Review of the Literature:
The Health Effects of Air Toxicants in Bushfire Smoke on Volunteer Firefighters

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Abstract

The aim of this paper was to undertake a comprehensive review of the relevant literature which identified that volunteer firefighters are exposed to a number of hazards including smoke that contains unhealthy levels of respirable particles, carbon monoxide, acrolein, formaldehyde, benzene and toluene. A variety of factors such as work activity on the fire ground, fire type and fuel type significantly influence the level of exposure experienced by firefighters. Many studies have found that acute symptoms of exposure include dizziness, nausea, difficulty breathing, lung dysfunction and cognitive impairment, but that the long term effects of chronic exposure are not well known and require further research. It is suggested that through this research, the Rural Fires Services of each State and Territory will be better informed to investigate opportunities to provide volunteer firefighters (who are members of brigades of any classification) with respirators or masks that will protect them against all air toxicants they are exposed to. This could also involve a cultural and mind-set change among volunteer firefighters to actually use resources available to protect themselves, which could come with more specific training and greater awareness of the risks.

Introduction

Smoke pollution in the atmosphere is becoming an increasing public health issue for the community, and particularly for people directly involved in firefighting operations (Brustet, et. al., 1991; Ward, et. al., 1993; Miranda, et. al., 1994; Reinhardt, et. al., 2001). Along with other occupations such as construction, mining and agriculture, firefighting is considered one of the most dangerous occupations in the world (Leonard, 2007). Due to a variety of hazards firefighters are exposed to (Guidotti and Clough, 1992), firefighting is associated with high levels of morbidity and mortality (Stefanidou, 2008).

One of the most recognised and prominent hazards for firefighters is the inhalation of smoke from combustion of materials causing respiratory and systemic health hazards (Leonard, 2007). Bushfire creates an incredibly complex and toxic environment of heat, flame, oxygen depletion, smoke, toxic gases, and fine particles that are hard to quantify between different types of fires (Stefanidou, 2008). Exacerbating the negative health effects from smoke inhalation of the use of heavy equipment and external stressors, such as heat, humidity, reduction of O2, increase in CO2, and emotional stressors (del Piano et al., 1983; Hong and Samo, 2007; Naeher et al., 2007).
The aim of this literature review is to critically evaluate literature related to the health effects of air toxicants in bushfire smoke on volunteer firefighters and to identify better ways of managing these effects. The objectives of the literature review are to thoroughly and systemically critically evaluate the relevant and current scientific literature from a range of sources. This review will investigate, compare and contrast the variety of arguments, methodologies, theories and conclusions. It will also identify current knowledge gaps, consider why these exist and provide some final conclusions.

**The Hazards of Firefighting**

Firefighters are trained to enter dangerous situations that ordinary people would flee (Guidotti and Clough, 1992). Firefighting has many unique occupational features, including unpredictable and sporadic periods of strenuous work, intermitted by long periods of waiting. Firefighting involves courage, teamwork and camaraderie (Sheppard et. al. 1986), and draws a great deal of public admiration and gratitude which drives firefighters to continue serving (Polakoff, 1976). Guidotti and Clough (1992) identified the complexity of hazards that firefighters face and categorised them into physical, thermal and ergonomic, chemical and psychological.

Although the physical hazards of firefighting are instantly recognisable, the psychological hazards require consideration. Studies by Frye and Stockton (1982) and Milmlincer and Solomon (1988) recognised that posttraumatic stress in firefighters was mainly due to a feeling of lack of control over traumatic events. This was substantiated by Bryant and Harvey (1996) who undertook a survey of volunteer firefighters in NSW, where they were required to describe periods of stress. The survey found that multiple and recent critical incidents instigate symptoms of posttraumatic stress, and most volunteers felt their safety had been threatened. Guidotti and Clough (1992) recognise firefighters as unique individuals who accept and are prepared for the personal risk they are exposed to.

**Primary Air Toxicants of Concern**

Apart from a few isolated studies, most research on the hazards of firefighting has been devoted to career firefighters (often involving structural firefighting), as opposed to volunteer rural firefighters who fight mostly grass fires and bushfires (Leonard et. al. 2007). Leonard et. al. 2007 recognised that the two work environments are vastly dissimilar in terms of the different combustion products and exposure profiles. Smoke is created from the chemical-physical process of combustion, where fuel properties (type and amount), fuel and soil moisture, temperature and ventilation influence the type and amount of combustion products which are present in smoke (De Vos, 2009; Beer and Meyer, 1999).

Through various studies over the last 20 years in Australia and overseas, approximately 200 distinct compounds of woodsmoke have been identified, including fine particles, carbon-monoxide, nitrogen, sulphur-based compounds, aldehydes, volatile organic compounds (VOCS), dioxins, organic acids, free radicals, and ozone (Dost, 1991; Malilay, 1999; Reisen and Brown, 2006; Ward, 1997, 1999). Most studies have occurred in the United States on wildland fire smoke, and due to differences in vegetation types, soils, combustion conditions and freighting methods, it is unclear whether the results of these studies are applicable to Australia (De Vos, 2009). Hinwood et. al. (2002) suggests that obtaining reliable and relevant data is complicated in real fire settings due to a variety of factors, such as changing weather conditions and difficulty accessing the fire ground.
Conducting burning of materials in chambers is a popular method of air sampling and exposure testing. Reisen et al. (2006b) conducted sampling on a variety of Australian bush and forest fuels under controlled conditions in a chamber. Air sampling identified the most toxic compounds to be respirable particles, volatile organic compounds (VOCs; benzene, toluene, xylene, phenol), carbon monoxide and aldehydes (acetaldehyde, acrolein, 3 furaldehyde). Respirable particles, carbon monoxide and acrolein were the compounds found to exceed the Exposure Standards for Atmospheric Contaminants in the Occupational Environment (ASCC, 1995). Further studies during prescribed and experimental burns using firefighter personal air samplers identified formaldehyde, benzene and toluene also to be of most concern (Reisen et al. 2006a). These findings were also consistent with earlier studies by Reinhardt and Ottmar (2000) and Sharkey (1997).

De Vos et al. (2009) carried out a similar study, but combined the two contexts of using a smoke chamber and sampling at controlled burns to draw a direct comparison. Concentrations were found to be lower during prescribed burns (discrepancies were attributable to confinement and limited airflow in the smoke chamber), although concentrations of air toxicants during controlled burns were still found to be concerning. All of these studies look at exposure levels in the form of 8 hour TWA (Time Weighted Average), which is the acceptable concentration for a normal 8 hour workday in a 40 hour work week, to which people can be exposed each day without any adverse health effects. The TWA for particulate matter is 10 mg/m³, which was found to be exceeded on three occasions in the De Vos et al. (2009) study.

Reisen and Brown (2006) assert that the pollutant most consistently exceeding air quality guidelines in North America, Australia and South-East-Asia is particulate matter. At least 240 million kilograms of particulate matter is estimated to be released into the atmosphere in Australia by fires each year (Johnston et al. 2010). Biomass is biological matter from living or recently living sources, mostly plant material, and has been found to contain proportionally high concentrations of particles from the smaller, more toxic size classes of particulates, which are known to be damaging to health (Johnston et al. 2010). This has also been demonstrated in studies epidemiological and pathophysiological where smoke from vegetation fires has a greater respiratory toxicity than similar levels of particulate matter derived from motor vehicle emissions in urban environments (Barregard et al. 2006; Chen et al. 2006; Morgan et al. 2009).

Factors Determining Levels of Exposure

Although respirable particles, carbon monoxide, acrolein, formaldehyde, benzene and toluene have been identified as the toxicants of most concern to firefighters during bushfires, the level of exposure to these toxicants can vary greatly. Guidotti and Clough (1992) identified that exposure depends on the fuel, the combustion characteristics of the fuel, measures taken to control the fire, the location of any victims within the fire, and the position of the firefighter in respect to the fire. To assist in their various studies and account for variability among samples, Reisen and Brown (2009) were able to effectively categorise the factors for determining exposure levels.

Firstly, work activity (Figure 1) varies greatly and is influenced by time within and proximity to smoky conditions. Secondly, fire type has an influence, as it was found that prescribed burns create the highest exposure, while slash burns (burning of slashed material) generally create the lowest level of exposure. Thirdly, the types of fuel (Figure 2) will determine the amount of toxicants in the air. In their study, Reisen and Brown (2009) identified that work activity contributed most significantly heightened exposure levels. They found that limits were most likely exceeded by activities such as suppression of spot fires, holding the fire line and patrolling the edge of the burn area.
Figure 1 – Personal exposure levels to CO (Carbon Monoxide), RP (Respirable Particle) and formaldehyde according to work activities. Source: Reisen and Brown, 2009, p 349.

Figure 2 – Personal exposure levels to bushfire air toxics according to fuel type (number of samples in brackets). Source: Reisen and Brown, 2009, p 351.
Other studies have also identified that the decisions by firefighters regarding the use of PPE (Personal Protective Equipment) such as respirators and breathing apparatus also determines exposure levels (Guidotti and Clough, 1992; Thomas, 1971). Most volunteers who join the Rural Fire Service are allocated with a ‘P2 disposable respirator’, which they are trained to don, along with all other PPE, while working in ‘smoke conditions’ (NSW RFS, 2004). The P2 disposable respirator is specifically designed to filter out smoke sized particles (Gibos, 2005) and is discussed in further detail below.

Relevant studies have found that firefighters often judge the level of their exposure by what they see, and a fire ground may appear safe, but continue to be hazardous. This is particularly the case during clean-up periods when the flames have been extinguished but toxicants are still present in the air (Guidotti and Clough, 1992). Reisen and Brown (2009) also note that bush firefighters who are most often volunteers of the Rural Fire Service, do not wear eye of respiratory protection while on the fire ground. Most often volunteer firefighters wear a dampened cloth or bandana as a means of protection from smoke, instead of using any form of respirator (Foote, 1994).

Acute and Chronic Health Effects

Prescribed/hazard reduction burns are fires that volunteer firefighters are most often involved. These burns are undertaken during mild weather conditions to reduce fuel loads and the intensity of unplanned burns (Guidotti and Clough, 1992). During the right conditions, these burns can occur quite regularly and are periods where the health effects of smoke toxication are most prominent. As previously outlined, identifying the respiratory health effects (particularly acute effects) of bushfire smoke is reasonably straightforward. As seen in Figure 3, smoke inhalation was the second highest cause of injury and compensation cases amongst NSW volunteer firefighters during 2009. However, effectively quantifying air toxicants during real fire conditions, as well as understanding the chronic health effects, has been scarcely studied and is recognised as an area for more research (Annemarie et. al. 2009; Reisen and Brown, 2006).

<table>
<thead>
<tr>
<th>NSW RFS VOLUNTEER</th>
</tr>
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<tbody>
<tr>
<td>Injuries reported 2009/10</td>
</tr>
<tr>
<td>Sprains and strains of joints and adjacent muscles</td>
</tr>
<tr>
<td>Poisoning and toxic effects of substances (smoke inhalation)</td>
</tr>
<tr>
<td>Open wound not involving traumatic amputation</td>
</tr>
<tr>
<td>Contusion with intact skin surface or crushing injury</td>
</tr>
<tr>
<td>Effects of weather, exposure &amp; other ext. causes (heat stress)</td>
</tr>
<tr>
<td>Superficial injury</td>
</tr>
<tr>
<td>Burns</td>
</tr>
<tr>
<td>Unable to ascertain</td>
</tr>
<tr>
<td>Foreign body in eye, ear, nose, respiratory or digestive systems</td>
</tr>
<tr>
<td>Fracture</td>
</tr>
<tr>
<td>Psychological disorders</td>
</tr>
<tr>
<td>Internal injury of chest, abdomen and pelvis</td>
</tr>
<tr>
<td>Intracranial injury</td>
</tr>
<tr>
<td>Eye disorders</td>
</tr>
<tr>
<td>Diseases and other non traumatic injury</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
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*Figure 3 – Number of injuries to NSW volunteer firefighters during 2009 based NSW Rural Fire Service Workers Compensation Statistics 2009/10. Source: NSW RFS Annual Report 2009/10, p. 139.*
Reisen and Brown (2009) have undertaken the most recent and thorough investigations of acute health effects of bushfire smoke. Carbon monoxide is rapidly absorbed into the body, causing elevated levels of Carboxyhemoglobin (COHb), which leads to cognitive impairment. It has also been found to cause dizziness and nausea, which all reduce work capacity and potentially hinder the safety of firefighters on the fire ground. Exposure to high concentrations of particulates during bushfires can cause difficulty breathing and airway reactivity, as well as lung dysfunction over longer periods. Aldehydes have been identified as a cause of respiratory irritation, which was found to be the primary symptom of discomfort after a shift in the study by Reisen and Brown (2009). These findings are well documented in various other studies over the last 20 years (Rothman et al., 1991; Materna et. al., 1992; Liu et. al., 1992; Bergstrom et al., 1997; Mustajbegovic et. al., 2001).

There have also been a few studies undertaken that suggest the respiratory effects on firefighters is not so significant (Betchley et. al. 1997; Slaughter et. al. 2004). In comparing Reisen and Brown (2009) and Slaughter et. al. (2004), the methodology behind these studies is very different. Reisen and Brown (2009) concentrated on exposure levels, comparing results with TWAs, while Slaughter et. al. (2004) concentrated on lung function, measuring the result of exposure with spirometry. Perhaps the limitation of the Slaughter et. al. (2004) study was that lung function will inevitably vary between individuals, depending on age, sex, smoking status and general health. The study Reisen and Brown (2009) could be considered pertinent as the results are not dependant on individual health and circumstance. Also, the Reisen and Brown (2009) study was undertaken in Australia, while the Slaughter et. al. (2004) study was undertaken in the United States, inexorably producing varying results, such as those discussed above.

Chia et. al. (1990) undertook a similar study as Slaughter et. al. (2004), looking at the ventilator function and airway reactivity of firefighters in a smoke chamber. The study found that eight of the ten firefighters exposed to smoke in the chamber experienced an increase in airway reactivity in the first hour after exposure. Six hours later, three were still reactive and all were non-reactive after 24 hours. Chia et. al. (1990) found that duration of exposure is the main contributing factor to changes in airway reactivity. Indeed, occasionally firefighters can be exposure to visible smoke for 16 hour periods over consecutive days, which significantly increases the risk of exceeding exposure limits for carbon monoxide, respirable particulates and aldehydes (Harrison et al. 1995).

This continuous exposure gives the body less chance to eliminate toxicants and is thought to increase chronic effects of exposure (Materna et al. 1992). Sharkey (1997) asserts that chronic exposure to smoke can have a number of negative health implications, such as increasing the risk of heart disease, chronic lung disease and cancer, and compromise the effectiveness of the immune system. However, it is generally agreed in the literature that there is not enough evidence to date regarding the chronic health effects of smoke exposure on firefighters, as much more research is required (De Vos et. al. 2009).

**Exposure Mitigation Measures**

Many of the studies discussed have investigated the exposure to and health effects of bushfire smoke on firefighters, but give little mention to mitigation measures that limit exposure to harmful toxicants. Reinhardt et. al. (2000) asserts that incident commanders and captains should implement effective management practices to minimise exposure to smoke. However, in emergency situations, bushfire fighters may have little opportunity to limit the amount of smoke they are exposed to (De Vos, 2006). Mitigation measures such as stepping back from flames and smoke or rotating through tasks may not be an option, particularly bushfire emergencies on the rural/urban interface where persons and property are being protected.
The studies have, however, significantly contributed to the understanding of the constituents of bushfire smoke, and therefore guided the requirements and optimum designs for personal protective items such as respirators (Guidotti and Clough, 1992). There is a great variety of respirators on the market today with varying degrees of technology, some protecting from particulate matter or toxic gases, and some are able to protect against both. Career firefighters and volunteers of Rural Fire Service brigades classified as ‘Village 2’ (predominantly interface structural fires) (NSW RFS, 2009, Service Standard 1.1.15) are equipped with Self-Contained Breathing Apparatus (SCBA), which are considered very effective in protecting against all air toxicants (Gibos, 2005). The NSW RFS ‘Service Standard 5.1.9 - Breathing Apparatus’ (2009, p. 2), states:

“BA [Breathing Apparatus] shall be used wherever firefighters may be subject to hazards, (such as toxic gases, hazardous dusts/fibres, hot atmospheres, smoke and oxygen deficiency) that may injure their respiratory system. Scenarios for its use may include interior structural firefighting, some vehicle incidents, and when assisting in some capacities at HAZMAT incidents.”

Essentially, these standards do not acknowledge what has been identified in recent literature as discussed above. Volunteer firefighters of all levels, including the other three classifications of bushfire brigades (‘Rural Remote’, ‘Rural’ and ‘Village 1’), are exposed to ‘hazards that may injure the respiratory system’ when interfacing bushfires. However, some designs of SCBA are not practical for bushfire situations because they are too bulky, restrict breathing and vision, decrease the ability to communication and are difficult to use over long periods of time and distance (Hall and Adams 1998; Budd et al. 1996). Respirators are more practical for bushfire fighters, and should be portable and convenient, comfortable for long periods in hot conditions and have minimal negative effect on air intake (Gibos, 2005).

De Vos et. al. (2007) has undertaken the most comprehensive study to date regarding the effectiveness of respirators and filters available for use during bushfire suppression. The study was undertaken in Western Australia during simulated conditions in a chamber (Figure 4) and prescribed burns (Figure 5) to test the effectiveness of three different types of filters; (1) Particulate (P) filter; (2) Particulate/organic vapour (P/OV) filter; and (3) Particulate/organic vapour formaldehyde (P/OV/F) filter. The study was based on air sampling and health outcomes of participants with a comprehensive survey. The P/OV/F filter performed far better than the P and P/OV filter group as far fewer participants reported increase in coughing, wheezing and shortness of breath during and after exposure. The Fire and Emergency Service Authority of Western Australia has now endorsed the use of the P/OV/F filter (3M™ 6075A1) for all career firefighters.
As stated above, although volunteer firefighters are provided with P2 disposable respirators, they are not commonly used during bushfire suppression or prescribed burns. Instead, a dampened cloth or bandana to cover the nose and mouth are most often used, which does not seem to be widely acknowledged in the literature. Foote (1994) is one of the few studies which looked at the performance of using cloth to protect against smoke toxicants, and compared the performance of a respirator (with an activated carbon cartridge and electrostatic pre-filter) with a cotton bandana.

The study was undertaken in the United States using Japanese Black Pine Needle common to the area, which was burnt in a chamber. Foote (1994) acknowledges that undertaking this study in a chamber creates the ‘worst case’ conditions and results are still valid, however, the fuel used would not be applicable to Australian conditions. Regardless of this, the study found that neither methods of protection were particularly effective and that the bandana was only partially effective at collecting smoke particles and completely ineffective at filtering toxic gases.

**Conclusions**

As was the aim of this paper, a comprehensive review of the relevant literature has identified that volunteer firefighters are exposed smoke that contains unhealthy levels of respirable particles, carbon monoxide, acrolein, formaldehyde, benzene and toluene. A variety of factors such as work activity on the fire ground, fire type and fuel type significantly influence the level of exposure experienced by firefighters. Many studies have found that acute symptoms of exposure include dizziness, nausea, difficulty breathing, lung dysfunction and cognitive impairment, but that the long term effects of chronic exposure are not well known and require further research.

It can be deduced from the above literature review that volunteer firefighters are not taking stringent enough measures to protect themselves from the toxic substances known to be present in bushfire smoke. Although, the responsibility of this cannot be given to individuals alone. Many of the studies outlined here were undertaken through the Bushfire Cooperative Research Centre (Bushfire CRC), established under the Commonwealth Government’s Cooperative Research Centres Program. The Centre is moving towards developing a much greater understanding of bushfires in Australia and involves eight Universities, the CSIRO, the BOM, Emergency Management Australia and State fire and land management agencies.

It is recommended that the Rural Fires Services of each State and Territory use the recent literature to become better informed and investigate opportunities to provide volunteer firefighters with respirators or masks that will protect them against all air toxicants they are exposed to. This should include volunteer firefighters who are members of brigades of all classifications. It is also recommended that efforts are made to instil a cultural and mind-set change among volunteer firefighters to appreciate resources available to protect them, which could include with more specific training and raising awareness of the risks.

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New South Wales Rural Fire Service (NSW RFS), (2009), Service Standard 1.1.15 - Service Delivery Model, Version 3.0, p. 4

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