanta för svensk arbetsmarknad. Luftkonditionering finns ibland på kontor och i industriella miljöer, men under värmeböljor kan belastningen på strömförsörjningen bli så hög att strömavbrott uppstår. Det är då viktigt att de anställda har kunskap om och tillgång till enkla, alternativa sätt att minska värmestressen (Gao et al 2012 a, 2012b, Jay 2015, Lundgren och Kjellström 2015). Arbetsorganisatoriska åtgärder inkluderar att planera scheman för arbete respektive vila, eller växling mellan arbetsuppgifter i varma respektive svala miljöer, eller under svalare tider på dygnet. Det är viktigt att denna planering görs under normala förhållanden så att produktionen/servicen kan upprätthållas. Tillgången till dricksvatten och rutiner för att säkra tillräckligt vätskeintag är nödvändigt för att undvika värmestress och sjukdom orsakad av denna. En bibehållen produktion kan också understödjas av rätt klädsel, skyddsutrustning och kylningsåtgärder, men det finns en gräns där exponeringen för hetta innebär att arbetet måste avbrytas. Ett exempel på när detta skulle bli kraftigt begränsande för effektiviteten var bekämpningen av Ebola, som krävde full skyddsutrustning för personalen i ett tropiskt klimat (Kuklane et al 2015b).

Även om förarhytterna i det moderna *jordbruket* vanligen är luftkonditionerade, görs mycket av arbetet utanför dessa i det öppna landskapet. Det är inte heller ovanligt att fönstret i traktorn måste hållas öppet för att få bättre sikt. Fordonsklimat är också komplexa eftersom temperaturen blir ojämn i hytten och bestäms av till exempel luftintagens placering och solstrålningen genom fönstren (Bohm et al 1990 och 2002). Det finns ISO-standarder för att utvärdera och förbättra klimatet i fordon (ISO/TS 14505-1:2007, ISO 14505-2:2006, ISO 1405-3:2006).

De huvudsakliga problemen med värmestress i jordbruket finns i dagsläget i redan varma länder och väntas öka där med en negativ effekt på produktiviteten. Värmestressen ökar väsentligt om skyddsutrustning måste användas, till exempel mot gödselmedel, eller mot bekämpningsmedel (Schenker et al 2002). Skyddskläder med låg permeabilitet kan orsaka värmestress även vid måttliga temperaturer. I ett tempererat klimat (som vårt) kan växthusarbete vara förknippat med hög risk för värmestress på grund av den höga temperaturen och luftfuktigheten (Callejón-Ferre et al 2011, Marucci et al 2012).

Som tidigare beskrivits är möjligheten att själv reglera arbetstakten en viktig väg att hantera problem med värmebelastning. Om det inte är möjligt, eller tillräckligt, behöver, som tidigare nämnts, arbetets organisering, vätskeintag, samt tillgång till sval (skuggig) miljö för vila, ses över.

Klimatförhållandena är, i kombination med måttligt tungt till tungt fysiskt arbete och ibland personlig skyddsutrustning/-klädsel, den huvudsakliga källan till värmestress i *byggnadsindustrin*. Vid husbyggen är det ofta möjligt att arbeta inomhus i skugga, medan man är mer exponerad vid vägarbeten (Nag et al 2013a och 2013b). Ett sätt att minska värmestressen är att skapa skydd från solstrålningen och svala områden att pausa i. Lunchpausen kan förlängas för att minska exponeringen för värme mitt på dagen. Under eftermiddagen då luften är varmare kan fler pauser läggas in. Vätskeintag skall säkras. Klädseln skall helst vara ljus och luftig, samt täcka huden om solstrålningen är stark (Roy och Gies 1977). Det kan vara svårt att förena med andra skyddsaspekter, inklusive risken att fastna. Rowlinson och medarbetare (2014) har sammanfattat kunskapsläget och åtgärder.

Keramisk industri, metallindustri, glasbruk och livsmedelsindustri, är industrigrenar med välkända problem med höga temperaturer på grund av sina industriella processer. Mycket tyder på att problemen kvarstår, till exempel i keramisk industri även om extrema temperaturer reducerats (Oliveira et al 2015). Värmestressen kan accentueras av klimatförändringen, till exempel under en värmebölja, om inte de anställda kan återhämta sig i områden utanför den varma processen. Växling mellan arbete i varma och kalla områden i produktionen kan vara ett sätt att upprätthålla produktiviteten. Vätsketillförsel är avgörande. NIOSH har publicerat utvärdering och rekommendationer för arbete i hetta i en fabrik som tillverkade glasflaskor (Dowell och Tapp 2007).

Klädseln skall vara luftig, men i områden med extrem hetta kan den behöva vara isolerande. Vid exponering för stark strålningsvärme behövs reflekterande lager. Studier har visat att om värmestressen är måttlig är arbetstakten ofta högre och pauserna kortare än om värmestressen är mer uttalad (Oliveira et al 2015).

I livsmedelssindustrin kommer värmestressen från varma ytor, uppvärmning av den omgivande luften och en förhöjd luftfuktighet på grund av förångning. Risken för värmestress är hög även om den fysiska arbetstyngden vanligen är lägre än i jordbruk och byggnadsindustri (Lundgren et al 2014, Matsuzuki et al 2011).

Brandmansarbete innebär en hög risk för brännskador, mycket tung fysisk belastning och skydd mot till exempel eldslågor, höga lufttemperaturer och kemikalier. Brandmän arbetar 90 % av tiden med annat än att släcka bränder, till exempel med trafikolyckor (Ilmarinen et al 2008). Men eftersom de alltid snabbt måste vara beredda att rycka in vid en eldsvåda, har de vanligen full utrustning hela arbetstiden. Det ökar arbetsbelastningen och värmestressen och gör att optimering av brandmännens klädsel bör ha hög prioritet.

Åtgärds-och forskningsbehov

Det finns en gedigen kunskap om betydelsen av värmestress i arbetslivet, särskilt vid fysiskt krävande arbete. Vi hoppas att denna kunskapsöversikt skall bidra till att tillgängligöra den. Som framgår av översikten finns det starka skäl att vid risk för värmestress göra en planering för hur man kan förebygga att de leder till ohälsa. Värmestress, särskilt i kombination med vätskeförlust, sänker arbetsförmågan. Vid hög värmestress är hälsoriskerna betydande.

I vissa processer och yrken med exponering för extrema temperaturer är problematiken välkänd (livsmedels-, metall- och keramisk industri, i pappersbruk, glastillverkning, med fler) och här kan förbättringspotentialen kanske främst finnas i systematiken i riskbedömningen, samt i val av skyddskläder m m.

För andra arbeten, där impermeabla skyddskläder och fysisk ansträngning kombineras med förhöjda temperaturer, kan problematiken vara undervärderad. En delvis ny problematik är tätare, intensivare och långvarigare värmeböljor, som vid arbete i skyddskläder, till exempel i vård- och omsorg, kan ge påtaglig värmebelastning och kräva en riskbedömning och eventuellt åtgärdsplanering under normala förhållanden. Riktad, branschspecifik, kortare information (till exempel korta utbildningsfilmer) kan öka medvetenheten och kunskapen om hur man förebygger skador.

Arbete vid extrema temperaturer, till exemepl för rökdykare och vid bekämpning av större skogsbränder, kan leda till att kärntemperaturen ökar så mycket att omdömet sviktar. Detta har orsakat dödsfall. Effektivare övervakning av värmebelastningen under arbetet skulle minska risken. Det finns teknisk möjlighet att övervaka värmebelastning under arbete, men en vidare utveckling behövs för att omvandla den insamlade informationen så att den ger ett bättre stöd för åtgärder. En fortsatt forskning kring säkerhet och åtgärder för arbetssituationer då lätt-måttlig kognitiv påverkan innebär en säkerhetsrisk (till exempel yrkeschaufförer) är också motiverad.

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