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Physiological Responses to Fire-fighting:thermal and Metabolic Considerations

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Abstract

It is well documented that fire-fighting involves strenuous activity in harsh environmental conditions. The combination of increased metabolic heat production and high ambient temperature will result in an elevated deep body temperature and heart rate. These responses will be exacerbated if the fire-fighter is dehydrated. The protective clothing worn by the fire-fighter reduces the heat gain from the environment, but can also add thermal strain by increasing work load and impeding metabolic heat loss. An inexperienced fire-fighter may be less economic and under greater psychological stress; this will affect both the work rate and performance. The extent to which all of these factors affect performance will also depend on the fitness level of the fire-fighter and how close they are to their maximum physical capacity. Therefore, there are many inter-related factors that influence a fire-fighter's response and ultimately his or her ability to perform the task. This review examines the physiological responses to fire-fighting and discusses the factors that may impact on fire-fighter performance.

Key words: fire-fighter, protective clothing, hyperthermia, energy expenditure, fitness

Introduction

It is well established that fire fighting involves physically demanding tasks (Gledhill and Jamnik, 1992; Holmer and Gavhed, 2007; Lemon and Hermiston, 1977; Smith et al., 2001a and 2001b; Sothmann et al., 1992). The successful performance of these tasks depends on a variety of inter-related factors as shown in Fig. 1. The metabolic heat produced during fire-fighting tasks and the high ambient temperatures will result in an increase in deep body temperature. If deep body temperature increases too much, a decrement in physical (Nielsen et al., 1981) and mental performance (Hancock, 1982) will occur. Whilst fire-fighter protective clothing reduces the risk of burns, it also adds a thermal burden by increasing metabolic cost of the task and by impeding heat dissipation, especially evaporation of sweat (Goldman, 1990). Excessive sweating without adequate fluid intake will result in dehydration, which impairs thermoregulation (Gonzales-Alonzo et al., 1997) and performance (Cheuvront and Haymes, 2001; Nielsen et al., 1981). The physical fitness of the fire-fighter will affect both their ability to thermoregulate and perform the tasks required. A less fit fire-fighter will either have to perform the task at a slower pace, or work at a higher percentage of their maximum capacity resulting in earlier fatigue (Sothmann et al., 1990). The psychological stress experienced by the fire-fighter and their level of experience will also affect their ability to perform the fire-fighting task. This review will focus on the physiological responses to fire-fighting and discuss the major factors affecting the performance of fire-fighting tasks.

Environmental conditions

The duration of heat exposure is often determined by the self contained breathing apparatus and is usually limited to approximately 20 min, however fire-fighter instructors are exposed to the heat for an average of 40 min during live fire training exercises (Eglin and Tipton, 2005) and fire-fighters suppressing wildfires undertake 12 to 18 hour shifts (Ruby et al., 2002). The ambient temperature to which a fire-fighter is exposed also varies considerably. During wildfire suppression exercises, air temperature averaged 29°C with a mean radiant temperature of 66°C

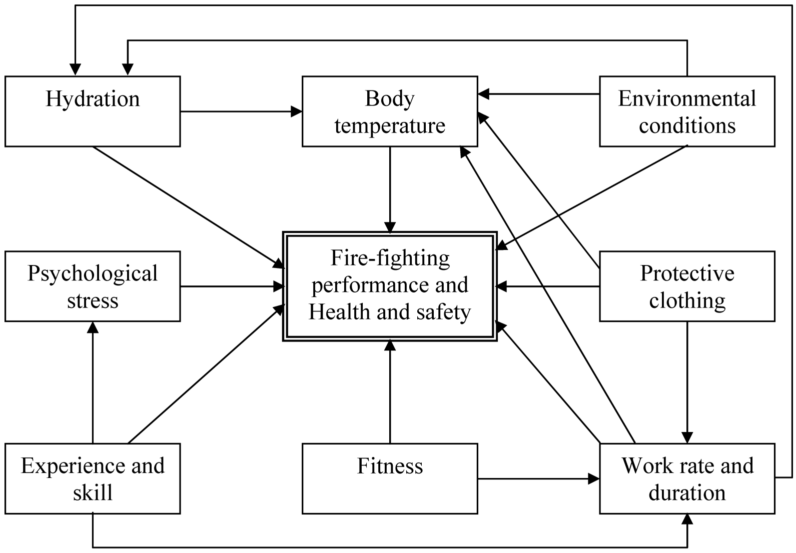

Fig. 1. Schematic diagram of the main factors affecting fire-fighting performance.

(Budd, 2001). In more enclosed live fire suppression exercises conducted in fire houses, average temperatures range between 67°C and 190°C (Eglin et al., 2004; Smith and Petruzzello, 1998; Smith et al., 1996; Smith et al., 1997; Stirling and Parsons, 1999) with a radiant heat load of 5 to $10\,kW \cdot m^{-2}$ (Rossi, 2003). In compartment fires where flashover simulations are conducted, average temperatures of 139°C have been recorded (Eglin et al., 2004). Although these temperatures have been recorded in the fire houses, it is unclear what temperature the fire-fighter is actually exposed to, as it is impossible to record the temperature throughout the fire buildings. A comparison of the temperature measured within the fire house (at positions where it was anticipated the instructors would place themselves) with that recorded on the outside of fire-fighter instructors' tunic revealed the tunic temperature was lower than the average ambient temperature (Eglin et al., 2004). Thus behaviourally the fire-fighters reduce their heat load by staying low and sheltering from the radiant heat.

Microclimate and skin temperature

The fire protective clothing is designed to reduce the environmental heat load experienced by a fire-fighter. Measurements of the microclimate temperature between the fire jacket and underclothing during live fire training exercises showed the average temperature was 48°C with a maximum of 62°C (resulting in slight burns, Rossi, 2003). A mean abdominal microclimate temperature of 32°C was recorded between the skin and underclothing in instructors during live fire training exercises (Eglin et al., 2004). Interestingly, in the latter study the mean chest skin temperature during the heat exposure was 38°C indicating that, due to the insulative properties of the protective clothing, the skin temperature was determined by the deep body temperature (which on average was elevated to 38.5°C) rather than the environment. Similar findings have been reported by Heus et al. (2005) where the temperature of the underclothing exceeded that of the skin temperature in only 3 out of 17 live fire training exercises. Whilst the maximum chest skin temperature during fire-fighting tasks in the heat averages 38°C (Eglin et al., 2004; Ilmarinen et al., 1997; Romet and Frim, 1987), in areas where there is less protection, either due to fewer layers or compression of the clothing, higher skin temperatures, and in some cases burns, have been reported. The maximum microclimate temperature recorded under the fire-hood was 55°C (Eglin et al., 2004) and between 39°C and 45.5°C on the shoulder (Rossi, 2003). In severe environmental conditions a temperature gradient is observed across the clothing ensemble. The highest temperatures recorded during flash-over simulations were 91°C (inner tunic), 59°C (outer shirt), 54°C (inner shirt), and 42°C (chest) indicating that the under clothing also provides an important layer of insulation (Taylor, 2006).

The threshold skin temperature for a burn to occur is 44°C, however at this temperature, the exposure will need to be approximately 6 hours (Henriques and Moritz, 1947). Between 44°C and 51°C the rate at which burning occurs increases logarithmically with skin temperature, above 51°C the rate declines (Henriques and Moritz, 1947). A skin temperature of 55°C will result in injury after only 10 s exposure (Henriques and Moritz, 1947). The occurrence of burns may be predicted for exposures of less than 15 s using measurement of free air temperature, the critical value being 1315°C-s (Ripple et al., 1990). Whilst there are many skin properties that affect thermal energy uptake to the basal layer, the amount of surface water and moisture content of the skin is the most important (Ripple et al., 1990). Relative humidity under the protective clothing reaches between 80% and 100% during live fire training exercises (Heus et al., 2005; Rossi, 2003). With such high moisture contents there is also risk of burns through scalding (Rossi, 2003).

Deep body temperature

Several studies have measured deep body temperature (T_c) during simulated fire-fighting exercises (Table 1). As expected, quite a range in T_c has been observed because of the varying metabolic and external heat loads and differing methodologies employed. Rectal temperature is probably the most reliable continuous measure of deep body temperature as the communications used by fire-fighters would probably preclude the use of aural thermistors. Gastrointestinal temperature pills have also been employed and showed a similar temperature profile to rectal temperature when measured simultaneously (Eglin et al. 2004). Several groups have measured T_c using an infrared tympanic thermometer (Table 1) before and after fire-fighting exercises. Although this measure is relatively non-invasive and has proven reliable in the clinical setting (Shinozaki et al., 1988), in a field situation it can result in erroneous readings, with a tendency to record lower readings than rectal temperature (Hansen et al., 1996; Sato et al., 1996). Dickinson et al. (2003) suggest that after live fire training exercises, oral temperature may be more reliable than infra-red tympanic temperature as an estimate of deep body temperature. This may explain the low peak tympanic temperature of only 36.9°C, as measured by an infra-red sensor, reported by Smith et al. (2001a), despite HR being at age-predicted maximum at the end of the fire fighting drills (Table 1).

T_c continues to increase following fire-fighting exercises (Smith et al., 2001b; Eglin et al., 2004) and therefore a fire-fighter should be actively cooled before another heat exposure or performance of strenuous physical activity. In a cool environment the simplest method of reducing T_c after heat exposure would be to remove as much protective clothing as possible (helmet, fire hood, gloves and fire tunic) to enable evaporative and convective cooling. The cooling rate will be increased if the conditions are windy or the individual is placed in front of a fan to promote forced convection (Carter et al., 1999). However, for health and safety reasons removal of protective clothing may not be possible, in these cases placing the hands in a cool water has been shown to be effective in reducing the deep body temperature of hyperthermic individuals (House, 1998; Livingstone et al., 1989). The colder the water temperature the hands are immersed in, the greater the rate of cooling observed (House et al., 2005; Livingstone et al., 1989) as elevation of deep body temperature overrides the normal vasoconstriction observed in normothermic

Table 1. Summary of studies reporting deep body temperature (T_c) during simulated fire-fighting tasks. The nature of the task, subject population (M=male, ff=fire-fighter, tff=trainee fire-fighter, ffi=fire-fighter instructor), duration of the task, ambient temperature, method of T_c measurement (Tre=rectal temperature, IR Tymp=infrared tympanic membrane temperature, GI pill=gastrointestinal pill temperature), T_c reported at start and end or maximum and change in Tc are given. *Ambient temperature not stated, temperature is estimated from Smith et al. (2001a) and Smith and Petruzzello (1998) where identical tasks were performed.

Task	Subjects	Duration	Ambient temperature	Measurement	Start T_c	Max/end T_c	Change in T_c	Reference
Fire-fighting drills (dummy drag, extinguisher carry, hose hoist, wood chopping)	10 M ff	3×6 min	54–79°C	IR Tymp	35.8°C	37.3°C	1.5°C	Smith and Petruzzello (1998)
	7 M tff	3×7 min	47–61°C	IR Tymp	36.1°C	36.9°C	0.8°C	Smith et al. (2001a)
	11 M ff	3×5.5−6.3 min	47–79°C*	Tre	36.7°C	38.6°C	1.9°C	Smith et al. (2001b)
Fire-fighting training exercise	19 M tff	20 min	106°C	IR Tymp	36.4°C	37.6°C	1.2°C	Stirling and Parsons (1999)
Fire fighting training exercise	17 M ff	60 min	100–190°C	GI pill			0.6 to 1.0°C	Rossi (2003)
Fire-fighting activities	12 ff	15 min	11–25°C	Tre	37.5°C	38.4°C	0.9°C	Griefahn et al. (2003)
Leading hand	5 M ff	24 min	16°C	Tre	37.7°C	39°C	1.3°C	Romet and Frim (1987)
Secondary help	7 M ff	20 min	16°C	Tre	37.7°C	38.4°C	0.7°C	
Ceiling haul	16 M ff	16 min	90°C	IR Tymp	36.7°C	39.8°C	3.1°C	Smith et al. (1997)
Fire hose advance & chopping wood	15 M ff	16 min	77–93°C	IR Tymp	36.9°C	40.1°C	3.2°C	Smith et al. (1996)
Wildland fire	179 M ff	36–217 min	19–35°C	Tre		38.7°C		Budd (2001)
Instructor in live fire training exercise	30 M ffi	33 min	66°C	Tre &/or GI pill	37.5°C	38.5°C	1.0°C	Eglin et al. (2004)
	10 M ffi	12–92 min	48°C	Tre	37.6°C	38.0°C	0.4°C	Eglin and Tipton (2005)
	7 M ffi	23–63 min	39°C	Tre	37.6°C	38.1°C	0.5°C	

individuals.

Fluid balance

Sweat losses during simulated fire-fighting tasks range between $0.5\,L \cdot hr^{-1}$ and $2\,L \cdot hr^{-1}$ (Eglin and Tipton, 2005; Eglin et al., 2004; Griefahn et al. 2003; Ilmarinen et al., 1997; Richardson and Capra 2001; Stirling and Parsons, 1999). When fluid intake was taken into consideration, these sweat losses resulted in a fluid deficit of less than 1% body mass (Eglin and Tipton, 2005; Stirling and Parsons, 1999). From the literature pertaining to sports performance, such a low level of dehydration is unlikely to affect either thermoregulation or performance (Cheuvront and Haymes, 2001; Yoshida et al., 2002). However, we measured a sweat loss of 3.23 L over 112 min, during which the fire-fighter instructor was exposed to the heat for 43 min. This caused a 3.1% loss in body mass and coincided with the instructor feeling dizzy and nauseous at the end of the training exercise (Eglin et al., 2004). Dehydration will compound the effect of hyperthermia on the cardiovascular system, resulting in a greater reduction in stroke volume and therefore cardiac output (Gonzalez-Alonso et al., 1997). Plasma volume has been shown to decrease by 15% after only three 7 min bouts of fire-fighting tasks, but was returned to normal after 90 min rest with aggressive rehydration (Smith et al., 2001b).

To prevent decrements in both physical and mental performance the fire-fighter should be hydrated prior to heat exposure and then rehydrate properly afterwards. Whilst it would also be ideal if the fire-fighters were able to rehydrate during their exposure, this may not be practical and during uncompensatable heat stress, fluid replacement may not actually decrease the rate of rise in body temperature or improve tolerance time, although it may reduce heart rate (McLellan and Cheung, 2000). Much research has been conducted into the formulation of rehydration drinks and their subsequent effects on exercise performance (for review see Coyle, 2004). For the fire-fighter, where the exposures are generally short (less than one hour) the main concern is the ingestion of water to prevent dehydration, rather than carbohydrate to fuel exercise metabolism. Addition of carbohydrate will increase palatability and may also enhance water absorption; and inclusion of electrolytes, particularly sodium, will maintain thirst, aid fluid retention and increase water absorption from the intestine (Coyle, 2004). However, if food is also consumed, the effect of the composition of the drink on its absorption and retention will be reduced (Maughan et al., 1996). Caffeinated drinks and alcohol should be avoided due to their diuretic and therefore dehydrating effect. However, the diuretic effect of caffeinated drinks may be over-estimated and in the short-term, drinking large quantities of tea or coffee will rehydrate the individual (Stirling and Parsons, 1999).

Repeated exposure to the heat will result in physiological adaptations occurring which in general improve an individual's ability to work in the heat. The most prominent physiological changes with heat acclimation include an increased sweat rate, expanded plasma volume, and lowered heart rate and T_c (Nielsen, 1998). However, when wearing protective clothing, heat acclimation did not improve tolerance to exercising in the heat as the increased sweating response resulted in greater dehydration (Windle, 1996). Therefore a heat acclimated fire-fighter may not have improved heat tolerance and may be at greater risk of becoming dehydrated, although they are likely to have an improved cardiovascular stability.

In addition to the effect on performance and thermoregulation, sweating, in particular non-evaporated sweat, will also have an impact on comfort. Skin wettedness, estimated by the evaporation required to maintain thermal balance (Ereq) divided by the evaporative potential of the environment (Emax), is an important factor in determining both comfort and performance. An Ereq/Emax of 20% is associated with the start of heat discomfort, above 40% and 60% performance of mental and physical tasks are reduced respectively. At an Ereq/Emax 80% the risk of becoming heat exhausted is increased considerably (Goldman, 1990).

Energy expenditure

Fire-fighting involves strenuous physical activity (Table 2). The energy expenditure required depends on the nature of the task and its duration (Gledhill and Jamnik, 1992) and the role of the individual (Romet and Frim, 1987). The highest oxygen consumption (VO_2) recorded during fire-fighting tasks is approximately $3.5\,L \cdot min^{-1}$ (Table 2). Near maximum heart rates have been reported during several simulated fire-fighting tasks and appear to be similar to that reported during actual incidents (Table 2). Blood lactate concentrations have been found to be elevated to between $2.2\,mmol \cdot L^{-1}$ and $10\,mmol \cdot L^{-1}$ following fire-fighting drills indicating the strenuous nature of the tasks and the involvement of anaerobic metabolism (Eglin and Tipton, 2005; Gledhill and Jamnik, 1992; Smith et al., 1996; Smith et al., 1997).

Estimating VO_2 from measurement of heart rate during simulated fire-fighting tasks results in an over-estimation by approximately 20% of VO_2 predicted from treadmill testing (Sothmann et al., 1991). This is a result of the impact of hyperthermia, dehydra-

Table 2. Summary of studies reporting heart rate and/or energy expenditure during actual or simulated fire-fighting tasks. The nature of the task, subject population (M=male, F=female, ff=fire-fighter, tff=trainee fire-fighter, ffi=fire-fighter instructor), duration of the task, ambient temperature, energy expenditure or oxygen consumption (VO_2) and heart rate or percentage of heart rate reserve (HRR) are given.*Ambient temperature not stated, temperature is estimated from Smith et al. (2001a) and Smith and Petruzzello (1998) where identical tasks were performed.†Rescue performed after exposure to heat. Unless otherwise stated mean values are given for HR and VO_2.

Task	Subjects	Duration	Amluient tempereture	Energy expenditure or VO_2	HR (bpm)	Reference
Actual structural fires	10 M ff	15 min		$25.6\,mL \cdot kg^{-1} \cdot min^{-1}$ estimated	157	Sothmann et al. (1992)
Actual fire	5 M ff	65–95 min			140 to 188	Barnard and Duncan (1975)
Actual turn out	429 M & F ff	88 min			30.6% HHR	Bos et al. (2004)
Actual SCBA tasks	15 (×5) ff	12 min			58% HHR	
Actual wildfire suppression	8 M ff 9 F ff	12–18 hr		M 20.4 MJ/day F 14.8 MJ/day		Ruby et al. (2002)
Fire-fighting drills	10 M ff	3×6 min	54–79°C		184	Smith and Petruzzello (1998)
	7 M tff	3×7 min	47–61°C		189	Smith et al. (2001a)
	11 M ff	3×5.5−6.3 min	47–79°C*		187	Smith et al. (2001b)
Fire-fighting activities	15 M ff	22 min		$2.75\,L \cdot min^{-1}$	168	Holmer and Gavhed (2007)
Stair climbing	15 M ff	3 min		$3.55\,L \cdot min^{-1}$	179	
Fire-fighting activities	12 ff	15 min	11–25°C		160	Griefahn et al. (2003)
Ladder climb	24 M ff	100 s		$2.44\,L \cdot min^{-1}$	189	Lemon and Hermiston (1977)
Victim rescue	24 M ff	30 s		$2.53\,L \cdot min^{-1}$	184	
Hose run	24 M ff	30 s		$2.55\,L \cdot min^{-1}$	187	
Ladder raise	24 M ff	30 s		$2.3\,L \cdot min^{-1}$	185	
Simulated smoke dive	35 M tff	17 min	119°C	$2.4\,L \cdot min^{-1}$ estimated	Mean 150 Peak 180	Lusa et al. (1993)
Simulated fire-fighting tasks	2–12 ff	21–239 s		16.8 to 44 $mL \cdot kg^{-1} \cdot min^{-1}$	119 to 174	Gledhill and Jamnik (1992)
Fire fighting exercise	5 M ff	191 s	36°C		180	Manning and Griggs (1983)
Simulated fire suppression	10 M ff	8.25 min	54°C	$31\,mL \cdot kg^{-1} \cdot min^{-1}$	176	Sothmann et al. (1991)
Ship fire-fighting tasks	34 M	5×4 min		$39\,mL \cdot kg^{-1} \cdot min^{-1}$	170	Bilzon et al. (2001)
Ship fire-fighting tasks	15 F	5×4 min		$35\,mL \cdot kg^{-1} \cdot min^{-1}$	170	
Instructor in training exercise	4 M ffi	65 min			159	Williams et al. (1996)
Fire attack	4 M ffi	5 min			Mean 161 Peak 192	
Instructor in training exercise	30 M ffi	33 min	66°C		138	Eglin et al. (2004)
Dummy rescue	4 M ffi	133 s		46.6 kcal	160	
Dummy rescue	10 M ffi	90 s	19°C	$2.25\,L \cdot min^{-1}$	162	Eglin and Tipton (2005)
	10 M ffi	79 s	19°C†	$2.50\,L \cdot min^{-1}$	180	
	7 M ffi	42 s	16°C†		182	
Ceiling haul	16 M ff	16 min	90°C		176	Smith et al. (1997)
	16 M ff	16 min	14°C		139	
Hose run & chopping wood	15 M ff	16 min	77–93°C		182	Smith et al. (1996)
Leading hand	5 M ff	24 min	16°C		153	Romet and Frim (1987)
Secondary help	7 M ff	20 min	16°C		130	
Wildland fire	179 M ff	36–217 min	19–35°C		152	Budd (2001)

tion, upper body work and psychological stress on heart rate. However, it is arguable that as a result, heart rate may give a better overall indication of the strain experienced by the fire-fighter than the measurement of VO_2.

Whilst fire-fighting can be a strenuous task, one should also consider the frequency with which these tasks are performed. A fire-fighting instructor at a training establishment may be exposed to a hot environment more than once a day, five times a week. Although they are not usually undertaking fire-fighting tasks *per se*, activities such as climbing stairs, replacing dummy casualties, and stoking fires can result in high heart rates (Eglin et al., 2004). Furthermore, an instructor may be under more psychological stress due to the additional responsibility of their role, and can result in them having a higher heart rate than the trainee (Williams et al., 1996).

A study on the demands of Dutch fire fighters revealed that an average of 1.5 incidents occur in a 24 hr shift (Bos et al., 2004). The average mean turn out time was 88 min during which the fire-fighters' heart rate averaged 31% of their heart rate reserve. The "inside" and "self-contained breathing apparatus" activities were found to be most energetic averaging 58% of heart rate reserve, and since these lasted on average 12 min, this should not give too much cause for concern. However, when one looks at the range of responses, it is apparent that some fire-fighters are under severe stress. In the study of Bos et al. (2004), the maximum heart rate recorded during self-contained breathing apparatus (SCBA) activities was 92% of heart rate reserve. Similarly in the study of Eglin et al. (2004), whilst the mean heart rate during the training exercises was only 109 bpm, heart rate exceeded 90% of heart rate reserve in five instructors. Therefore, some fire-fighters will experience considerable physiological strain either due to the activity undertaken, effects of the heat (hyperthermia and dehydration), lack of sufficient physical fitness, or more likely, a combination of these factors.

Performing work in the heat elevates heart rate compared to the same task conducted in a cooler environment. Heart rate after a 16 min ceiling haul was 37 bpm higher when the ambient temperature was increased from 14°C to 90°C (Smith et al., 1997). Similarly, performing a simulated rescue after being exposed to the heat resulted in much higher heart rates than when the fire-fighter was normothermic despite the oxygen consumption being similar (Eglin and Tipton, 2005). This elevation in heart rate is a result of an increase in demand for the cardiac output to both the active muscles and cutaneous circulation.

Protective Clothing

For a fire-fighter, radiation from fires is the most significant source of external heat. Radiation is the transfer of energy by electromagnetic waves with an average wave length of 10 μm. Heat gain by radiation will only occur if the environment is at a higher temperature than the surface of the clothing worn. The amount of heat transferred through the protective clothing will depend on the ability of that material to absorb or reflect thermal radiation. Radiation of heat from a fire will increase the temperature of the outermost layer of clothing; this heat will then be transferred to the skin via conduction and convection through the inner layers of clothing. The heat will then move down the thermal gradient between the skin and the deeper tissues resulting in an increase in deep body temperature. The protective clothing worn by the fire-fighter has therefore been designed to insulate the wearer from the radiant heat of a fire and has a Clo value of approximately 3 or 0.465°C $\cdot$ $m^2 \cdot W^{-1}$ (Goldman 1990; Taylor 2006). As a result the clothing is heavy and bulky weighing on average 10 kg, increasing up to a total of approximately 25 kg with self-contained breathing apparatus (SCBA). This increases the workload for any activity due to the extra weight and also due to the hobbling effect created by the restrictive nature of the clothing (Duggan, 1988; Teitlebaum and Goldman, 1972).

Several studies have examined the effect of wearing fire-fighter protective clothing on energy expenditure. Heart rate and VO_2 are increased by 17% and 11% respectively when running at 7 $km \cdot hr^{-1}$ with fire-fighter protective clothing compared to shorts and T shirt (Baker et al., 2000). Compared to a tracksuit, a "Gold Fire" suit increases the metabolic rate of walking by 21% and that of stepping by 15% (Dorman et al., 2005). Walking with a similar mass (7 kg) around the waist increases the metabolic rate by approximately 9% and by 16% when the weight is worn on the wrists and ankles (Dorman and Havenith, 2005). Therefore the elevated work load associated with walking in the "Gold Fire" suit can be attributed to the mass of the garment particularly on the extremities, and a hobbling effect of the thick clothing, as the bulkiness around the thigh correlated with the increased workload over a range of different garments (Dorman and Havenith, 2005). When SCBA is also worn, VO_2 is increased by approximately 50% during treadmill walking (Duncan et al., 1979; Skoldstrom, 1987). In addition, wearing fire protective clothing including SCBA reduces maximal power output, as assessed by the maximum speed attained on an incremental treadmill test, by 25% compared to standard clothing (Louhevaara et al., 1995).

When the effect of the mass of the personal protective equipment (PPE) is reduced by undertaking non-weight bearing exercise such as cycle ergometry, fire-fighting clothing is found to have little effect on either heart rate or VO_2 (Faff and Tutak, 1989). When the ambient temperature was increased from 20°C to 39°C and 70% relative humidity, heart rate was significantly elevated with the PPE and fatigue occurred much sooner. Similarly, during treadmill walking the effect of increasing the ambient temperature on heart rate and T_c is greater when wearing fire-fighter PPE than standard clothing (Duncan et al., 1979; Skoldstrom, 1987). The increase in heart rate is a result of the increased thermal stress of the environment. Blood flow to the skin is increased to facilitate heat loss and since in upright exercise stroke volume is maximal at about 50% VO_2max (Levick, 2000), the increase in cardiac output must be met by an increase in heart rate. T_c is elevated, as in ambient temperatures above approximately 35°C the only route of heat loss from the body is evaporation of sweat (Nielsen, 1938). Fire-fighter PPE creates a barrier to evaporation of sweat due to its limited permeability, this results in a humid microclimate and reduces the vapour pressure gradient between the skin and microclimate, which is required for evaporation to occur. In addition, if sweat is evaporated from the fire-fighter clothing rather than the skin surface, less body cooling occurs as the site of phase change is away from the skin and hence the heat comes from the environment rather than the body (Richardson and Capra, 2001).

Goldman (1990) suggested that it is only in mild environments, or at low work rates that differences in materials are likely to have any effect on a fire-fighter's physiological responses and that when the ambient temperature is elevated or work rate high the effect on tolerance time will be minimal. This is supported by White and Hodous (1988) who found no difference between "breathable" and "non-breathable" liners in fire-fighter PPE during moderate or high intensity exercise.

Smith and Petruzzello (1998) compared two configurations of fire-fighter PPE. During fire-fighting tasks in the heat, they found that the PPE that weighed 2 kg more and provided greater protection from burns, resulted in greater thermal strain, perception of effort and thermal sensation and slower task performance. Thus, with fire-fighter PPE there is a trade-off between the configuration of clothing that will provide the greatest protection against burns and that which will enable dissipation of body heat. For example, flame testing with manikins indicates that two layers of fire hoods should be worn to prevent burns to the head in flash-over scenarios (House et al., 2001). However, this may result in greater heat strain during fire-fighting tasks (Smith and Petruzzello 1998).

The SCBA worn as part of the fire-fighters PPE also has an effect on performance. Individuals who are not accustomed to wearing SCBA use more air and have a greater sensation of breathlessness (Donovan and McConnell, 1999). Therefore, recruits who are inexperienced at fire-fighting tasks and probably less efficient at performing them, may be further burdened by their SCBA compared to an experienced fire-fighter. Face masks have been found to increase the level of thermal strain experienced by individuals exercising in a hot environment wearing PPE (Martin and Callaway, 1974). During exercise, VO_2 is increased by 7% when wearing a face mask and by 20% when wearing SCBA (Louhevaara et al., 1984). The increase in VO_2 with the face mask was attributed to the increase in the work of breathing, due to increased resistance and equipment dead space. The increase in VO_2 with the SCBA is also attributable to the mass of the equipment (15 kg).

As the mass of the SCBA has such an impact on the physiological responses of the wearer, investigations have been conducted to evaluate the use of light weight SCBA. Heart rates during a fire-fighting exercise whilst wearing either no SCBA, a light weight SCBA (7 kg) or a heavy SCBA (15 kg) were found to be very similar averaging about 180 bpm, although the task took longer to complete with the heavier SCBA (Manning and Griggs, 1983). Load distribution may also be important as lower heart rates and faster times to complete fire-fighting tasks were observed with a SCBA that was designed to spread the load more evenly over the middle and lower regions of the back (Griefahn et al., 2003).

Fire-fighter fitness

As fire-fighting involves periods of intense physical activity (Table 2), the fire-fighter has to be physically fit enough to be able to perform these tasks. In most work places it is unacceptable for individuals to have to perform work averaging above 30 to 35% of maximum oxygen uptake (VO_2max) over a 8 hour shift or over 50% of VO_2max over a one hour period (Kemper et al., 1990; Saha et al., 1979; Wu and Wang, 2002). For high intensity work, the maximum acceptable work duration for young individuals working at 60% of VO_2max has been suggested as 18.8 min, and 6.5 min when working at 70%VO_2max. This is based on the mean or peak heart rates during the activity not exceeding 150 bpm or 180 bpm respectively (Wu and Wang, 2001). ISO-8996 (2004) classifies metabolic rate in occupational work into 5 classes, the highest being a metabolic rate above $260\,W \cdot m^{-2}$. This is considerably below the rate measured by Holmer and Gavhed (2007) during simulating fire-fighting tasks of $474\,W \cdot m^{-2}$ or $2.75\,L \cdot min^{-1}$ over 22 min. They therefore recommended that two new classes should be included in ISO-8996 to cover intensive work lasting between 15 to 20 min (metabolic rate $= 475\,W \cdot m^{-2}$ or $VO_2 = 2.45\,L \cdot min^{-1}$) and exhaustive work lasting less than 5 min (metabolic rate $= 600\,W \cdot m^{-2}$ or $VO_2 = 3.10\,L \cdot min^{-1}$).

Maximum acceptable work limits are not easily transferable to fire-fighting due to the nature of the work and associated urgency, and because fire-fighters tend to pace themselves such that they are working close to maximal levels (Manning and Griggs, 1983). In an attempt to objectively determine the fitness levels required for fire-fighting, task analyses have been conducted to establish the most strenuous core activities. The energy expenditure and strength required to perform these tasks were measured and the results used to set fitness level recommendations.

Sothmann et al. (1990) undertook a large study to establish the minimum standard for aerobic fitness for fire-fighters. In their study the average VO_2max of 136 fire-fighters between the ages of 20 and 65 years was $35\,mL \cdot kg^{-1} \cdot min^{-1}$. A representative group of these fire-fighters then undertook a fire suppression exercise considered to be typical in both duration and activities to those reported in actual emergencies. During the task, the fire-fighters worked on average at 76% of their VO_2max or $31\,mL \cdot kg^{-1} \cdot min^{-1}$ and their performance time correlated to their aerobic fitness (fire-fighters with a high VO_2max performed the task faster). A performance cut-off was set at a time within 2 standard deviations of the mean time taken by the group to complete the fire suppression task. The average VO_2 to complete the task in this time was $25.5\,mL \cdot kg^{-1} \cdot min^{-1}$ and if this represents 76% of VO_2max, then the minimum standard for aerobic fitness should be a VO_2max of $33.5\,mL \cdot kg^{-1} \cdot min^{-1}$. Those with a VO_2max below the minimum standard had a high probability of not being able to complete the task in time, however the minimum VO_2max of all fire-fighters who could perform the task was 41 $mL \cdot kg^{-1} \cdot min^{-1}$. This level is more in line with other studies conducted to determine the minimum aerobic fitness levels required to perform fire-fighting tasks (Bilzon et al., 2001; Gledhill and Jamnik, 1992).

Gledhill and Jamnik (1992) found the most demanding fire-fighting task required a mean VO_2 of $41.5\,mL \cdot kg^{-1} \cdot min^{-1}$ and therefore recommended that the minimum VO_2max for a fire-fighter applicant should be $45\,mL \cdot kg^{-1} \cdot min^{-1}$. Bilzon et al. (2001) determined the metabolic demands of shipboard fire-fighting tasks undertaken at a rate considered to be the minimal acceptable standard. The mean VO_2 during the most demanding task (drum carry) was similar for the men and women averaging $41\,mL \cdot kg^{-1} \cdot min^{-1}$ and therefore this was proposed as the minimum aerobic fitness level required. Although all of the men (n=34) managed the drum carry, 11 out of the 15 women were unable to complete the task at the prescribed rate. This was attributed to a lower VO_2max and isometric grip strength and greater fat mass in these women. In addition, in most of the tasks examined, the women were working at a higher percentage of their VO_2max and maximum heart rate compared to the men. Misner et al. (1987) reported that men performed better than women at simulated fire fighting tasks and this was related to differences in body composition, with fat-free mass correlating to an improved performance and fat mass hindering performance.

The current statutory requirement for entry into the UK fire service is $45\,mL \cdot kg^{-1} \cdot min^{-1}$ and it has been recommended that fire-fighters should maintain their VO_2max above $40\,mL \cdot kg^{-1} \cdot min^{-1}$ (Home Office, 1996). The mean VO_2max of fire-fighters involved in physiological studies has been reported around 40 to $45\,mL \cdot kg^{-1} \cdot min^{-1}$ (Ben-Ezra and Verstraete, 1988; Faff and Tutak, 1989; Lemon and Hermiston, 1977; Louhevaara et al., 1995; Smith and Petruzzello, 1998; White and Hodous, 1987) although in one study the average VO_2max was considerably higher at $61\,mL \cdot kg^{-1} \cdot min^{-1}$ (Carter et al., 1999). Studies investigating the general fitness levels of fire-fighters have measured more subjects, over a wider age range, and recorded lower VO_2max levels of around $34\,mL \cdot kg^{-1} \cdot min^{-1}$ (Byrd and Collins, 1980; Sothmann et al., 1990). These studies, because they do not require the fire-fighter to perform further physiological tasks, may give a better indication of the general fitness levels of the fire-fighting population. Whilst emphasis has been placed on the aerobic fitness, other measurements of muscle strength and power (grip strength, back and leg strength) in addition to more task-specific tests (hose running, SCBA test, ladder climb and extend) are often conducted as part of the selection process for fire-fighters.

Fitness and age

Whilst, within limits, age has little effect on performance it is often associated with a decline in physical fitness (Hossack and Bruce, 1982) as a result of adopting a more sedentary life style (Buskirk and Hodgson, 1987). Although, even when endurance training is maintained, physical capacity decreases by 8 to 15% per decade (Pollock et al., 1997). A reduction in fitness and therefore cardiovascular, respiratory and thermoregulatory function will impair the ability of a fire-fighter to perform in the heat. Faff and Tutak (1989) reported fire-fighter exercise tolerance time in the heat was not related to age (21 to 32 y vs 36 to 42 y) but was increased with fitness ($>39\,mL \cdot kg^{-1} \cdot min^{-1}$). However, it may be more important for older fire-fighters to retain their fitness levels, as even when matched for VO_2max, fire-fighters between the age of 41 and 50 years were slower at performing a fire suppression task than those who were 21 to 26 years (Sothmann et al., 1990).

A decline in aerobic fitness has been observed in older fire-fighters, worryingly most of the fire-fighters measured over the age of 30 y were not able to meet a proposed minimum standard of $39\,mL \cdot kg^{-1} \cdot min^{-1}$ (Saupe et al., 1991; Fig. 2). It is unclear whether this situation remains or has been attenuated by the introduction of fitness training over the last 15 years. Lower fitness levels in older fire-

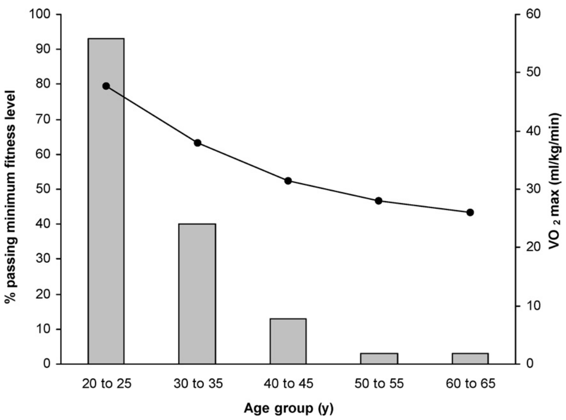

Fig. 2. The relationship between age and aerobic fitness in fire-fighters. The line shows the average maximum oxygen consumption in each age group and the bars the percentage of fire-fighters in each group which would pass a minimum standard of $39\,mL \cdot kg^{-1} \cdot min^{-1}$. n=30 for each group. Data taken from Saupe et al. (1991).

fighters will mean that for any given task older fire-fighters will be working at a higher percentage of their VO_2max and therefore be under greater physiological strain. Exercise, in particular maximal exertion, has been linked to sudden cardiac death (Vuori, 1995). The occurrence of sudden cardiac death is however rare, and in general the beneficial effects of exercise on health outweigh the risks (Shephard, 1995). Despite fire-fighters undertaking periods of very strenuous work, there is no evidence to suggest that they are at greater risk of death from heart attack than the general population (Guidotti, 1995).

Psychological stress and training

As well as the physiological stress associated with fire-fighting there are also considerable psychological stresses (Guidotti, 1995). These include the "heroic" expectations of the fire-fighters and others (which in some cases may be unreasonable); the threat to their personal safety and safety of others; witnessing pain and injury; being subjected to other individuals' strong emotions e.g. anxiety, grief and violence; the unpredictable nature of an incidence and the loss of a victim especially a child (Guidotti, 1995). In response to a call out, fire-fighter heart rate increases rapidly and remains elevated on the truck (Barnard and Duncan, 1975; Kuorinka and Korhonen, 1981). These elevated heart rates indicate the fire-fighters were in a state of anxiety and sympathetic arousal, the extent of which varied between call outs and did not appear to be related to fire-fighter experience or fitness (Barnard and Duncan, 1975; Kuorinka and Korhonen, 1981). Urinary excretion of catecholamines has also been reported to increase in fire-fighters working as operators at the alarm centre reflecting their perceived psychological stress (Kalimo et al., 1980).

Feelings of apprehension and nervousness assessed using a state anxiety questionnaire increased and remained elevated after a fire-fighting exercise in a hot environment (Smith et al., 1997). This elevation in anxiety could have an impact on cognitive functioning and therefore decision making processes (Kivimaki and Lusa, 1994). Mental performance has been found to increase on initial exposure to a hot environment, but with prolonged exposure it is reduced (Ramsey, 1983). The effect of heat will partially depend on the initial skill of the individual. Where there has been limited previous experience—for example in an emergency situation, there is likely to be a greater decrement in performance compared to a task that is routinely undertaken (Hancock, 1982). An increase in T_c of only 0.2°C decreases dual task performance (e.g. simultaneous arithmetic and monitoring tasks), an increase of 0.9°C decreases tracking efficiency and an elevation by 1.3°C slightly impairs mental and cognitive skills and is close to the limit of heat tolerance (Hancock, 1982). Following strenuous fire-fighting drills that resulted in tympanic temperature increasing by 0.8°C, reaction time was not affected, however the accuracy of the response was reduced (Smith et al., 2001a).

Conclusion

In general, the average physiological responses to fire-fighting appear to be within acceptable limits although they still exceed the norms suggested for other occupational groups (ISO-8996 2004; Kemper et al., 1990; Saha et al., 1979; Wu and Wang, 2001). However, in some fire-fighting situations some fire-fighters can experience severe physiological strain (Tables 1 and 2). Deep body temperatures of over 40°C (Eglin et al., 2004), skin temperatures high enough to cause burns (Rossi, 2003), fluid deficits of over 3% body mass (Eglin et al., 2004) and maximal heart rates (Bos et al., 2004; Eglin et al., 2004) have been reported. This level of strain will impair performance and may cause collapse even in a fit fire-fighter. It is therefore imperative that the fire-fighter is prepared for the occasional bout of intense activity by maintaining an appropriate level of physical fitness throughout their career. Remaining adequately hydrated and having the capability to cool down after heat exposure are also important health and safety considerations as they have an adverse effect on both physical and mental performance.

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