

Fatigue in industrial workers under thermal stress on extended shift lengths

D. J. Brake and G. P. Bates

School of Public Health, Curtin University, Perth, WA 6845, Australia

A field investigation to examine the fatigue levels in industrial workers working extended (10, 12 and 12.5 h) shifts under significant levels of thermal stress was conducted on 45 male underground miners. Studies were conducted both before and after a major change to the working-in-heat protocol used at the operation. Prior to the change, shortened (6 h) shifts had been used when thermal conditions exceeded certain values. This reduced shift length was removed and replaced with other protocols. Heart rates were continuously monitored, and a cycle ergometer was also used to assess cardiovascular fatigue over the shift. Average heart rates, as well as highest 10 and 30 min averages, and heart rate durations within various bands were analysed. No worker reported heat illness during the study. Results showed that removing the shortened shift did not increase the fatigue levels. Workers did experience fatigue, but this occurred in the first half of the shift. Evidence was found that these workers practised self-pacing.

Key words: Extended hours; fatigue; heart rate; industrial worker; shift work; thermal stress.

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Introduction

Fatigue is a general term used to describe a wide variety of conditions [1]. Acute fatigue can be divided into mental fatigue, due to mental overload or underload (associated with monotony and boredom), and physical fatigue. Physical fatigue has been noted in heat exhaustion and attributed to several possible physiological disturbances: hyperthermia [2], circulatory strain due to excessive call on cardiac output to deal with hyperthermia and/or reduced circulating volume due to dehydration [3], sweat gland fatigue [4], depleted muscular glycogen concentration [5] and muscle soreness due to overuse [6].

Work rate is directly proportional to $\dot{V}O_2$. In terms of physical fatigue, several authors have found that endurance is not limited if work rate does not exceed 33–50% of $\dot{V}O_{2max}$ [7–9]. This is the aerobic capacity (defined as the $\dot{V}O_2$ at which no significant oxygen debt accumulates [10]) or the anaerobic threshold [11]. Most humans' aerobic capacity is about that of a brisk walk ($\dot{V}O_2$ of

1 l/min, or 5 kcal/min). However, $\dot{V}O_{2max}$ is not generally limited by respiratory or cardiovascular function, but by the exercise capacity of the musculature [6]. Its value will therefore vary depending on which muscle group is being used in its assessment, and whether the exercise is dynamic or static [12].

Whilst $\dot{V}O_2$ is difficult to measure directly in an occupational setting, % $\dot{V}O_{2max}$ is known to be approximately equivalent to % cardiac reserve [11]. As % cardiac reserve is a function of working and resting heart rates only, and resting heart rates do not change for a particular individual, changes in working heart rates serve as a good approximation for changes in work rates and changes in $\dot{V}O_2$. Whilst heart rate is known to be affected by both physical and psychological factors, it is a good index of strain if an appreciable stress is already imposed as a baseline [13].

In this regard, Minard [14] found that impaired performance for an industrial worker did not occur until the mean heart rate over a full shift was 120 beats/min or higher, with the World Health Organization (WHO) recommending a lower figure of 110 beats/min whilst allowing brief excursions above 120 beats/min for acclimatized, fit persons [15]. ISO9886 recommends an

Correspondence to: Derrick J. Brake, 12 Flinders Parade, Sandgate, QLD 4017, Australia. Tel: +61 7 3269 3733; fax: +61 7 3269 3538; e-mail: rick.brake@mvaust.com.au

increase in heart rate due to thermal strain to not exceed 30 beats/min with an absolute limit from all causes to not exceed the individual's maximum heart rate less 20 beats/min [16].

Except for new workers or new activities, muscle soreness is unlikely to be a cause of physical fatigue unless it involves excessively repetitive or forceful activities, as work hardening (muscle hypertrophy) results in rapid adaptation to job requirements [12].

Heavy exercise is known to result in a decline in pH due to an accumulation of lactate in the muscle cells, which can result in fatigue [17]. Blood lactate has also been found to be an indicator of decreased muscle blood flow [18]. A level of ~ 4 mmol/l in arterial blood is considered to indicate the anaerobic threshold [19].

Heat exhaustion is a form of thermal fatigue. It is generally defined as a circulatory deficiency due to water or salt depletion. It is characterized by thirst, weakness, fatigue, dizziness, anxiety, oliguria, tachycardia and moderate hyperthermia [20], weakness, inability to continue work and frontal headaches [21]. It has recently been described in an occupational setting [22].

Adolf [23] also described a condition he called dehydration exhaustion. This was not associated with hyperthermia, and related to non-working (resting) subjects exposed to hot environments who gradually dehydrated to the point of total exhaustion, i.e. a survival situation. Its onset was at 12% or more hypohydration. This is not a level of dehydration likely to be encountered in an occupational setting, except in extended emergency entrapment or rescue situations.

Dehydration and hyperthermia have both been found to result independently in decrements in mental performance [24], and especially attention overload [25]. Mental and physical decrements in performance have been associated with hypohydration of as little as 2% total body water [26], with pronounced effects at 4% [3,27]. Fatigue due to hyperthermia has been associated with a deep body temperature of as low as 38°C [20,28], with most persons suffering fatigue at deep body temperatures exceeding 38.5°C [29].

Hypohydration also results in muscle fatigue [30]. Both hyperthermia and dehydration are known to result in cardiovascular strain [29,31], and hence manifest as an increase in heart rate.

Background

This study reports a field investigation to examine the fatigue levels in industrial shift workers under considerable thermal stress, both before and after the introduction of a major change to the working-in-heat (WIH) protocols under which the workforce had been working for in excess of 30 years. All workers were employed on 10, 12 or 12.5 h shifts in a hot, deep, underground mine located well inside the tropics in northern Australia. The prior

WIH protocol was based on a variation [32] of the Predicted Four Hour Sweat Rate [33], and provided for a 6 h shift when thermal conditions exceeded a wet bulb globe temperature (WBGT) of $\sim 32.5^\circ\text{C}$, considered an extreme heat stress under American Conference of Governmental Industrial Hygienists (ACGIH) guidelines [34]. The 6 h shift itself had been in use for 56 years. A shortened shift length is a very common method of reducing the risk of heat illness in British and Continental mines, but is rarely practised in Australia or South Africa. The new protocol was based on a new heat stress index called the Thermal Work Limit (TWL) [35], and removed the 6 h working shift, irrespective of the thermal conditions in the workplace, and replaced it with a different method of managing environmental extremes [35–37], predicated on the workforce being able to self-pace, being well informed about the various issues of WIH, and with progressive management interventions (including withdrawal of workers) at increasing levels of heat stress, depending on the state of acclimatization and hydration; however, it did not provide for a reduced shift length.

All workers were drawn from a target group of those most exposed to severe thermal environmental conditions and gave their written informed consent to a series of studies that was authorized by management, their labour unions, and Curtin University's ethics committee on human experimentation.

In addition to the heat and humidity in the environment, these workers must cope with poor illumination, dust, noise and broken ground. Their uniforms consist of long cotton trousers and short- or long-sleeved shirts, safety boots, helmet and eye protection. The workforce is highly mobile, and some work was conducted from within air-conditioned cabins of mobile equipment. Therefore, not all work was in extreme conditions or physically strenuous. Lunch breaks were all taken in air-conditioned underground lunchrooms.

Work rates have been measured previously [32] and found to be generally low (e.g. driving machinery, <120 W/m²) to moderate (laying bricks, <200 W/m²), with short periods of heavy work (shovelling, <400 W/m²), and to vary between workers, between shifts and even over the course of each shift. This is also consistent with the observed heart rates. Workers are heat acclimatized and work hardened to the conditions in which they work. They are not generally subject to any regular form of health assessment, apart from a pre-employment medical screen.

No worker reported heat illness during this study, although heat illness is experienced in this workplace and has recently been described [22,37].

The urinary specific gravity (hydration state) of the workers was also measured before, during and at the end of each shift during the study. On average, there was no change in hydration state [38].

The objectives of this study were to determine: (i) whether the changes in protocols resulted in a change in heart rates during the working shift; (ii) whether the elicited heart rates exceeded advisory levels; and (iii) if fatigue was occurring, whether it was related to shift length.

Method

The investigation was conducted over two consecutive summers, before and after changes to the WIH protocols.

In aggregate, the fatigue results consist of the following:

- Pre- and post-intervention heart rates recorded continuously using PolarTM ECG-type sports heart rate recorders (hereafter called the 'continuous heart rate' studies).
- Pre- and post-intervention steady-state heart rates collected on a cycle ergometer pedalling at 50 r.p.m. at 100 W under a standardized test at the start and end of each shift (and at the middle of each shift for one series of tests) (hereafter called the 'cycle fatigue results'). All ergometer tests were performed underground at a hot location near the lunchroom. Heart rates typically plateaued after 3–6 min. This test was effectively a measure of $\dot{V}O_2$ using the Åstrand Rodahl protocol.
- Blood lactate measured at the earlobe immediately at the conclusion of the shift, collected in the post-intervention continuous heart rate study only.
- Pre- and post-intervention environmental conditions measured approximately every 60–90 min, including psychrometric wet and dry bulb temperatures, globe temperature, WBGT, wind speed and barometric pressure.
- Anthropometric data, body morphology and $\dot{V}O_{2max}$ data on subjects.

A negative (non-fatigued) control group of 15 workers (all males) working in the same operation in sedentary work in thermoneutral conditions was also tested over several shifts using the cycle ergometer protocol. This produced 32 paired sets of results (before and after shift), with nine workers (26 paired sets) being underground workers and the other six workers (six paired sets) being office workers.

Data were collected on both day and night shifts.

Heart rate data were analysed in the following manner: for each individual shift, and for the aggregated data, the following statistics were calculated: average heart rate, highest 10 consecutive minute average heart rate, highest 30 consecutive minute average heart rate and time spent in the following heart rate zones: <60 beats/min, 60–80 beats/min, 80–100 beats/min, 100–120 beats/min, 120–140 beats/min and >140 beats/min.

The difference in continuous heart rates before and after the change in protocols was tested using the

unpaired, two-tailed Student's *t*-test assuming equal variances. The cycle ergometer results were tested using the paired, one-tailed Student's *t*-test, with the null hypothesis being that heart rates did not increase during the work shift. Results are reported as (mean, SD, range) or (SD, range).

Results

Environmental

A total of 350 environmental observations were taken over both summers (excluding observations inside air-conditioned areas). The WBGT in the first summer averaged 30.8°C (1.7, 26.8–36.9), compared with 30.9°C in the second summer (2.1, 25.7–35.2), which was not significant ($P = 0.44$). Comparisons using the TWL index also showed no significant change between the summers.

Continuous heart rates

Over the two summers, continuous heart rates were measured on 45 workers (all males) over 71 shifts (Table 1). The body mass index (BMI) of the target group averaged 27.9 (4.0, 22.1–38.1), which is in the middle of the 'overweight' range of 25–30 kg/m² as designated by the WHO [39]. The $\dot{V}O_{2max}$ of the target group averaged 39.1 ml/kg/min (7.7, 28.0–56.3), and is at the lower limit of the normal range (39–48 ml/kg/min) for non-athletes aged 30–39 years [40]. The target group was typical of industrial workers at this operation. A test of 469 contract employees joining the organization for project work under similar levels of heat stress during this period had a measured $\dot{V}O_{2max}$ of 39.0 ml/kg/min (SD = 7.8 ml/kg/min) and a BMI of 25.9 (SD = 5.4).

The full-shift average heart rate for the 51 sets of continuous heart rate data from the first summer of 103.6 beats/min (13.9, 76–135) was not significantly differently ($P = 0.53$) to the average of 101.2 beats/min (9.4, 76–123) from the 20 sets of data from the second summer. Likewise, there was no significant change in the mean values of the highest 10 consecutive minute ($P = 0.53$) and highest 30 consecutive minute ($P = 0.98$) averages during the shifts, from pre- to post-change. On this basis, the data were pooled to form 71 sets of results, also shown in Table 1.

Cycle fatigue

Control group

A paired *t*-test was applied to the 32 sets of data in the cycle ergometer control group. The average increase in heart rate on the ergometer was 1.1 beats/min (SD = 6.3 beats/min, range = –16 to 16). The end of

Table 1. Continuous heart rate data

Period of study	Shift average heart rate (beats/min)	Highest 10 min heart rate (beats/min)	Highest 30 min heart rate (beats/min)	Heart rate <60 beats/min (% of time)	Heart rate 60–80 beats/min (% of time)	Heart rate 80–100 beats/min (% of time)	Heart rate 100–120 beats/min (% of time)	Heart rate 120–140 beats/min (% of time)	Heart rate >140 beats/min (% of time)
Data from first summer, before changes to protocols									
Mean	103.6	143.1	129.7	0	15	35	29	14	8
SD	13.9	20.9	22.5	0	20	17	13	10	10
Range	76–135	103–202	81–193	0–1	0–77	2–69	4–60	0–39	0–38
Data from second summer, after changes to protocols									
Mean	101.2	139.4	129.0	0	14	46	30	10	7
SD	9.4	15.7	15.9	N/a	14	15	7	10	14
Range	76–123	103–170	81–161	0–0	0–48	2–73	4–68	0–28	0–39
Combined data from both summers									
Mean	102.9	142.1	129.5	0	14	38	29	13	7
SD	12.8	19.6	20.7	0	18	17	13	9	10
Range	76–135	103–202	81–193	0–1	0–77	2–73	4–68	0–39	0–39
<i>P</i> , 1st to 2nd summer	0.53	0.53	0.98						

shift heart rate does not show any significant increase compared with the start of shift ($P = 0.16$).

Target group

The cycle ergometer target group comprised 39 of the workers from the continuous heart rate study. A total of 46 sets of data (before and after shift) were collected. Of these 46 sets, 24 also included cycle fatigue results collected at approximately mid-shift, immediately prior to taking the main meal break.

The average increase in heart rate on the cycle ergometer from the start to the end of the shift for the 46 sets of data in the target group (Table 2) was 4.6 beats/min (8.9, –11 to 28). This is highly significant ($P = 0.0007$).

For the subjects ($n = 24$) tested at the start, the middle and the end of the shift, the increase in ergometer heart rates from the start to the end of the shift was 4.2 beats/min (8.9, –11 to 28), which was significant ($P = 0.02$). The increase from the shift start to the main meal break of 8.0 beats/min (11.6, –10 to 35) was highly significant ($P = 0.001$). There was actually a significant decrease ($P = 0.04$) of 3.8 beats/min (9.9, –24 to 15) in ergometer heart rate between the middle and the end of the shift in both day and night shifts.

Continuous heart rates versus cycle fatigue

Comparisons were made between continuous heart rate results and the cycle ergometer results. No significant linear regressions could be found in terms of the average, highest 10 min or highest 30 min values compared with

the cycle ergometer increase over the shift, or compared with the shift-ending ergometer value, or between the ratio of the end to the start of the shift cycle ergometer values and the average heart rate during the shift. Resting heart rates were not taken, so comparisons involving cardiac reserve could not be prepared.

Lactate

Lactate levels were measured within 30 min of the conclusion of physical work in the second summer. Of the 18 workers measured, only two exceeded 2 mmol/l, six were recorded as being 'low' (below reading level) and the average of all the data (including the two above 2 mmol/l) was only 1.44 mmol/l.

Discussion

Environmental

The average environment did not change between summers, and over both summers averaged 30.9° WBGT (2.0, 25.7–36.9). Environmental conditions exceeded a WBGT of 30°C (the ACGIH [34] recommended maximum level for a continuous moderate work rate by acclimatized workers) for 66% of the exposure time. Under the ACGIH guidelines, these conditions are clearly stressful.

Continuous heart rate

The mean \pm SD of the pooled heart rate data was 103 \pm 13 beats/min. Approximately 14% of the work-

Table 2. Steady-state heart rate data from cycle ergometer tests over the working shift, as an indicator of fatigue

	Ergometer data from all subjects			Ergometer data from individuals who completed each of the start, middle and end of shift tests		
	Start	Middle	End	Start	Middle	End
<i>n</i>	47	24	46	24	24	24
Mean heart rate (beats/min)	126.6	136.3	131.2	128.3	136.3	132.5
SD (beats/min)	13.05	15.13	11.98	14.78	15.13	13.61
Range (beats/min)	98–152	105–165	107–158	105.0–152.0	105.0–165.0	110.0–158.0

Some subjects only completed cycle ergometer tests at the start and end of the shift; other subjects also completed a test at mid-shift immediately prior to their lunch break.

ing shifts resulted in a mean full-shift heart rate >110 beats/min. Less than 5% averaged >120 beats/min. A shift average for industrial workers of 120 beats/min was also found to be a suitable maximum by Minard [14] and the WHO [39], and is probably a realistic upper limit for an average heart rate over a full shift.

On average, workers experienced a peak 10 min heart rate of ~140 beats/min and a peak 30 min heart rate of ~130 beats/min during their shifts. Heart rates in excess of 140 beats/min exceeded ~7% of the shift duration. These values confirm that excursions above the recommended levels for significant periods are frequent.

Cycle fatigue

Control group

The fact that there was no significant increase in heart rate on the cycle ergometer from the start to the end of the shift for workers in sedentary work in thermoneutral conditions (defined as 'non-fatigued' workers in this study) provides a baseline for evaluating the target group.

Target group

The average increase in heart rate on the set-work cycle ergometer from the start to the end of the shift for the target group (Table 2) was 4.6 beats/min, which was highly significant ($P = 0.0007$). For precisely the same mechanical work output on the ergometer at the end of the shift, this group was clearly more fatigued compared with the non-fatigued control group. The cause of this fatigue has not been demonstrated and, in particular, has not been partitioned between skeletal and cardiac muscle fatigue or central fatigue.

The highly significant increase ($P = 0.001$) in heart rate (8.0 beats/min) from the start to mid-shift suggests that the major component of fatigue in these workers was occurring in the first half of the shift, i.e. when the workers were 'fresh'. Fatigue appeared actually to decrease from the middle to the end of the shift. However,

a 'slow down' period of 2–3 h was frequently observed in workers prior to the end of these long 12 h shifts, and this may be reflected in these second-half results. This is consistent with anecdotal evidence that there may be reduced productivity [41] from self-paced, manual workers in the last few hours of an extended (12 h) shift, although there appear to be other significant factors as well [42].

The fact that no correlations could be found between the continuous heart rate and cycle ergometer data could not be explained. However, given the wide range of age and $\dot{V}O_{2\max}$ in the subjects, comparisons on the basis of cardiac reserve, age or some other basis might have produced a correlation.

Nevertheless, the cycle ergometer test, which does not require any data-logging device in the field, may be a useful test of the fatigue levels of groups of industrial workers, given that it produced a negative result in the non-fatigued control group and a positive result in the target group.

Note that neither the continuous heart rate nor the cycle fatigue data have been correlated to BMI or $\dot{V}O_{2\max}$. However, it has been reported from a different study of the same operation over the same period that BMI was a significant risk factor in developing heat illness but $\dot{V}O_{2\max}$ was not significant [43].

Lactate

The low lactate levels recorded at shift end suggest that work is being conducted within the aerobic capacity of workers, and that this is not a cause of fatigue.

Conclusions and recommendations

Mine workers under thermal stress are undergoing fatigue during their shift, as evidenced by repeating a cycle ergometer test at a fixed work rate before, during and after their shift, but not necessarily to dangerous levels.

Most workers experienced mean heart rates during the shift that were lower than the 110 beats/min recommended by some authorities, with ~14% of workers having mean heart rates that were >110 beats/min; ~5% had mean heart rates >120 beats/min.

Given that the environmental conditions were on average very thermally stressful (WBGT = 30.8°), it is highly likely that these workers were self-pacing. This finding of self-pacing is also in accordance with other findings in occupational settings in the Western world [11,26,43–46]. However, Soule *et al.* [47] found that self-pacing produced excessive deep body core temperatures when environmental conditions exceed 33.5° wet bulb. Therefore, it is possible that self-pacing exists only within reasonable environmental conditions. This is also in accordance with Brake *et al.* [36], who proposed that when work rates become excessively slow under a 'self-pacing' protocol, the increasing frustration levels and desire to complete the activity and escape the stress can result in a self-imposed excessive work rate, which can lead to hyperthermia. Therefore, upper limits of thermal stress remain essential in a WIH protocol, even with self-paced and well-educated workers. The inability to self-pace is probably a significant reason why heat stress and stroke are more common in military settings.

There was no significant increase in average heart rate as a result of removing the 'shortened shift' from the WIH protocol. This further indicates that workers are 'self-pacing' and that the fatigue levels found are not related, in this operation, to extending the duration of the heat exposure beyond 6 h. This is also in accordance with the much earlier observation of Leithead and Lind [13], who stated:

It does not seem logical to suggest that if conditions are extreme for an exposure of 8 hours, then the duration of exposure should be reduced to 6 hours; it is probable that any acute heat disorder that may develop as a result of an 8-hour exposure will also occur during a 6-hour exposure. Therefore it is preferable to retain the 8-hour duration of exposure and to reduce the average rate of work by an appropriate amount.

In a self-paced context, this 'reduction in the average rate of work' is self-imposed, rather than externally imposed.

Blood lactate levels were very low at the end of the shift, indicating no significant oxygen debt at shift end and only a minor anaerobic contribution to metabolic rate.

It is important to recognize that this study was conducted on non-dehydrating, acclimatized workers who are reasonably well educated about the impacts of working in heat and have a measure of control over their pace of work during the course of their shift. Moreover, the principal source of heat stress for these workers is generally the environmental heat load, rather than an internally produced heat load due to sustained strenuous metabolic rates.

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