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WILDLAND SMOKE EXPOSURE VALUES AND EXHALED BREATH INDICATORS IN FIREFIGHTERS

Ana Isabel Miranda[1], Vera Martins[1], Pedro Cascão[1], Jorge Humberto Amorim[1], Joana Valente[1], Carlos Borrego[1], António Jorge Ferreira[2], Carlos Robalo Cordeiro[2], Domingos Xavier Viegas[3], Roger Ottmar[4]

[1]CESAM & Department of Environment and Planning, University of Aveiro, Aveiro, Portugal
[2]Centre of Pulmonology of Coimbra University Medical School, Coimbra, Portugal
[3]Association for the Development of Industrial Aerodynamics, University of Coimbra, Coimbra, Portugal
[4]Pacific Wildland Fire Sciences Laboratory, U.S. Forest Service Pacific Northwest, Research Station, Seattle, Washington, USA

Smoke from forest fires contains significant amounts of gaseous and particulate pollutants. Firefighters exposed to wildland fire smoke can suffer from several acute and chronic adverse health effects. Consequently, exposure data are of vital importance for the establishment of cause/effect relationships between exposure to smoke and firefighter health effects. The aims of this study were to (1) characterize the relationship between wildland smoke exposure and medical parameters and (2) identify health effects pertinent to wildland forest fire smoke exposure. In this study, firefighter exposure levels of carbon monoxide (CO), nitrogen dioxide (NO_2), and volatile organic compounds (VOC) were measured in wildfires during three fire seasons in Portugal. Personal monitoring devices were used to measure exposure. Firefighters were also tested for exhaled nitric oxide (eNO) and CO before and after their firefighting activities. Data indicated that exposure levels during firefighting activities were beyond limits recommended by the Occupational Exposure Standard (OES) values. Medical tests conducted on the firefighters also indicated a considerable effect on measured medical parameters, with a significant increase in CO and decrease in NO in exhaled air of majority of the firefighters.

Wildland firefighters are exposed to many hazards, including burns, heat stress, tripping and falling hazards, accidents with hand and power tools, being struck by falling rocks and trees, and exposure to air toxics due to smoke inhalation. Many experienced firefighting personnel consider the air toxics to be only an inconvenience that occasionally produces acute eye and respiratory irritation, nausea, and headache (Reinhardt and Ottmar 2000). Other investigations express concern regarding chronic health impacts, especially cancer, from years of exposure (Austin et al. 2001; Golka and Weistenhofer 2008) or when large-scale fires occur in terrain and atmospheric conditions that force firefighters to work for many days in smoky conditions (Reinhardt et al. 2000).

Smoke from forest fires contains significant amounts of pollutants such as carbon monoxide (CO), particulate matter (PM), nitro-

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Address correspondence to Ana Isabel Miranda, CESAM & Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal. E-mail: miranda@ua.pt

gen dioxide (NO_2), volatile organic compounds (VOC), and other chemical compounds (Golka and Weistenhofer 2008). Carbon monoxide is a colorless, tasteless, odorless, and nonirritating gas formed when carbon in fuel is not burned completely, and it produces lethality. Carbon monoxide is present in all fire environments and has been described as one of the most common and serious acute hazards for firefighters (Austin et al. 1997; Treitman et al. 1980). Nitrogen dioxide is an oxidant gas that is produced by combustion processes. Both clinical data and results from the exposure of animals under controlled conditions demonstrated that NO_2 is a powerful pulmonary toxin, inducing both tissue necrosis and chronic inflammation (Morrow 1984; Sandstrom et al. 1990). Particulate matter (PM) is abundantly produced during wildland fire, is highly visible, affects ambient air quality, and exerts various adverse health effects depending on its size and chemical composition.

Inhalation is the predominant route of exposure during forest fires, and when particles are in the ambient air, there is a significant likelihood that firefighters will inhale them. It is difficult to determine the adverse health effects attributed to PM in smoke, as the damaging properties of the particles depend not only on the chemical and toxic characteristics but also on their size, shape, and density (Dost 1991; Naeher et al. 2007; Schwela 2001).

Currently there is a growing awareness that smoke produced during forest fires exposes individuals and populations to hazardous concentrations of air pollutants. However, the current state of knowledge regarding the potential health impacts on firefighting personnel is limited, in particular within Europe. The most extensive measurements of smoke exposure among wildland firefighters were conducted in the United States and Australia (Materna et al. 1993; McMahon and Bush 1992; Reinhardt and Ottmar 2000; 2004; Reinhardt et al. 2000; Reisen and Brown 2009). From these field studies it was concluded that firefighters may be exposed to significant levels of CO and respiratory irritants, including formaldehyde, acrolein, and respirable particles (Reinhardt and Ottmar 2000; 2004). Consequently, adverse health effects occur that are acute and instantaneous, and include eye and respiratory irritation, shortness of breath, headaches, dizziness and nausea lasting for hours, and mild impairment of lung function for hours to days (Reinhardt et al. 2000). In addition, chronic health effects such as impaired respiratory function, increased risk of cancer, and cardiovascular disease may be produced by these pollutants (Golka and Weistenhofer 2008; Rothman et al. 1991). Special concern is raised by exposure to respirable particles and potentially toxic compounds adsorbed to them, including polycyclic aromatic hydrocarbons (PAH) and semivolatile organic compounds, some of which may be carcinogenic (Austin et al. 2001; IARC 2010; Le Masters et al. 2006; Youakim 2006), as well as aldehydes, compounds that are classified as probable human carcinogens. The overall evaluation by the International Agency for Research on Cancer (IARC) is that occupational exposure as a firefighter is possibly carcinogenic to humans (IARC 2010b). There are a number of factors that affect the impact of smoke on health, including concentration of air pollutants within the breathing zone of the firefighter, exposure duration, exertion levels, and individual susceptibility such as preexisting lung or heart diseases (Reisen and Brown 2009).

There is a considerable lack of data on firefighters exposed to smoke in Europe. These data are needed for the establishment of cause/effect relationships between exposure to smoke and firefighter health effects. The composition of smoke depends on the type of vegetation consumed, the efficiency of combustion, fuel moisture content, temperature of the fire, and wind conditions (Reisen and Brown 2009). Consequently, exposure results from the U.S. and Australian experiments may not be applicable to European wildland firefighters due to differences in vegetation, fire conditions, and firefighting operations. Further, a major factor influencing exposure is the type of work activities that firefighters carry out and their position relative to the fire during those activities. Therefore it is crucial to (1) assess exposure at the individual level in Europe, (2) determine whether this exposure might result in health damage, and (3) identify the primary factors influencing the exposure of wildland firefighters. Miranda et al. (2005) presented the first smoke measurements in experimental fires in Europe. Passive sampling devices were used to monitor NO_2 exposure levels. Measurements showed high exposure values affecting firefighters during experimental burns. Recently, Miranda et al. (2010) used portable "in continuum" measuring devices to monitor a group of firefighters' individual exposures to toxic gases and particles during experimental field fires. Measured levels were high, exceeding the Occupational Exposure Standard (OES) limits, in particular for peak limit thresholds. The aims of this study were to (1) further characterize the relationship between wildland smoke exposure and medical parameters during real firefighting situations, and (2) identify health effects pertinent to wildland forest fire smoke exposure.

METHODOLOGY AND EQUIPMENT

Four fire brigades (3 volunteer and 1 professional) were contacted and 40 firefighters were selected to be involved in this study. The fire brigades were from different central districts in Portugal, including Leiria, Coimbra, and Aveiro. More than one fire brigade and district were selected to increase the chances of measuring exposure of firefighters to smoke during a wildland fire. The study was conducted during the 2008, 2009, and 2010 fire seasons (May–October).

Smoke Exposure

Taking into account the available human resources, firefighter age, type of work, years of experience as a firefighter, respiratory diseases, and smoking habits, 10 firefighters from 4 brigades were chosen to be monitored for their individual exposure to smoke emitted during wildfires. From this group of firefighters, seven were volunteers and three were professional. The 10 firefighters were monitored during each fire season. The number of firefighters selected for the study was limited by the number of personal monitoring devices. The firefighters were equipped with a personal device for CO monitoring, and another for VOC and NO_2. The selection of monitoring equipment was based on toughness, weight, possibility of continuous data acquisition, and ease of operation. Table 1 summarizes the instruments specifications. More information regarding the monitoring devices is found in Miranda et al. (2010). Figure 1 shows firefighters with the exposure monitoring equipment and using a respiratory bandana.

The 10 selected firefighters were instructed on how to use the equipment and how to record basic fire data information, including beginning and end of firefighter exposure period (date; hours), fire location (district; municipality, submunicipality), type of fire, and dimension of fire (small fire [less than 1 ha] or large fire [more than 100 ha]). When the selected firefighters were sent to a wildland fire during the 2008, 2009, and 2010 fire seasons, the subjects carried the exposure monitoring equipment. When returning the individuals downloaded the exposure data and filled out the fire occurrence form (fire report).

TABLE 1. Characteristics of the Exposure Equipment

			Characteristics	
Pollutant	Type of data	Equipment	Range	Resolution
VOC	Continuous measurement: 5 s interval	GasAlertMicro 5 PID from BW Technologies	0–1000 ppm	1 ppm
NO_2			0–99.9 ppm	0.1 ppm
CO	Continuous measurement: 5 s interval	GasAlertextreme from BW Technologies	0–1000 ppm	1 ppm

FIGURE 1. Firefighters with the exposure monitoring equipment (color figure available online).

Table 2 presents the available information on exposure duration, geographic location, and area burned for all the monitored fire occurrences (52 in total). Data presented on location and area burned were provided by the fire brigade reports or by the national fire inventory (Portuguese National Forest Authority 2010) developed by the National Forest Authority. For some wildfires the data were not available (n.a.). The data available for 2010 were limited, resulting in only one occurrence where data was collected.

During the 2008, 2009, and 2010 fire seasons, the firefighters were involved with 11, 13, and 28 wildland fire operations. The burned areas were generally smaller than 1 ha. The wildfires of July 30, 2008, August 1, 2008, and July 26, 2010, were the exceptions, with 80, 3, and 5 ha, respectively. These fire seasons were mild and the amount of burned area was small in central Portugal. The exposure periods were always shorter than 8 h, except on July 26, 2010, for firefighter 23, with an exposure period of 11 h. With the exception of this particular situation, in general these periods varied between 15 min (firefighter 7, 01/09/2008) and 7.5 h (firefighter 23, 27/07/2010).

The vegetation burned by wildfires is characterized by resinous (*Pinus pinaster, Pinus pinea*), decidous (*Quercus spp., Castanca sativa*), and eucalyptus species (*Eucalyptus* spp.), and shrubs, namely, *Erica umbellata*, *Erica australis*, and *Chamaespartium tridentatum*.

Medical Tests

The studied sample initially encompassed 38 healthy firefighters. During the 3 years of study, 3 firefighters left their corporations and the final tally of sample individuals was 35, with a mean age of 29.92 yr (standard deviation of 7.065) and a median height of 173 cm (standard deviation of 6.2 cm). The median of years spent in the firefighting force was 9.7, with a standard deviation of 5.6 yr. All firefighters were healthy and were clinically examined by a team of pulmonologists to determine respiratory and general health status. None had previous history of respiratory pathology.

The respiratory function of the 35 firefighters sample was evaluated prior to any exposure, during April 2008, and at the end of the 2010 fire season. Data were collected using the calibrated MicroMedical Spirometer, model MicroLab ML3500. Evaluation was completed following standard procedures and international norms (ATS/ERS 2005). The following spirometry parameters were measured:

- Forced expiratory volume in 1 s (FEV1).
- Forced vital capacity (FVC).
- Ratio FEV1/FVC (Tiffeneau Index, Tiff.).
- Peak expiratory flow (PEF).
- Flow at 50% of FVC (F50).
- Flow at 75% of FVC (F25).
- Midexpiratory flow rate (MEF).

Firefighters were examined, before and after fire-fighting, regarding their NO (eNO), CO, and percent carboxyhemoglobin (COHb) in the exhaled breath for the 2009 and 2010 fire seasons. In case of a wildland fire occurrence, one or two elements of the medical team were contacted by phone by the fire department when firefighters were to be deployed to an incident. All measurements were collected during the first 1.5 h following the work shift. All measurements were acquired in a smoke-free environment,

TABLE 2. Wildland Fires Characteristics and Exposure Durations for 2008, 2009, and 2010 Fire Seasons

Firefighter	Date	Firefighter exposure period			Location (region)	Burnt area (ha)	
		Beginning	End	Duration		Forest	Shrubs
3	01/08/2008	00:42	01:15	0:33	Coimbra	1.5	1.5
4	16/07/2008	17:35	22:12	4:37	Coimbra	0	0.08
	02/08/2008	15:49	17:51	2:02	Coimbra	0	0.2
5	17/08/2008	12:54	13:53	0:59	Coimbra	0.5	0
	04/10/2008	14:59	17:37	2:38	Coimbra	0	0.02
6	30/07/2008	17:49	20:32	2:43	Coimbra	80	0
	19/08/2008	17:08	17:57	0:49	Coimbra	0	0.02
	23/08/2008	17:15	17:32	0:17	Coimbra	0	0.02
7	31/07/2008	20:32	21:50	1:18	Coimbra	0.1	0
	01/09/2008	15:07	15:22	0:15	Coimbra	0	0.01
9	18/07/2008	16:13	19:22	3:09	Aveiro	1	0
11	05/08/2009	08:59	10:12	1:13	Leiria	n.a.	n.a.
14	28/07/2009	15:43	17:13	1:30	Coimbra	0.2	0
	01/09/2009	21:33	01:41	4:08	Coimbra	0	n.a
	05/09/2009	12:20	18:51	6:31	Coimbra	0.6	0
15	15/07/2009	15:26	16:38	1:12	Coimbra	n.a.	n.a.
	17/09/2009	10:23	10:45	0:22	Coimbra	n.a.	n.a.
17	08/09/2009	15:45	17:17	1:28	Coimbra	0.5	n.a.
	12/09/2009	17:32	18:13	0:41	Coimbra	0	0.015
	20/09/2009	10:55	11:25	0:30	Coimbra	n.a.	n.a.
18	13/08/2009	16:09	16:35	0:26	Aveiro	0	0.03
	15/08/2009	17:10	17:44	0:34	Aveiro	n.a.	n.a.
	27/09/2009	14:47	15:06	0:19	Aveiro	0	0.015
	30/09/2009	06:58	10:51	3:53	Aveiro	0	0.5
22	07/08/2010	14:05	17:10	3:05	Leiria	n.a.	n.a.
23	26/07/2010	13:00	24:00	11:00	Coimbra	n.a.	n.a.
	27/07/2010	16:30	24:00	7:30	Coimbra	n.a.	n.a.
	04/08/2010	13:54	17:43	3:49	Coimbra	n.a.	n.a.
	05/08/2010	17:20	19:40	1:40	Coimbra	n.a.	n.a.
	09/08/2010	14:53	16:13	1:20	Coimbra	n.a.	n.a
	10/08/2010	17:19	18:30	1:11	Coimbra	n.a	n.a
	11/08/2010	17:34	20:35	3:01	Coimbra	n.a	n.a
	30/08/2010	16:37	20:25	3:48	Coimbra	n.a.	n.a.
	03/10/2010	03:49	09:00	5:10	Coimbra	n.a.	n.a.
24	24/07/2010	16:47	20:00	3:13	Coimbra	n.a.	n.a.
	26/07/2010	17:25	24:15	5:50	Coimbra	n.a.	n.a.
	07/08/2010	22:57	23:47	0:50	Coimbra	n.a.	n.a.
	11/08/2010	17:34	20:35	3:01	Coimbra	n.a.	n.a.
25	26/07/2010	18:42	20:42	2:00	Coimbra	5	0
	17/09/2010	22:32	23:28	0:56	Coimbra	n.a.	n.a.
28	27/07/2010	14:44	18:30	3:46	Aveiro	n.a.	n.a.
	28/07/2010	12:48	15:48	3:00	Aveiro	n.a.	n.a.
	29/07/2010	15:25	23:24	7:59	Aveiro	n.a.	n.a.
	03/08/2010	13:26	14:44	1:18	Aveiro	n.a.	n.a.
	04/08/2010	14:36	23:56	9:20	Aveiro	n.a.	n.a.
29	25/05/2010	11:04	18:04	7:00	Aveiro	n.a.	n.a.
	31/05/2010	15:53	17:52	1:59	Aveiro	n.a.	n.a.
	07/06/2010	10:40	12:57	2:17	Aveiro	n.a.	n.a.
	10/06/2010	13:34	15:14	1:40	Aveiro	n.a.	n.a.
30	19/07/2010	15:33	16:08	0:35	Aveiro	n.a.	n.a.
	21/07/2010	17:55	23:35	5:40	Aveiro	n.a.	n.a.
	26/07/2010	11:25	23:59	12:34	Aveiro	n.a.	n.a.

Note. References 1 to 10 correspond to fire season 2008 firefighters, 11 to 20 to 2009, and >20 to 2010; n.a., not available.

away from the forest fire area. The eNO was measured using Nioxmino equipment from AEROCRINE. In 2008 the MICRO CO/Smoke-check from Micromedical was used to measure alveolar CO. This equipment allows monitoring four classes of values. In 2009 and 2010 wildfires the Micro CO (Micromedical Viasys) was used instead of the previous equipment and therefore quantitative measures of CO were possible, as well as measurement of COHb.

RESULTS AND DISCUSSION

Exposure Results

Exposure results were compared to Occupational Exposure Standards (OES) defined for different air pollutants. According to the American Conference of Governmental Industrial Hygienists (ACGHI), OES are presented as: (i) threshold limit value (TLV) of the time-weighted average (TWA); (ii) TLV of the short-term exposure limit (STEL); and (iii) peak limit. The TWA is calculated over a normal 8-h working day and a 5-d working week. The TLV-STEL corresponds to a 15-min TWA exposure that should not be exceeded at any time during a workday, even if the 8-h TWA is under the TLV. The TLV-STEL is the higher concentration to which it is believed that workers may be exposed continuously for a short period of time without suffering effects. In Portugal, OES values for occupational activities are established by Occupational Health and Safety (OHS) regulations through the Portuguese Regulation NP 1796:2007. In the case of CO and NO_2, TLV-TWA values are established by the NP 1796:2007. Table 3 presents the OES values for the different air pollutants analyzed under this study.

For CO TLV-STEL and peak limit, the exposure limits set by the Australian Safety and Compensation Council (1995) were considered. Due to the lack of a NO_2 peak limit in the Portuguese OHS regulation, a value of 20 ppm was considered. This value is proposed by the National Institute for Occupational Safety and Health (NIOSH), taking into consideration recommendations derived from acute inhalation toxicity data (Patty 1963), which indicate this limit value as immediately dangerous to life or health (IDHL). Table 4 shows the TWA and the number of exceedances of the peak limit (and the maximal value), and indicates whether the STEL was fulfilled or not, for firefighters exposed in the wildfires of 2008, 2009, and 2010. It is worth mentioning that the TWA values were calculated based on exposure time and not on 8-h periods. In bold are the situations in which the limit values are exceeded or criteria not fulfilled. Exposure data are missing (n.d.) for some of the firefighters due to technical issues.

Although most firefighters use a bandana for respiratory protection, the protection offered by this filtering device is limited. According to Reh et al. (1994) the pore size of this type of bandanas is approximately 200 μm × 200 μm, roughly 500- to 2000-fold larger than the smaller smoke particles (0.100–0.400 μm); consequently, gases and fine particulate matter pass through the fabric.

There were several exceedances to the TWA, STEL, and peak values for CO. The CO peak limit concentration was exceeded 40% of the time for the 52 reported occurrences and

TABLE 3. OES Limit Values for Different Air Pollutants Contained in Biomass Burning Smoke

Air pollutant	TLV-TWA	Reference	TLV-STEL	Reference	Peak limit	Reference
CO	25 ppm	NP 1796:2007	200 ppm	Australian legislation	400 ppm	Australian legislation
NO_2	3 ppm		5 ppm	NP 1796:2007	20 ppm	NIOSH
VOC	n.a.		n.a.	n.a.	n.a.	n.a.

Note. For some VOC these values are not available (n.a.) in national or international regulations.

TABLE 4. TWA, Number of Peak (n), Peak Values, and TLV-STEL Fulfillment for CO, NO_2, and VOC for Firefighters Exposed to Smoke During Wildland Fires

Firefighter	Date	Parameter	CO (ppm)	NO_2 (ppm)	VOC (ppm)
3	01/08/2008	TWA	5.8	1.9	2.3
		n (Peak value)	0 (143)	0 (3)	5
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
4	16/07/2008	TWA	11.6	0.05	1.2
		n (Peak value)	**3 (544)**	0 (4)	25
		Fulfilment of TLV-STEL criteria	**No**	Yes	n.a.
	02/08/2008	TWA	22.8	0.17	0.9
		n (Peak value)	**6 (684)**	0 (6)	21
		Fulfilment of TLV-STEL criteria	**No**	Yes	n.a.
5	17/08/2008	TWA	12.6	1	0.8
		n (Peak value)	0 (367)	0 (3)	34
		Fulfilment of TLV-STEL criteria	**No**	Yes	n.a.
	04/10/2008	TWA	**30.5**	0.7	1.2
		n (Peak value)	**2 (422)**	0 (5)	20
		Fulfilment of TLV-STEL criteria	**No**	Yes	n.a.
6	30/07/2008	TWA	8.1	n.d.	n.d.
		n (Peak value)	0 (155)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	19/08/2008	TWA	**53.4**	n.d.	0.8
		n (Peak value)	**1 (410)**	n.d.	12
		Fulfilment of TLV-STEL criteria	**No**	n.d.	n.a.
	23/08/2008	TWA	1.8	n.d.	n.d.
		n (Peak value)	0 (93)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
7	31/07/2008	TWA	2.8	1.1	0.04
		n (Peak value)	0 (128)	0 (5)	5
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	01/09/2008	TWA	8.8	n.d.	n.d.
		n (Peak value)	0 (78)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
9	18/07/2008	TWA	n.d.	2.5	0.2
		n (Peak value)	n.d.	0 (7)	11
		Fulfilment of TLV-STEL criteria	n.d.	Yes	n.a.
11	05/08/2009	TWA	12.6	n.d.	n.d.
		n (Peak value)	0 (170)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
14	28/07/2009	TWA	7.9	0.1	0.2
		n (Peak value)	**1 (413)**	0 (0.9)	42
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	01/09/2009	TWA	3.1	0.1	n.d.
		n (Peak value)	0 (89)	0 (3.7)	n.d.
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	05/09/2009	TWA	4.6	0.4	n.d.
		n (Peak value)	0 (64)	0 (7)	n.d.
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
15	15/07/2009	TWA	8.4	0.06	n.d.
		n (Peak value)	0 (179)	0 (1.8)	n.d.
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	17/09/2009	TWA	1.4	0.1	n.d.
		n (Peak value)	0 (72)	0 (2.8)	n.d.
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
17	08/09/2009	TWA	23.9	1.1	1.4
		n (Peak value)	**7 (597)**	0 (9)	14
		Fulfilment of TLV-STEL criteria	**No**	Yes	n.a.
	12/09/2009	TWA	2.8	n.d.	n.d.
		n (Peak value)	0 (62)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	20/09/2009	TWA	5.1	n.d.	n.d.
		n (Peak value)	**1 (893)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.

(*Continued*)

TABLE 4. (Continued)

Firefighter	Date	Parameter	CO (ppm)	NO_2 (ppm)	VOC (ppm)
18	13/08/2009	TWA	23.8	n.d.	n.d.
		n (Peak value)	**1 (405)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	**No**	n.d.	n.a.
	15/08/2009	TWA	13.7	n.d.	n.d.
		n (Peak value)	0 (182)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	27/09/2009	TWA	7.4	n.d.	n.d.
		n (Peak value)	0 (182)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	30/09/2009	TWA	4.3	n.d.	n.d.
		n (Peak value)	0 (201)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
22	07/08/2010	TWA	**25**	0.01	1.1
		n (Peak value)	0 (253)	0 (2.5)	6
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
23	26/07/2010	TWA	**34**	0.03	1.7
		n (Peak value)	**15 (817)**	0 (1.8)	12
		Fulfilment of TLV-STEL criteria	**No**	Yes	n.a.
	27/07/2010	TWA	11	n.d.	n.d.
		n (Peak value)	**10 (1,000)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	04/08/2010	TWA	17	n.d.	n.d.
		n (Peak value)	**1 (704)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	05/08/2010	TWA	23	0.01	0.15
		n (Peak value)	**8 (708)**	0 (2.9)	4
		Fulfilment of TLV-STEL criteria	**No**	Yes	n.a.
	09/08/2010	TWA	19	n.d.	n.d.
		n (Peak value)	0 (241)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.a.	n.a.
	10/08/2010	TWA	**38**	1.1	2.1
		n (Peak value)	**4 (671)**	0 (2.3)	6
		Fulfilment of TLV-STEL criteria	**No**	Yes	n.a.
	11/08/2010	TWA	17	0.05	0.2
		n (Peak value)	0 (283)	0 (1.6)	8
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a
	30/08/2010	TWA	13	0.01	1.8
		n (Peak value)	0 (276)	0 (1.5)	15
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	03/10/2010	TWA	23	n.d.	n.d.
		n (Peak value)	**16 (1,000)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
24	24/07/2010	TWA	11	n.d.	n.d.
		n (Peak value)	0 (108)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	26/07/2010	TWA	11	n.d.	n.d.
		n (Peak value)	**7 (991)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	07/08/2010	TWA	24	0.1	0.2
		n (Peak value)	0 (173)	(0.9)	40
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	11/08/2010	TWA	5	n.d.	n.d.
		n (Peak value)	0 (153)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
25	26/07/2010	TWA	1	0.04	0.16
		n (Peak value)	0 (30)	2	2
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	17/09/2010	TWA	18	0.24	1.1
		n (Peak value)	0 (214)	0 (5)	5
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.

(Continued)

TABLE 4. (Continued)

Firefighter	Date	Parameter	CO (ppm)	NO_2 (ppm)	VOC (ppm)
28	27/07/2010	TWA	21	n.d.	n.d.
		n (Peak value)	0 (294)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	28/07/2010	TWA	11	n.d.	n.d.
		n (Peak value)	0 (174)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	29/07/2010	TWA	11	n.d.	n.d.
		n (Peak value)	**6 (1,000)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	03/08/2010	TWA	21	n.d.	n.d.
		n (Peak value)	**6 (599)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	04/08/2010	TWA	15	n.d.	n.d.
		n (Peak value)	0 (341)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
29	25/05/2010	TWA	**29**	n.d.	n.d.
		n (Peak value)	**11 (1,000)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	**No**	n.d.	n.a.
	31/05/2010	TWA	17	n.d.	n.d.
		n (Peak value)	**1 (446)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	07/06/2010	TWA	7	n.d.	n.d.
		n (Peak value)	0 (111)	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
	10/06/2010	TWA	16	n.d.	n.d.
		n (Peak value)	**3 (443)**	n.d.	n.d.
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.
30	19/07/2010	TWA	16	0.3	0.5
		n (Peak value)	**2 (578)**	0.9	5
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	21/07/2010	TWA	19	0.01	0.6
		n (Peak value)	0 (360)	5.1	64
		Fulfilment of TLV-STEL criteria	Yes	Yes	n.a.
	26/07/2010	TWA	9	n.d.	0.1
		n (Peak value)	0 (364)	n.d.	25
		Fulfilment of TLV-STEL criteria	Yes	n.d.	n.a.

Note. References 1 to 10 correspond to fire season 2008 firefighters, 11 to 20 to 2009, and >20 to 2010; n, number of exceedances to the peak limit; n.a., not applicable - there is no limit value to compare; n.d., no data; in bold, limit values are exceeded or criteria not fulfilled.

for 67% of them more than once. The highest CO peak limit observed was 1,000 ppm. The STEL also exceeded the TLV for nearly 19% of the monitored situations. The exceedence of the STEL is in agreement with studies of Reinhardt and Ottmar (2004), Reisen and Brown (2009), and De Vos et al. (2009).

No exceedances of the TWA, STEL, or peak limits for NO_2 were noted.

There is no national or international legislation that sets TLV-TWA, TLV-STEL, or peak limits for the total VOC but only for the specific compounds. Thus, it was not possible to compare the monitored concentrations with any limit value.

As an example of the time evolution of the monitored concentrations, Figure 2 shows the CO levels for a specific firefighter when combating a specific fire occurrence. The OES limit values defined by the National and International regulations are also indicated (according to Table 3) for a better understanding of the attained exposure values. Data represented in Figure 2 show that the acquired instantaneous concentration values were often high. The CO peak limit was

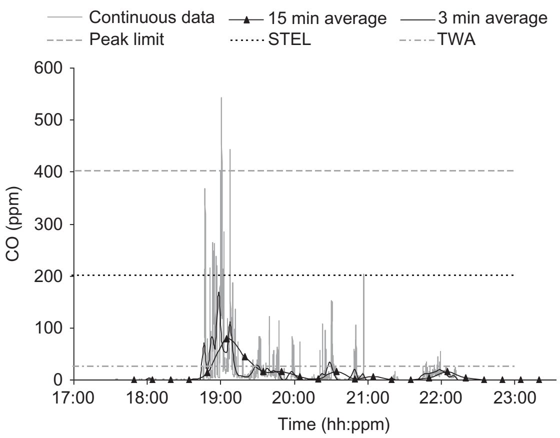

FIGURE 2. Measured CO concentrations for a specific firefighter during a wildfire.

exceeded three times. Similar results were also obtained from other wildfires and for field experiments (Miranda et al. 2010).

Data show the magnitude of the exposure peaks that occurred during regular firefighting operations. De Vos et al. (2009) found that a healthy individual starts experiencing mild headaches after 2–3 h of exposure to CO at 232,840 $\mu g/m^3$ (200 ppm). At 465,680 $\mu g/m^3$ (400 ppm) exposure, the individual experiences nausea, headache, and dizziness after 1 or 2 h. With an exposure concentration of 931,360 $\mu g/m^3$ (800 ppm) or higher, confusion, ataxia, coma, and seizures might develop. At high work levels, such as in the case of firefighting, these symptoms may be expected to appear at lower exposure levels (De Vos et al. 2009). Therefore, knowledge of CO concentration peaks to which firefighters are exposed is crucial.

The presented exposure concentration results are not directly proportional to the area burned. For instance, firefighter 6 was involved in the July 30, 2008, fire that burned 80 ha of forest. His measured exposure values were low; for CO the TWA was 8.1 ppm with a peak exposure of 155 ppm. In contrast, firefighter 4 worked in the August 2, 2008, fire within a smaller burned area (0.2 ha) of mainly shrub. His CO exposure values were higher (the TWA reached 22.8 ppm) and peak and STEL exceedances were recorded. The exposure period for both firefighters was similar, 2h43 and 2h02, respectively. Exposure values depend especially on firefighter position relating to the fire line and task in the crew. Sometimes in small forest fires firefighters are more exposed than in larger fires, because usually the strategy for large fires is to stay back and contain them rather than making a direct attack, as is the usual strategy for smaller fires.

Medical Parameters Results

The respiratory function of the 35 firefighters in April 2008 and at the end of the 2010 fire season was compared and results are presented in Table 5. Data demonstrated a statistically significant decrease of four spirometric parameters (FEV1, F25, F50, and MEF), indicating that firefighters experienced a reduction of respiratory function between the two evaluations. As an example of the eNO measurements before and after smoke exposures, Figure 3 illustrates the changes in the eNO, CO, and COHb values measured just before and after the exposure to smoke in 2010 wildland fires.

There was a significant decrease of eNO between the values measured before and after the exposure to smoke. This result is somewhat unexpected since a decrease on eNO indicates a reduction in airways inflammation. However, this may indicate an effect similar to exposure to cigarette smoke. Indeed, in current smokers Malinovschi et al. (2006) observed a decrease on eNO, probably related to the inhibition of nitric oxide synthetase. In previous studies regarding eNO and smoking habit, peak concentrations were significantly reduced in smokers compared to nonsmokers (Kharitonov et al. 1995), with a significant relationship between the measured values and amount of cigarette consumption. These findings suggest that smoke may inhibit the enzyme NO synthase. Endogenous NO plays an important role protecting the respiratory tract against infection, and counteracting bronchoconstriction, vasoconstriction, and platelet aggregation. This effect may contribute to increased risks of chronic respiratory and cardiovascular disease

TABLE 5. Statistical Comparison Between Spirometric Parameters Obtained in 2008 (Before the Fire Season) and 2010 (After the Fire Season)

		Average	n	Standard deviation	p
Pair 1	FEV1	103.49	35	12, 349	.028*
	FEV1 2010	101.83	35	10, 063	
Pair 2	CVF	101.26	35	12, 802	ns
	CVF 2010	100.83	35	11, 369	
Pair 3	PEF	96.09	35	13, 744	ns
	PEF 2010	97.57	35	13, 349	
Pair 4	Tiff	105.57	35	8, 624	ns
	Tiff 2010	104.34	35	6, 743	
Pair 5	F50	101.71	35	23, 130	.028+
	F50 2010	96.83	35	20, 024	
Pair 6	F25	93.80	35	35, 192	.005*
	F25 2010	82.11	35	22, 418	
Pair 7	MEF	95.74	35	24, 888	.009*
	MEF 2010	89.77	35	18, 130	

Note. Student's *t*-test for paired data. Asterisk indicates Wilcoxon test.

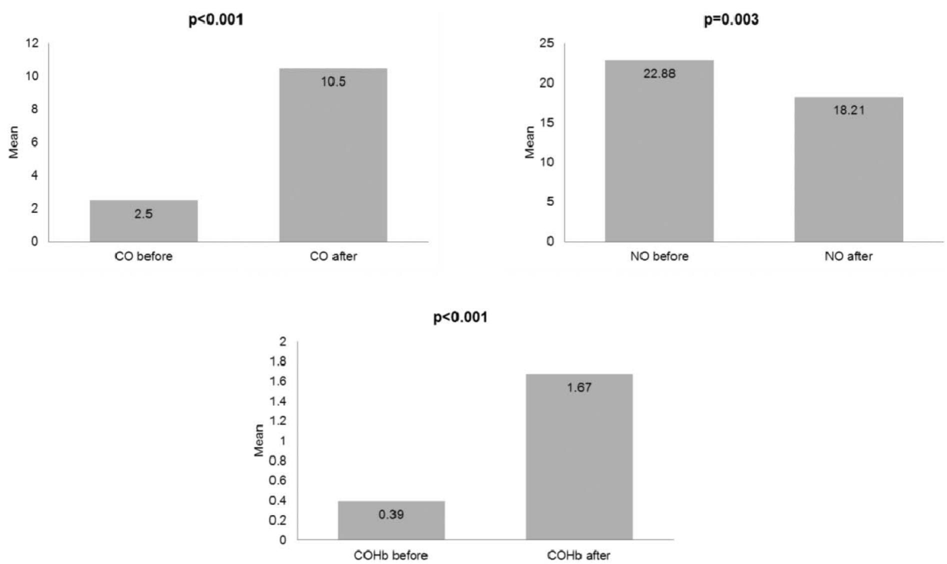

FIGURE 3. Exhaled NO (ppb), CO and COHb (ppm) values measured just before and after exposure to smoke in 2010 wildland fires.

in cigarette smokers. Whether similar findings on eNO represent a similar risk after inhalation of different types of smoke is a matter that needs further investigation.

There was a marked increase of exhaled CO and COHb after exposure to smoke, indicating that O_2 delivery to the body organs and tissues is significantly diminished after smoke exposure, as seen in Figure 3.

CONCLUSIONS

The amount and characteristics of noxious occupational exposures of forest firefighters are not widely recognized, as attention historically focused on risks of urban firefighting. This study indicates that forest firefighting exposed firefighters to very high concentrations of CO, and also high concentrations of NO_2 and VOC, with potential harmful effects on health, even in wildfires with small burn areas. A particular concern is the peak and short-term exposure to CO. When comparing experimental fires based on Miranda et al. (2010) results to wildland fires data, on average the results present the same order of magnitude for each pollutant analyzed, but higher values were observed in experimental fires. It is not easy to establish a direct relationship between smoke exposure and health respiratory indicators, but results point to an increase of exhaled CO when a higher exposure to CO occurs and a decrease of exhaled NO when the exposure to NO_2 is higher.

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