

The Deep Body Core Temperatures, Physical Fatigue and Fluid Status of Thermally stressed Workers and the Development of Thermal Work Limit as an Index of Heat Stress

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Abstract

Objectives:

To determine the physiological strain on industrial workers under thermal stress on extended shifts. Continuously-measured deep body core temperatures and heart rates, fluid intake, changes in hydration state, and physical fatigue were monitored to establish acceptable levels of physiological strain. A rational heat stress index compatible with these limits was developed. Working-in-heat protocols specifically designed for a self-paced workforce were established.

Methods:

A series of studies was conducted over 77 shifts on a group of approximately 50 male volunteers working in thermally stressful environments. Continuously-recorded deep body core temperatures, heart rates, fluid consumption, urinary specific gravity and physical fatigue were measured and recorded. A new field protocol was developed to assess physical fatigue over the working shift.

An original methodology was developed to allow any heat stress index to be assessed on a comparative basis with any other index. A review of the commonly used occupational heat stress indices was conducted.

A new rational heat stress index was developed, based on existing biophysical relationships and recommended physiological strain limits of deep body core temperature and sweat rate.

New protocols designed for self-paced work incorporating the significant risk factors for heat illness were developed and implemented in a workforce of approximately 2000 workers exposed to heat stress. The previous protocols used a shortened shift as the primary intervention to protect worker health. The subsequent protocols removed the shortened shift and replaced this with a range of other interventions. Deep body core temperature, heart rate, fluid consumption, hydration state and fatigue were measured before and after the changes in protocols.

Results:

Comparisons of heat stress indices confirmed the wide divergence in guidance provided by many of the commonly-used indices in terms of acceptable working environments. It also highlighted a number of serious shortcomings in the most widely-used indices, especially WBGT and ISO7933.

A new, rational heat stress index called Thermal Work Limit (TWL) was developed. This included development of a computer model incorporating key thermal physiological parameters (deep body core temperature, mean skin temperature, sweat rate, skin wettedness).

There was no increase in heat stress (as indicated by average workplace environmental conditions), deep body core temperature, mean heart rate, or changes in hydration status after the changes in protocols.

Average environmental conditions were severe (WBGT 30.9⁰ C, sd 2.0⁰ C, range 25.7-35.2⁰ C). Environmental conditions in the study were much hotter than those considered acceptable under standards such as the ACGIH.

The results showed that miners regularly exceeded those limits allowable under most current indices in terms of maximum deep body core temperature (avg 38.3⁰ C, std dev 0.4⁰ C),

maximum temperature rise (1.4⁰ C, 0.4⁰ C) and maximum heat storage (431 kJ, 163 kJ), without reporting any symptoms of heat illness. A significant component of the observed elevated core temperatures was due to the normal circadian rhythm, which was measured at 0.9⁰ C (std dev 0.2⁰ C). Evidence was found that workers “self-pace” when under thermal stress.

Fluid intake averaged 0.8 l/h during exposure (sd 0.3 l/h, range 0.3-1.5 l/h). Average urinary specific gravity at start-, mid- and end of shift was 1.0251, 1.0248 and 1.0254 respectively; the differences between start and mid-shift, mid and end-shift, and start and end-shift were not significant. However, a majority of workers were coming to work in a moderately hypohydrated state (urinary specific gravity avg 1.024, std dev 0.0059).

Involuntary dehydration was not found to occur in the study group. This is in contrast to several other studies and some of the leading heat stress standards, which are based on the premise that workers are unable to maintain their hydration status when working in the heat, even when their fluid consumption is equal to their sweat rate.

Continuous heart rates measured over a shift (avg 103 bpm, 14% of shifts exceeding avg 110 bpm, 5% exceeding avg 120 bpm) were in excess of those allowable under most current indices. On average, workers experienced a peak 10-minute heart rate of 140 bpm and a peak 30-minute heart rate of 130 bpm during their shifts.

There was a significant increase in fatigue in the first half of the working shift (p=0.001), with workers on average showing a significant recovery in the second half of their shift (p=0.04).

Conclusions:

Current heat stress indices provide little common agreement as to acceptable levels of thermal strain or stress for workers, at equivalent levels of environmental stress. ISO7933 is seriously flawed and the ACGIH WBGT guidelines are too conservative for acclimatised workers and are unlikely to become widely adopted by industries with well-acclimatised workers.

Many of the existing indices show internal inconsistencies.

Most of the physiological heat strain limits used in existing rational heat stress indices (in terms of deep body core temperature and heart rate) are conservative for self-paced, acclimatised, non-dehydrating male workers.

Involuntary dehydration is not unavoidable when acclimatised workers are exposed to thermal stress. Heat stress standards should not limit heat exposure durations for self-paced workers who have access to water on the basis of an unavoidable body water loss.

Physical fatigue does occur in workers under heat stress on extended shifts; however, most workers show a significant increase in fatigue in the first half of their shift; whereas data indicates self-paced workers undergo significant recovery in terms of fatigue in the second half of the shift.

As the heat exposures in this study cover a wide range of temperatures, humidity levels, wind speeds, body morphology and $\dot{V}O_{2\max}$, these conclusions are applicable to most thermally stressful settings involving well-informed, well-acclimatised and self-paced male workers. The major category of work type not covered by this study is that of workers in fully-encapsulated (vapour-barrier) protective clothing. In addition, this study examined acute effects of heat stress and strain, not effects that might only be manifest with chronic exposure to heat.