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OCCUPATIONAL HEALTH CONCERNS OF FIREFIGHTING

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INTRODUCTION

The health effects of exposures related to fighting fires has long been a major interest of occupational health investigators. Municipal firefighters are an unusually accessible and well-documented group of workers, as there are extensive records on their health and work history. The occupation has been studied intensively for evidence of chronic health effects. Interest in the health problems of firefighting increased considerably during the 1980s. A substantial body of work is now available that may lead to a reevaluation of many unresolved issues.

Firefighters are exposed to serious chemical and physical hazards, to a degree that is unusual in the modern work force. The acute hazards of firefighting, primarily trauma, thermal injury, and smoke inhalation, are obvious. A large literature has been developed on acute pulmomary injury associated with inhalation of hot air and toxic constituents of smoke, particularly the combustion products of commonly used plastics (18, 30, 63). The hazards of carbon monoxide and cyanide are particularly well recognized (4, 18). Although the acute health effects of these life-threatening hazards and the risk of physical injury in structures affected by fire are indisputable, the chronic health effects that follow recurrent exposure are not clear (3). Studies that directly address the health experience of firefighters have not yielded consistent results until relatively recently. This uncertainty has led to a patchwork of employment and workers' compensation board policies.

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Firefighting is an unusual occupation, as it is perceived as dirty and dangerous, but indispensable and admirable. Firefighters, almost universally, enjoy public admiration and gratitude to a degree unmatched by other occupations, particularly in the public sector (90). Their occupation is rich in stories of personal courage, spirit in the face of adversity, and teamwork. However, firefighters also experience a constant awareness of imminent danger and the feeling that the next alarm may challenge them to the limit (100). The health of firefighters, and their willingness to face the hazards, cannot be fully understood without appreciating this psychological dimension (105).

HAZARDS

Occupational hazards experienced by firefighters may be categorized for convenience as physical, thermal and ergonomic, chemical, and psychological. The level of exposure experienced by a firefighter in a given fire depends on what is burning, the combustion characteristics of the fire, the structure on fire, the presence of nonfuel chemicals, the measures taken to control the fire, the presence of victims requiring rescue, and the position or line of duty held by the firefighter while fighting the fire. The hazards and levels of exposure experienced by the first firefighter to enter a burning building are different from those of the firefighters who enter later or who clean up after the flames are extinguished. However, the career exposure profiles of firefighters tend to average out the longer they spend in a particular rank. There is rotation among the active firefighting jobs in each platoon and a regular transfer of personnel between fire halls. Firefighters therefore have a similar probability of exposure in typical fire situations as long as they stay classified as a "firefighter"; "captains" accompany and direct the crews, but are still actively involved in fighting the fire on site. Thus, firefighting exposures tend to become similar over a longer period of time, although individual firefighters may still experience unusual exposures in particular incidents.

Within the last 20 years, the introduction of the self-contained breathing apparatus (SCBA) and other protective equipment has created a much safer working environment for the firefighter. However, the added weight of the equipment increases the physical exertion required. The protective clothing also becomes much heavier when it gets wet.

Thermal Hazards

Heat stress is compounded in firefighting by the combination of insulating properties of the protective clothing and physical exertion, which results in endogenous heat production (6).

Hot air alone is not usually a great hazard to the firefighter. Air heated above body temperature cools as it passes through the larynx (38). Dry air also does not have much capacity to retain heat and delivers little to the lower respiratory tract, so that heat-induced inhalation injury is not usually a risk when the air is dry. However, inhaled steam or hot wet air can cause serious burns to the lower airway simply because of the high latent heat capacity. Much more heat energy can be stored in water vapor than in dry air. Fortunately, steam inhalation is not common (91).

Radiant heat is typical of a fire situation and may be associated with skin changes, particularly erythema and telangiectasia, in the absence of obvious burns (107).

Chemical Hazards

Firefighters on the scene of a fire are frequently exposed to carbon monoxide, hydrogen cyanide, nitrogen dioxide, sulphur dioxide, hydrogen chloride, aldehydes, and such organic compounds as benzene (41, 59, 113). Before arriving and on return, firefighters are exposed to diesel exhausts at the fire station (37).

In the 1970s, about 80% of injuries of firefighters in service resulted from smoke inhalation or oxygen deficiency. More than 50% of fire-related fatalities are the result of smoke exposure, rather than burns (4, 18, 30, 77). One of the major contributing factors to mortality and morbidity in fires is hypoxia because of oxygen depletion in the affected atmosphere, which leads to loss of physical performance, confusion, and inability to escape (91). Another factor is the toxicity of the constituents of smoke, singly and in combination.

The study of the toxicology of smoke as a complex mixture and its individual constituents has advanced in recent years and has led to better designs for personal protective and fire management strategies. Smoke is a variable mixture of compounds, each possessing specific toxicological properties and contributing to interactive toxic effects. Therefore, the toxicity of smoke varies greatly, depending primarily on the fuel, the heat of the fire, and whether or how much oxygen is available for combustion. However, all smoke, including that from simple wood fires, is hazardous and potentially lethal with concentrated inhalation (26). The complexity of the chemical composition of smoke is also due, in part, to the presence of secondary products; after the products of combustion are formed, they remain chemically active and continue to react long after the fire has ceased to burn. The list of chemicals of toxicological concern is long (21, 26). Smoke from burning oil has been characterized and found to have mutagenic activity in in vitro assays (5); this is undoubtedly also true for other common types of fires.

Smoke is made up of two components, particulates and gases, which are suspended or dissolved in a third component, hot air. (Table 1) The degree of exposure experienced by a firefighter is determined by the chemistry and quantity of gases produced at the fire, the concentrations reached, the size

Table 1 Products of combusion of commonly burnt materials

Combusted material	Fuel component of original material	Toxic decomposition products[a]
wood, paper, cotton, jute	cellulose	aldehydes, acrolein
clothing, fabric, blankets, furniture	wool, silk	hydrogen cyanide, ammonia, hydrogen sulfide
tires	rubber	sulphur dioxide, hydrogen sulfide, methyl mercaptan, benzene-related compounds
upholstery material, wire, pipe coating, wall, floor, furniture coverings	polyvinyl chloride	hydrogen chloride, phosgene
insulation, upholstery material	polyurethane	hydrogen cyanide, isocyanates, oxides of nitrogen
clothing, fabric	polyester	hydrogen chloride
upholstery material, carpeting	polypropylene	acrolein
appliances, engineering plastics	polyacrylonitrile	hydrogen cyanide, nitriles, oxides of nitrogen
carpeting, clothing	polyamide (nylon)	hydrogen cyanide, ammonia, oxides of nitrogen
household and kitchen goods	melamine resins	hydrogen cyanide, ammonia, formaldehyde, oxides of nitrogen
aircraft windows, textiles	acrylics	acrolein
kitchen goods, electrical insulation, gaskets	polytetrafluorethylene (Teflon®)	octafluoroisobutylene
photographic film	nitrocellulose	oxides of nitrogen

[a] Carbon monoxide and carbon dioxide are produced in all cases. Other gases, such as the aldehydes, methane, and low-molecular-weight organic acids, are common in most fires.

distribution of the particulate phase, solubility properties of the gaseous constituents as a predictor of the degree of penetration to the lower respiratory tract, and the duration of exposure (24).

Particulates generated from burning wood or other organic matter are composed of chemically inert carbon particles that become adsorbed (coated) with other chemical substances. These agents produce an irritating effect and cause cough and an acute bronchitis. The particles may also become carriers of less volatilé substances, such as chlorinated hydrocarbons, depending on the composition of the combustion products (16, 91).

The chemical components of the gaseous phase of smoke, many of which are adsorbed onto the particulates and thereby penetrate more deeply into the lower respiratory tract than they otherwise would, are responsible for most of the toxicological effects that result from smoke inhalation (38). Laboratory simulations of different fire conditions have permitted the characterization of many of the combustion products given off by burning natural and synthetic materials commonly found in building structures and furnishings. The exact composition of the combustion products vary, depending upon the composition of the burning material and the temperature at which each material undergoes thermal decomposition (54).

Carbon monoxide is considered the most common, characteristic, and serious acute hazard of firefighting. Carboxyhemoglobin accumulates rapidly with duration of exposure as a result of the affinity of carbon monoxide for hemoglobin, and high levels may result, particularly when heavy exertion increases minute ventilation and increases delivery of carbon monoxide to the lung during unprotected firefighting (42, 62, 98). Not surprisingly, levels of carbon monoxide measured on the scene at fires often exceed the Occupational Safety and Health Administration's short-term exposure levels (8). Carbon monoxide and carbon dioxide, which are natural products of combustion, are necessarily present at every fire. Hydrogen cyanide is also formed from the lower temperature combustion of nitrogen-rich materials, including such natural fibers as wool and silk and such common synthetics as polyurethane and polyacrylonitrile (92, 109, 115). Although elevated levels of thiocyanate as a marker for cyanide exposure are less common among firefighters than elevated carboxyhemoglobin levels (61), there is a close relationship between the two in firefighters who have sustained clinically significant smoke inhalation (20).

Light-molecular-weight hydrocarbons, aldehydes (such as formaldehyde), and organic acids may be formed by hydrocarbon fuels that burn at lower temperatures (78). The oxides of nitrogen are also formed in large quantity when temperatures are high, as a consequence of the oxidation of atmospheric nitrogen, and in lower temperature fires in which the fuel contains significant nitrogen. When the fuel contains chlorine, particularly in the form of polyvinyl chloride (PVC), hydrogen chloride is formed (24, 30).

Most toxic components of smoke, with the exception of carbon monoxide and hydrogen cyanide, are only rarely produced in lethal concentrations. Different gas combinations are likely to present different degrees of hazard (91).

The toxic products of polymeric, plastic materials have come under increasing scrutiny. Since the 1950s, these materials have been used in building construction and furnishings in Europe and North America in large amounts (83, 114). They were soon found to combust into particularly hazardous products. Acrolein, formaldehyde, and volatile fatty acids are common in smoldering fires of several polymers, including polyethylene and natural cellulose (78). These products were characterized in a series of elegant studies by Wooley, who found a close relationship between the temperature of combustion and the mix of nitrogen-containing products released from polyurethane. Generally, cyanide levels increase with temperature; acrylonitrile, acetonitrile pyridine, and benzonitrile occur in large quantity above 800°C but below 1000°C (114, 116, 124, 125). Combusted polyacrylonitrile is even richer in cyanide and nitriles (116). Polyvinyl chloride has been proposed as desirable polymer for furnishings because of its self-extinguishing characteristics, caused by the high chlorine content. Unfortunately, the material produces large quantities of hydrochloric acid when fires are sustained, as they are when PVC is only part of the fire (33).

Since the 1970s, there has been much interest in the relative toxicity of the mixed products of combusted materials, along with the recognition that no two fires are exactly alike (49, 54). Alarie and Anderson (1, 2), have conducted extensive research on the decomposition products of polymeric materials, by comparing the toxic effects to those of the wood of Douglas fir as a standard. Some materials, such as PVC, decompose rapidly and are rapidly lethal, but others, like polytetrafluoroethylene (PTFE), which also decomposes rapidly, kill more slowly even though they are ultimately more lethal over the duration of exposure than PVC. When rating the toxicity hazard of materials, one must consider the period of evaluation. Table 2 rates the toxicity of a variety of materials compared with a standard of 100 representing Douglas fir, and considers both the time and exposure level required to produce a lethal effect (2).

Within the last 20 years, the toxicity of smoke and its hazard to the firefighting profession have been fully recognized. In the early 1970s, the

Table 2 Index for burning components of original products summarizing several characteristics that contribute to or suppress toxicity (lower the index, the higher the toxicity)

Burning material	Index
Douglas fir	100.00
compressed spruce, pine, fir slab	65.92
fiberglass insulation	63.59
polyester resin	41.58
cellulose fiber	17.80
polyurethane foam	12.95
phenol formaldehyde-phenol resin	8.98
isocyanate foam	7.57
modacrylic	6.28
PVC	5.85
wool	5.77
polystyrene	5.47
acrylonitrile/butadiene/styrene	4.04
urea formaldehyde foam	3.91
PTFE	0.36

National Fire Prevention Association published a report, "Breathing Apparatus for the Fire Service," which, through increased recognition of the problem, led to the introduction of SCBA (127). Fire departments, such as Boston's, adopted mandatory use regulations that markedly reduced the number of smoke inhalations in subsequent years by as much as 80% (113). In 1976, an evaluation of the effectiveness of SCBA showed that blood levels of carboxyhemoglobin in firefighters, as a measure of carbon monoxide exposure, were lowest in firefighters who used SCBAs, but roughly the same for intermittent uses or nonusers. This study and others showed that firefighters who do not wear SCBAs during the "knock-down" and "overhaul" phases are at risk; unfortunately, this is the phase in which the flames are out, and the hazard only seems to be reduced (30, 93).

Firefighters judge the level of hazard they face by the intensity of smoke and decide whether to use an SCBA solely on the basis of what they see. This may be very misleading, especially in the clean-up phase after the flames are extinguished (112). On superficial inspection, the fire setting may appear safe at this stage; however, it can be dangerous (112). There is no apparent correlation between the intensity of smoke and the amount of carbon monoxide in the air (23, 60). Synthetic materials are most dangerous during smoldering conditions, as opposed to conditions of high heat (30, 53, 123). Concrete retains heat very efficiently and may act as a "sponge" for trapped gases that then out-gas from the porous material, thus releasing hydrogen chloride or other toxic fumes long after a fire has been extinguished (30, 108). Firefighters should also be cautioned against cigarette smoking during the clean-up phase, as this adds to the already elevated levels of carbon monoxide in the blood (65, 110). The hazards presented by unusual constituents in smoke are too variable and complex for detailed discussion here. The combustion products of many industrial chemicals and mixtures are unknown or only poorly characterized. A major problem with fires that involve chemical sources or storage facilities is knowing how to fight them with the least potential danger to the firefighter and local residents. Recent studies have suggested novel approaches to such situations. In the case of fires in an insecticide storage facility, Jeffries & Schiefer (52) have suggested that optimal management might be to enhance combustion intentionally to produce a fast, hot fire that combusts the material more completely and carries the airborne toxic products away from the vicinity vertically by convection currents.

Psychological Hazards

There are many sources of psychological stress in the life of a firefighter, in addition to the viscissitudes of daily life and career advancement (29, 70, 72). A firefighter regularly steps into a situation that others flee, thus accepting a level of personal risk that would be unacceptable in most other occupations. Although this risk is controlled to the extent possible with fire equipment and personal protection, the reality of firefighting is that much can go wrong in any fire, and the course of a serious fire is often unpredictable (51, 70).

Besides personal security, the firefighter must be concerned with the safety of others threatened by the fire and is sometimes a witness to pain, injury, and strong emotion. Rescuing victims is an especially stressful activity. The loss of a victim, especially a child, is reported in numerous anecdotes to be the most stressful experience a firefighter can endure.

The professional life of a firefighter is not an endless round of anxious waiting punctuated by stressful crises, however. Firefighters enjoy the many positive aspects of their work. The work is intrinsically interesting and, during alarms, presents a great deal of stimulation and variety. Few occupations are so unequivocally favored by public opinion or so respected by the community. Job security is largely assured in urban fire departments once a firefighter is hired, the pay usually compares well with other jobs, and the schedule allows ample opportunities for "moonlighting" between shifts. When a firefighter answers an alarm, there is a degree of apprehension and stress, but there is also exhilaration and a sense of purpose. These positive aspects of the job mitigate the stressful aspects and tend to protect the firefighter against the emotional consequences of repeated stress (51).

At the sound of an alarm, firefighters experience a degree of immediate anxiety because of the inherent unpredictability of the situation that they are about to encounter. Some investigators believe that the psychological stress experienced at this moment is as great and, perhaps, greater than any of the stresses that follow during the course of responding to an alarm. En route, hazardous traffic maneuvers and high noise levels from the sirens contribute to stress (94). Physiological and biochemical indicators of stress have also been assessed among firefighters (29).

HEALTH EFFECTS

Some jurisdictions attempt to justify cases of health disorders on an individual basis, and others prescribe selected chronic diseases as compensable occupational disorders among firefighters. The problem is compounded by changes in technology over several decades; the risks and their outcomes vary with the era during which the firefighters entered the workforce. Generally speaking, firefighters who entered service before the 1960s were exposed to smoke of less acute toxicity, but lacked personal protection equipment of acceptable effectiveness. Those entering within the last two decades have primarily been exposed to smoke of greater toxicity, but have had more effective respiratory protection available. Firefighters who joined the force in the last few years may have the benefit of both fire-retardant materials produced under more stringent safety codes and also respiratory protection meeting contemporary standards of effectiveness.

Acute Effects

INJURIES Injuries associated with firefighting are predictable: burns, falls, and injury from falling objects. Jobs with a high risk of burns include those involving early entry and close-in firefighting, such as holding the nozzle. Burns are more commonly associated with basement fires, recent prior injury, and training outside the fire department of present employment. Falls tend to be associated with SCBA use, assignment to truck companies with climbing equipment, and, suggestively, childlessness. (Without dependent children, an individual may be more likely to take risks.) However, age and experience do not seem to be associated with risk of injuries in service (47).

RESPIRATORY DISORDERS The respiratory effects of exposure to smoke and fumes from fires have been a major concern. Acute smoke inhalation carries a high mortality for unprotected victims (19) and is often combined with burns and other trauma. Fatal and overwhelming smoke inhalation has been reviewed extensively in the clinical literature (18, 22), and its manifestations are not unique to firefighting.

Transient changes have been associated with unremarkable fires (59, 82, 100), as well as fires involving certain chemicals (14), such as burning polyvinyl chloride (30), silicone plastic (39), butyl rubber insulation (82), and isocyanates (6, 73). In those cases in which the fires did not present an unusual hazard, the decrement in airflow (measured as the reduction in FEV_1, the forced expiratory volume in one second, between the beginning of a shift and return after an alarm) correlated with the concentration of particulate matter in the smoke cloud and the presence of eye irritation, but not the duration of exposure, work shift, or smoking history. Persistent effects, including neurological impairment, have been noted following exposures that involve isocyanate fumes (6), but in only a subset of firefighters exposed to burning polyvinyl chloride (30, 69, 111). In at least one case, these changes mimicked asthma, with wheezing and refractory bronchoconstriction (14).

Airway responsiveness increases after firefighting exposures (56, 82, 100, 101). Increased airways reactivity following minor smoke inhalation during routine firefighting is a complex response, more complicated than bronchoconstriction, which results from irritation. The response is persistent, does not correlate with baseline methacholine sensitivity, and is associated with acute but transient increases in airways responsiveness (82, 100, 101). In at least one case, exposure resulted in airflow obstruction—initially responsive to bronchodilators—that became progressively more severe despite treatment, until the patient died of respiratory failure two years later (14). In this case, the pathology may have resembled mucoid impaction syndrome.

There are very few studies of the pulmonary response to smoke in controlled situations in firefighting. Minty et al (74) studied nonsmoking firefighting instructors in the Royal Navy, by obtaining data on smoke composition, pulmonary function, and alveolar-capillary permeability following brief exposure to wood and diesel fires in training exercises. They found no change in pulmonary function; but, they did find an elevated permeability measure, which suggests that exposure to the smoke either damaged the integrity of the alveolar-capillary barrier or initiated a low-grade inflammatory response that in turn had the same effect because of release of proteolytic enzymes.

Chronic Health Effects

Several early studies examined firefighting, along with numerous other occupations, by using vital records for large populations (43, 45, 77, 88, 117, 118, 120, 121). These have sometimes been difficult to interpret because of methodological issues and misclassification (43). Two early cohort studies have been recognized for their usefulness in evaluating the health risks of firefighters: Mastromatteo's 1959 study on a cohort of firefighters in Toronto (71) and Musk et al's 1978 study on a large cohort from Boston (79). The Mastromatteo study was a pioneer effort in the field, which illustrated the use of basic techniques that have been adopted in many studies since. Because of its date, however, the findings have uncertain application to the current situation. Since these early landmarks, other major cohort studies have recently been contributed by Eliopulos et al (31) on a cohort from Western Australia, Feuer & Rosenman (36) on a cohort from New Jersey, Vena & Fiedler (122) on a cohort from Buffalo, New York, Heyer et al (48) and Rosenstock et al (96) on a cohort from Seattle, Beaumont et al (13) on a cohort from San Francisco, and Guidotti (44) on a cohort from the Canadian province of Alberta.

The chronic effects of greatest concern in studies of firefighters have been lung cancer, heart disease, and chronic obstructive pulmonary diseases. Recently, however, other forms of cancer, particularly genitourinary and colon and rectal, have emerged as likely associations.

A chronic effect that has only recently been documented is that of an increased risk of congenital cardiac defects in the offspring of male firefighters. The responsible exposure is not known (85).

CANCER Lung cancer has been the most difficult cancer site to evaluate in epidemiologic studies of firefighters. Despite the obvious exposure to carcinogens inhaled in smoke (15), it has been difficult to document an excess in mortality from lung cancer of a magnitude and consistency compatible with occupational exposure. Without question, cigarette smoking is a confounding exposure that complicates the analysis, but the prevalence of smoking among firefighters does not appear to be excessive compared with other blue collar occupations (40). Respiratory protection has probably reduced individual exposure levels since the 1970s, although it was not optimally used for many years in most fire departments. An effective form of respiratory protection was probably introduced too late to have substantially modified lung cancer rates that are currently observed. A major issue is whether the above-mentioned introduction of synthetic polymers into building materials and furnishings has increased the risk of cancer among firefighters because of exposure to the combustion products.

The empirical findings on lung cancer from recent, well-designed epidemiological studies have been inconsistent. One study from Denmark (46), in which the comparison population is unusual, reported a standardized mortality ratio of 317 for older firefighters, whereas studies on cohorts from San Francisco and Buffalo showed no excess (13, 122). The possibility that an association is obscured, in comparison to the general population by the healthy worker effect, is probably less likely for this cause of death than for other chronic diseases; over the long periods of observation typical for these studies, the mortality experience of initially selected workers can be expected to approach that of the general population more closely, especially for noncardiovascular causes of death. Most studies have shown an excess of lung cancer on the order of 20–80% (48, 97), a magnitude not uncommon in studies of other blue collar occupations with less plausible exposure levels (43). In the most detailed analyses to date, a nonsignificant excess showed no clear distribution that would be consistent with duration of employment, exposure opportunity, or era of entry into the occupation (44, 122).

Documentation of an association between lung cancer and occupational exposure as a firefighter remains elusive; many investigators continue to believe that an association exists. Markers of genotoxic effect suggest that carcinogenicity is likely to occur (64). An effect probably does exist, but it is likely to be heavily obscured by confounding factors and may not be as strong as anticipated.

Other cancer sites have recently emerged as more consistent associations with firefighting. Evidence for an association with genitourinary cancers seems strong (97, 122). There is a less strong suggestion in the literature for colon and rectal cancers and for leukemia, lymphoma, and multiple myeloma (97, 122).

PULMONARY DISEASE Most epidemiological studies of firefighters that report on mortality from chronic obstructive airways disease do not show an excess. There has been some concern that comparison to the general population may obscure a relative excess offset by the healthy worker effect. In one study, comparison with police showed a nonsignificant excess, but the police in this study showed an unusually low mortality (87).

Although excess mortality and morbidity are difficult to demonstrate, there is evidence from serial studies of pulmonary function that firefighters are at risk for airways obstruction. Reports of progressive abnormalities in lung function among firefighters have suggested as much as a doubling of the expected rate of decline in lung function that normally affects aging adults, and this difference is associated with an increased frequency of respiratory symptoms (87, 103, 106). These reports sparked a wave of concern in the mid-1970s because they suggested an eventual appearance of chronic lung disease among firefighters (3). This effect is most apparent following unusually severe exposures (119) and is associated with the number of fires fought over the first year or so. Declines of this magnitude have been associated with an increased risk for chronic obstructive airways disease (emphysema or chronic bronchitis) in other populations. Intense exposures have produced chronic changes in at least one case (63). If these findings are significant, one would expect an increase in mortality from chronic airways disorders compared with the general population. The above-mentioned studies show no such effect. The cohort study by Musk et al (79), for example, showed a standardized mortality ratio of 93, 83 for active firefighters and 101 for retired firefighters, which is well within the expected range. Significant abnormalities in pulmonary function have been reported in current firefighters among smokers only (28), and even that seems to represent minimal small airways disease in asymptomatic firefighters employed for at least 25 years (63). Thus, the weight of evidence suggests that firefighters are not at greatly increased risk of chronic respiratory disease unless they experience an unusual exposure (82, 126).

In the past, there had been some concern that firefighters with early lung disease leave the occupation and that the remaining firefighters are, therefore, selected for respiratory health (89). This effect may be less pronounced than initially assumed (104, 106). Fire departments, in effect, protect their own most vulnerable members by transferring them into positions with less opportunity for exposure, so that career firefighters with mild respiratory impairment may easily remain employed (102). Transfer patterns within the fire department result in a steady exit of those individuals most at risk for decline in airflow velocity from active firefighting positions and movement into positions in which their duties involved fighting few or no fires. A powerful selection bias at work apparently protects firefighters with abnormalities of pulmonary function from further exposure (80, 81).

The contribution of cigarette smoking to the overall picture remains difficult to sort out. Horsfield et al (50) studied 96 British firefighters and 69 nonsmoking, nonfirefighter control subjects over four years to evaluate the progression of their pulmonary function and any respiratory symptoms. The firefighters were regularly interviewed with respect to their smoking habits and the degree to which they felt affected by exposure to smoke on the job. This index was admittedly subjective, but took into account the situations in which personal protection may have failed. The authors found no evidence for functional abnormality on spirometry; indeed, pulmonary function in these firefighters deteriorated at a rate slower than in the controls. They did observe a consistent and suggestive pattern of reported symptoms: Symptoms, predominantly productive cough, were reported least often among the controls; more often among the nonsmoking, smoke-unaffected firefighters; at an intermediate frequency among smokers who were smoke-unaffected, as well as nonsmoking smoke-affected firefighters; and most often among smoking smoke-affected firefighters. Indeed, despite the crudely subjective index of occupational smoke exposure, the pattern strongly suggested a multiplicative interaction. The authors concluded that occupational exposure to smoke in firefighting is a determinant of respiratory symptoms almost as strong as cigarette smoking, with which it interacts, but that it does not appear to affect pulmonary function given current use of personal protection.

These investigations were extraordinary in detail, perspicacity, and tenacity. The picture now seems to be fairly clear: Within the firefighting profession, there is an effective, but largely tacit, mechanism that works by administrative means to protect the most vulnerable members. It now seems safe to conclude that occupational exposure can indeed cause respiratory disorders alone in extreme situations or in combination with cigarette smoking. That this was not reflected in greater mortality from respiratory diseases in past years may reflect the effectiveness of the administrative measures described above. The risk of death from respiratory causes in future will be further reduced by increasing compliance with and technical effectiveness of the use of personal protection devices.

CARDIOVASCULAR DISEASE Despite a presumption of occupational association in many jurisdictions when a firefighter dies of a myocardial infarction, firefighters have not been consistently shown to be at elevated risk for death from heart disease. Recent studies suggest that mortality is about that expected (13, 27, 44, 46, 96, 122), although some studies have suggested elevations of 50% (99). There is ergonomic evidence that some firefighters may be stressed to the limit during the exertions of their work. That this stress does not result in increased mortality probably reflects a strong healthy worker effect and the decreasing levels of exertion required with seniority and advancement beyond captain.

Two lines of reasoning suggest that cardiovascular disorders may be a problem among firefighters. The first is the documented presence of high degrees of cardiovascular stress during the response to alarms and the process of fighting the fire (10). The second is the known presence of carbon monoxide at high concentrations in smoke inhaled by firefighters (4, 18, 63). Several experiments have indicated that carbon monoxide exposure reduces the threshold for angina.

The cardiovascular response to an alarm is pronounced. Firefighters show a marked increase in heart rate during the response to a fire alarm. This increase averages about 50 beats within 30 seconds of the alarm sounding, which persists until arrival at the fire. The elevation in heart rate is much greater than that which would be expected in response to the exertion alone. During firefighting, heart rates of 150–160 beats/min were the norm, but occasional peaks of 175–195 occur, especially during the first 3–5 minutes of a fire and during stressful and dangerous crises. These are very high levels, associated with maximal exertion or anxiety. The response in heart rate does not show any consistent association with age or fitness of the firefighter, and there is great variation from person to person and in the same person from time to time (10, 55).

Electrocardiogram (EKG) changes suggesting coronary artery disease were found by Barnard et al (11) in nine of 90 randomly selected firefighters aged 40–59 in the city of Los Angeles. This level of prevalence of EKG-demonstrable coronary artery disease was comparable to that expected for a large group of middle-aged men but this in itself is surprising because firefighters, who are selected by stringent criteria for fitness, demonstrated a reduced prevalence of cardiovascular risk factors (12). Four of six firefighters with EKG abnormalities suggestive of ischemic changes had no evidence of advanced coronary artery disease, but three had abnormal left ventricular wall function (11). This raised the possibility that firefighters may be at risk for nonischemic myocardial injury on the basis of exposure to carbon monoxide or elevated circulating catecholamines (8–11). Indeed, of the original group tested, two had myocardial infarcts within two days of testing, an alarming experience (12).

Barnard and coworkers (9, 12) also described an ischemic response in healthy young men, including firefighters, who engaged in sudden, vigorous exercise without warm-up. They suggested a transient mismatch in oxygen supply and demand at the subendocardial level caused by temporarily inadequate perfusion for the suddenly increased demand for myocardial oxygen. Arterial pressure measurement confirmed that the relaxation time available for restoring coronary blood supply during diastole was markedly reduced during cold start-up exercise. Although this mechanism is probably not a cause of persistent or cumulative myocardial injury, it may play a role in unusual and emergent situations that require sudden maximal exertion.

The experience of firefighters who were studied in large groups has been quite different. Dibbs et al (27) examined a similarly "healthy" group of 171 firefighters in Boston enrolled in a cohort study on aging effects. They found a distribution of risk factors similar to that seen by Barnard and coworkers, but the incidence of detectable coronary heart disease and its complications over ten years of observation was no different than that for nonfirefighters of the same age in the study. The discrepancy suggests that Barnard's group of subjects, and the group studied before him by Felton (35) from the county of Los Angeles (distinct from the city, but recruited from the same population) differed in some important ways from the Boston firefighters.

ERGONOMIC ISSUES

Firefighting is a very strenuous occupation, which is often performed under extreme environmental conditions (67). The demands of firefighting are sporadic and unpredictable, characterized by long periods of waiting between bouts of intense activity. This irregular pattern of activity is an important feature of firefighting, as it adds to the component of stress that is probably caused by anxiety and responses to psychogenic stress.

There are several components to the physiological demands of firefighting, including energy cost of performing firefighting activities, heat stress associated with heat from the fire, and encumbrance by personal protection equipment. A detailed understanding of the physiological demands of firefighting must consider the contribution of each component and changes in each over time. For example, the use of personal protection equipment has imposed new physiological demands on firefighters, but has removed other demands by reducing exposure levels; personal protection equipment is also improving over time with advances in technology (66).

Energy Costs and Performance

Among common firefighting activities, climbing the aerial ladder is one of the most strenuous. Other strenuous activities include climbing stairs, dragging hose, rescuing a victim, and raising the ladder (58, 84, 95).

Firefighters adjust their levels of exertion in a characteristic pattern during simulated fire conditions, as reflected by heart rate. Initially, their heart rate increases rapidly to 70–80% of maximal within the first minute (68). As firefighting progresses, they maintain their heart rates at 85–100% maximal until the fire is out. With the addition of equipment and SCBA apparatus, they adjust their levels of exertion to remain at this intense level of activity. In other words, firefighters maintain their level of exertion at a relatively constant, intense level once active firefighting begins. Any additional burden, such encumbrance by the necessary protective equipment or victim rescue, reduces performance because firefighters are already exerting themselves to the maximum.

The energy requirements for firefighting are complicated by the adverse conditions in many inside fires. The metabolic demands of coping with heat transfer and fluid balance add to the existing demands of physical exertion. A major issue is the combined effect of the accumulation of internally generated heat during strenuous exercise and the external heat during fire conditions (38, 109).

Fitness and Performance Capacity

Numerous studies have evaluated the physiological characteristics of firefighters, usually in the context of other studies to determine the response to firefighting-related demands. Studies of the fitness of firefighters have shown fairly consistently that most firefighters are as or somewhat more fit than the general adult male population. However, they are not fit to an athletically trained level (17, 25, 57, 86). Fitness and health maintenance programs have been developed for firefighters, but have not been convincingly evaluated for their effectiveness.

The entrance of women applicants into firefighting caused a reevaluation of performance tests and studies comparing the sexes. Misner et al examined the performance of 37 men and 25 women on nine job-related tasks used as a screening battery in Chicago. The subjects were recruited from among athletes in training and individuals known to be highly physically fit. The intent was to compare the performance of suitably trained individuals who could achieve their potential maximum performance, rather than the assessment of typical applicants. They found that women demonstrated lower scores on average than men in all performance items, but that a subgroup of women performed nearly as well in some tasks. The overall difference in performance was primarily attributed to lower absolute lean body weight, which correlated most strongly and consistently with performance difference (76). The most difficult items for women were the stair-climbing exercises. Leg strength appears to be predicted by lean body weight, but not by other anthropometric measurements (75).

Given the potential for heat stress, toxic exposure, and hypoxia, Evanoff & Rosenstock (32) have suggested that women firefighters who are pregnant should cease firefighting activity sometime during the second trimester, and that contract policies facilitate pregnancy leave and temporary reassignment.

CONCLUDING REMARKS

The demands and harzards of firefighting have changed over the past decades (1, 4, 26, 34, 49, 90, 124), but the high quality and standard of service have remained the same (105). The use of highly sophisticated firefighting equipment and the introduction of innovative firefighting techniques, safer personal protective equipment (60), and better communications and information systems, as well as healthier life-styles (25, 40, 67), have helped meet public demands for service and, at the same time, have provided a safer and healthier working environment for the firefighter. In spite of these advances, firefighting continues to be a very hazardous occupation (47, 83, 90, 119).

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