International Journal of Environmental Health Research

ISSN: 0960-3123 (Print) 1369-1619 (Online) Journal homepage: www.tandfonline.com/journals/cije20

Adverse eye effects of smoke exposure at prescribed burns in wildland firefighters

Sukanya Jaiswal, Blanka Golebiowski, Ha T Duong, Michele C. Madigan & Isabelle Jalbert

To cite this article: Sukanya Jaiswal, Blanka Golebiowski, Ha T Duong, Michele C. Madigan & Isabelle Jalbert (06 Jul 2025): Adverse eye effects of smoke exposure at prescribed burns in wildland firefighters, International Journal of Environmental Health Research, DOI: 10.1080/09603123.2025.2519764

To link to this article: https://doi.org/10.1080/09603123.2025.2519764

Published online: 06 Jul 2025.

INTERNATIONAL JOURNAL OF ENVIRONMENTAL HEALTH RESEARCH
https://doi.org/10.1080/09603123.2025.2519764

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

Adverse eye effects of smoke exposure at prescribed burns in wildland firefighters

Sukanya Jaiswal[a], Blanka Golebiowski[a], Ha T Duong[a], Michele C. Madigan[a,b] and Isabelle Jalbert[a]

[a]Faculty of Medicine & Health, UNSW Sydney, Sydney, NSW, Australia; [b]Save Sight Institute, University of Sydney, Sydney, NSW, Australia

ABSTRACT

Objective: Despite exposure to high concentrations of particulate matter (PM) and gases on the fire ground, little is known about the impact of wildfire smoke on the eye surface of wildland firefighters. This field study investigated the impact of smoke exposure at prescribed burns on the eye surface of Australian wildland firefighters.
Methods: Twenty-three firefighters (19–60 years, 78% male) were evaluated before and after four prescribed burns for eye symptoms and clinical signs of eye surface damage. Types of protective eyewear used were recorded and a subset of firefighters wore PM2.5 personal monitors.
Results: Symptoms of eye discomfort, dryness and foreign body sensation increased after the burns, along with epithelial staining scores, eye surface redness and palpebral conjunctival roughness. Tear film stability reduced after the burns. Group mean PM2.5 exposure during the burns ranged from 130 to 480 $\mu g/m^3$. All firefighters reported wearing sunglasses or goggles 40% to 100% of the time during the burns. Four firefighters (17%) wore no eye protection for 20% to 90% of the time.
Conclusion: Wildland firefighters experience increased eye irritation and display eye surface clinical changes consistent with eye surface damage. Evidence-based recommendations on how to prevent and manage eye surface complications in firefighters are urgently needed.

ARTICLE HISTORY
Received 25 April 2025
Accepted 10 June 2025

KEYWORDS
firefighters; wildfire smoke; eye

Introduction

Changes in atmospheric climate are increasing the frequency and severity of wildfires worldwide (Wuebbles et al. 2017). This increases the burden on wildland firefighters to not only manage these wildfires, but to also conduct prescribed burns which build containment lines and reduce vegetation available to burn in wildfires. As a result, wildland firefighters are exposed to particulate matter and gases at concentrations beyond those considered safe, based on the standards developed by the United States Fire Service (Navarro et al. 2021, Reisen et al. 2011).

Exposure to wildfire smoke in firefighters is strongly associated with adverse respiratory and cardiovascular health effects. Field studies at prescribed burns have been conducted to analyse the toxicity of the smoke firefighters are exposed to, and to evaluate the impact of this smoke on respiratory and cardiovascular health (Reisen and Brown 2009; MacSween et al. 2020; Wu et al. 2020, 2021; Adetona et al. 2022). Serum inflammatory mediators were found to increase after 4 hours of wildland firefighting (Swiston et al. 2008; Adetona et al. 2017), while lung function and lung capacity were reduced after one shift of wildland firefighting (Adetona et al. 2011, 2016; Navarro et al. 2019). Exposure and resultant health effects, however, can vary depending on the tasks performed on the fireground. For example, firefighters who ignite burns are exposed to higher concentrations of particles and have increased inflammatory serum markers, compared to firefighters who conduct patrol (to monitor spread of the burns) (Adetona et al. 2017; Wu et al. 2021). To reduce dermal, respiratory and eye exposure to smoke, firefighters are provided with personal protective clothing and equipment. This includes fire retardant outerwear, gloves, and

CONTACT Sukanya Jaiswal suki.jaiswal@unsw.edu.au School of Optometry and Vision Science, Faculty of Medicine and Health, Room 3.029, North Wing, Rupert Myers Building, UNSW Sydney, NSW 2052, Australia

This article has been corrected with minor changes. These changes do not impact the academic content of the article.

respirators (disposable, half-face or full face). Eye protective devices can include goggles (which are designed to seal against the face), full-face respirators (with air filters), or self-contained breathing apparatus (with full face mask). It is notable however that use of such equipment is often not adhered to, and goggles are especially difficult to use on the fireground due to fogging and sweating (Jaiswal et al. 2024).

Although the eye surface is directly exposed and thus as vulnerable to smoke as the airways, the impact of smoke on firefighters' eyes has not been well studied. The eye surface is comprised of the cornea (an optically clear hypersensitive structure), conjunctiva (a mucous membrane), tear film (a hydrating fluid nourishes and repairs the eye surface and protects it from pathogens) and the eyelids (which contain glands that produce parts of the tear film). Clinically, disturbances in the homeostatic function of the eye surface components can result in an array of eye symptoms. A recent survey of Australian wildland firefighters conducted by this research group showed that eye symptoms such as soreness, stinging, watering and irritation commonly occurred during firefighting duties and persist beyond (Jaiswal et al. 2024). Another study reported that 80% of emergency services personnel (firefighters and police) working on a large forest fire in Israel experienced eye irritation (Amster et al. 2013). The impact of occupational smoke exposure on eye surface physiology and clinical signs however remains unknown, with current understanding based solely on findings derived from clinical records of wildland firefighters at hospitals. These studies from wildfires in the USA reported that eye injuries and corneal abrasions were responsible for up to 10% of all firefighter presentations to hospital emergency departments (Shusterman et al. 1993; Gallanter and Bozeman 2002; Squire et al. 2011).

Eye symptoms and adverse eye surface effects associated with exposure to wildfire smoke are highly prevalent in the general community. Up to 73% of people exposed to smoke in Australia's capital during the 2019–2020 Black Summer fires reported eye irritation (Rodney et al. 2021). Symptoms such as itchy, watery eyes were more prevalent in adults and children with respiratory conditions such as asthma during wildfires in Spain, USA and Australia (reviewed in Jaiswal et al. 2022)). An experimental study from this research group found that the corneal epithelium of healthy participants was damaged and their tear film was unstable following 15 minutes of exposure to fresh wildfire PM2.5 (particulate matter sized 2.5 μm or smaller) (Jaiswal et al. 2024). Although, the concentration of PM2.5 generated in that study was comparable to maximum concentrations of PM2.5 in the community following transport of wildfire smoke, the cumulative dose of exposure was far below that which might occur on the fireground during wildfires or prescribed burns.

To understand how exposure to wildfire smoke over several hours can affect eye surface physiology and clinical signs, this study investigated the impact of smoke exposure at prescribed burns on the eye surface of Australian wildland firefighters.

Methods

A pre-post exposure study was conducted to assess eye surface symptoms and signs in wildland firefighters attending prescribed burns around Sydney, New South Wales (NSW), Australia.

The study was approved by the University of New South Wales Human Research Ethics Committee (Project ID 230169) and was conducted in accordance with the tenets of the Declaration of Helsinki.

Participants

Participants were recruited from the firefighters attending four prescribed burns conducted by the New South Wales National Parks and Wildlife Service (NPWS) in local government areas neighbouring Sydney between August 2023 and May 2024. NPWS is a state government agency that employs the largest professional workforce of wildland firefighters in NSW. There is no upper age limit for NPWS firefighters to conduct field duties, although suitability for field duties is assessed annually with physical tests and 3-yearly with medical screenings. All firefighters aged 18 years or older who were rostered with duties on the fireground were eligible and invited to participate via an email sent by NPWS staff on the day prior to the burn and by in-person communication from the commanders in charge at the burn site. Participation was voluntary, and each firefighter was eligible to participate one time only. Firefighters who wore contact lenses on the day of the burn or had experienced occupational smoke exposure in the previous 72 hours were excluded.

Smoke exposure

One to four participants were fitted with personalised PM2.5 monitoring devices (Trolex XD1+, Active Environmental Solutions, Sydney) at each burn except during Burn 3 when monitoring devices were unavailable for use. Participants were instructed to attach the device on their outerwear, at or above their waistline, for the duration of their shift. These monitoring devices sampled air for PM2.5 concentration at 1-minute intervals. Data was downloaded from each device at the completion of each burn.

Outcome measures

The following measurements were conducted at the staging area of the prescribed burn. Staging areas were a designated indoor (e.g. depot) or outdoor (e.g. natural reserve) location within 1 km of the burn site where firefighters received final instructions prior to entering the fireground (Figure 1 Left). Measurements were conducted twice: within 1 hour prior to entering and within 30 minutes of exiting the fireground. Symptoms were measured for both eyes. All other measurements were conducted on the right eye only. Tear film samples were collected from the left eye only. Tear collection and analysis was conducted by an examiner who was masked to other measurements from the participants.

Visual acuity

Visual acuity (VA), with current spectacles if worn, was measured using a 3-m Snellen chart and converted into logMAR scores prior to analysis. Pinhole VA measurement was conducted for any results poorer than 0.3.

Figure 1. Left, wildfire smoke at the site of prescribed burn 1. Right, field eye examination conducted at the site of prescribed burn 4 using a portable slit lamp. Bottom, Protective clothing and equipment used by NSW National Parks and Wildlife Service firefighters. Picture taken from the NSW NPWS *Guidelines for the selection, use, care and maintenance of personal protective clothing and equipment (PPC and PPE)* manual.

Eye surface symptoms

The Instant Ocular Symptoms Survey (IOSS) (Boga et al. 2019) which measures the intensity of discomfort and dryness at the eye surface was used at Burn 1 (score range 0–10, where 0 represents no symptoms). This was replaced with the Numerical Rating Scale (NRS) (Papas et al. 2011) for burns 2, 3 and 4, so as to sample additional eye surface symptoms that contemporaneous research by this group had shown were commonly reported by Australian wildland firefighters following occupational smoke exposure (Jaiswal et al. 2024). The NRS measures intensity of eye discomfort, dryness, foreign body sensation, burning, watering, tiredness and blurriness on a scale from 0 to 100, where 0 represents "severe" symptoms and 100 represents "perfect". A total NRS score was also calculated by summing the scores of all seven symptoms. Both the IOSS and NRS were verbally administered by the examiner.

Eye surface examination

The eye surface was examined with a portable slit lamp (Shin Nippon XL-1, Japan, Figure 1). Redness of the inferior limbus and palpebral conjunctiva, the nasal and temporal bulbar conjunctiva, and roughness of the inferior palpebral conjunctiva (inner surface of the eyelid) were graded in 0.1 steps using the 0 to 4 BHVI grading scale (Terry et al. 1993). Sodium fluorescein was instilled (Fluorets 1 mg strips, Bausch + Lomb) to assess conjunctival roughness, staining and tear film stability. Corneal and conjunctival staining (an indicator of a breach of epithelial layer integrity) was graded using the 0 to 5 Oxford grading scale (Bron et al. 2003) and any distinctive patterns and locations of staining were qualitatively noted. Tear film stability was measured (in seconds) by averaging three measurements of tear break up time.

Tear film sample analysis

Basal tear collection using glass microcapillary tubes (BLAUBRAND® 10 μL micropipettes, Merck) was attempted immediately prior to entering and upon exiting the fireground. Microcapillary tubes were gently applied to the temporal inferior tear meniscus without conjunctival provocation as described previously (Jaiswal et al. 2024). Tear samples were transferred to sterile microcentrifuge tubes with 45 μl protease inhibitor (cOmplete Mini, EDTA-free Protease Inhibitor cocktail, Merck) transported on dry ice and stored at −80°C until analysis. The tear concentration of IL-1β was measured by enzyme-linked immunosorbent assay (ELISA) (IL-1β Human ELISA Kit #BMS224–2, Invitrogen Thermo-Fisher Scientific) as per manufacturers' instructions (as described previously (Jaiswal et al. 2024)). Absorbance was measured at 450 nm with a 630 nm reference wavelength using a TECAN safire2 plate reader and Magellan 7.2 SP1 software. IL-1β concentration (pg/ml) was calculated using a standard curve, prepared with the assay standards.

Firefighter duties and protective eyewear use

At the completion of their shift, firefighters were asked to estimate: the proportion of their shift spent on fire ignition, patrol, suppression and supervision duties (Reisen and Brown 2009); the proportion of their shift where they wore any of the following protective eyewear: goggles, sunglasses, full face respirator, spectacles, face-shield or no protective eyewear (Jaiswal et al. 2024); the proportion of their shift where they were positioned upwind (smoke towards them) or downwind (smoke away from them) of smoke; and if they had rinsed their eyes or used any eye drops during the shift. Study investigators did not observe or recommend any alterations to the standard operating protocols for firefighter duties on the fireground or for the use of protective eyewear. Firefighters were also not aware prior to leaving the fireground that they would be asked to report their use of protective eyewear, time spent upwind or downwind of smoke, or the types of duties performed on the fireground.

At the completion of their shift and of study measurements, all participants were offered eye rinsing with saline. For those firefighters with significant eye symptoms or clinically significant signs (as determined by study investigators), instillation of moisturising eye drops (Novatears, AFT Pharmaceuticals or Cationorm, Seqirus CSL) or of topical Prednisolone Phosphate 0.5% (Bausch & Lomb), preservative free was recommended by the study investigators who were therapeutically qualified eyecare practitioners.

Statistics

Data were assessed for normality using the Shapiro–Wilk test. Differences between the two time-points were analysed using paired t-test and Wilcoxon Signed-Ranks Test for parametric and nonparametric data, respectively. P-values determined from pairwise analysis of eye surface signs and symptoms were adjusted for multiple comparisons using Step-down Holm method (David and Geoffrey 2011; Barnett et al. 2022). All analyses were conducted in SPSS Statistics 27 and $p < 0.05$ was considered significant.

Results

Twenty-three out of 25 participants (18 males: 5 females) aged 19–60 years completed the study (Table 1). Two participants who failed to return for measurements after exiting the fireground were lost to follow up. Shift duration ranged from 5.5 to 8.5 hours. This sample size enabled a clinically significant change in bulbar conjunctival redness of 0.5 grade, SD ± 0.7 (Wolffsohn et al. 2017) to be detected, with 5% probability of false positive (α = 0.05) and 90% power.

Table 1. Summary of participant demographics, self-reported predominant task performed, and protective eyewear worn during burn by firefighters at four prescribed burns.

Participant	*Age (years)*	*Sex*	*Burn*	*Tasks performed (% of shift)*	*Protective eyewear used (% of shift)*
1	48	F	1	Supervision (100%)	None (50%) Goggles (50%)
2	48	M	1	Lighting (60%)	Sunglasses (100%)
3[#]^	32	M	1	Lighting (70%)	Goggles (100%)
4*[#]	42	F	1	Mopping up (60%)	Full face respirator (50%) Sunglasses (50%)
5	27	M	1	Mopping up (50%) Lighting (50%)	Face Shield (50%) Goggles (50%)
6	19	M	1	Lighting (70%)	Face Shield (80%) None (20%)
7*	30	M	2	Lighting (60%)	Sunglasses (100%)
8	22	M	2	Supervision (35%) Lighting (35%)	Sunglasses (100%)
9*^[ϑΔ]	41	M	2	Supervision (80%)	Sunglasses (100%)
10^[Δ]	40	M	2	Lighting (70%)	Sunglasses (100%)
11*	48	M	2	Lighting (85%)	Goggles (90%) None (10%)
12*	39	F	2	Mopping up (40%) Lighting (40%)	Goggles (60%) Sunglasses (40%)
13[#]	19	M	3	Supervision (50%)	Sunglasses (100%)
14	26	M	3	Mopping up (45%) & Lighting (45%) (45%, 45%)	Sunglasses (100%)
15	45	M	3	Lighting (100%)	Goggles (100%)
16[Δ]	27	M	3	Lighting (40%)	Sunglasses (95%) None (5%)
17	45	M	3	Supervision (100%)	None (50%) Sunglasses (50%)
18[Δ]	36	F	4	Lighting (85%)	Spectacles (75%) Goggles (25%)
19[Δ ϑ]	60	M	4	Mopping up (50%) Lighting (50%)	Spectacles (100%)
20*	57	M	4	Patrol (50%)	Sunglasses (50%) Full face respirator (30%) Face Shield (20%)
21[Δ]	55	M	4	Mopping up (50%) Lighting (50%)	None (90%) Goggles (10%)
22*[Δ]	52	M	4	Supervision (85%)	Sunglasses (100%)
23	46	F	4	Mopping up (60%)	Face Shield (50%) Goggles (50%)
24	30	M	4	N/A	N/A
25	27	M	4	N/A	N/A

* Indicates the participants who wore PM2.5 monitors ($n = 7$). [Δ] indicates participants who had soot present on their eyes, nose or eyebrows ($n = 7$). [#], [ϑ], ^ indicates participants whose symptoms after burn were managed with prednisone ($n = 3$), ocular lubricant (Cationorm, Seqirus, CSL or Novatears, AFT Pharmaceuticals) ($n = 2$) and saline wash ($n = 3$), respectively. F = female; *M* = male.

Description of tasks (Australasian Fire and Emergency Service Authorities Council (AFAC) 2015; Rural and Land Management 2012): Lighting – igniting the edge of the burn area with a drip torch; Mopping up – extinguishing or removing burning material along or near the edge of the burn area to prevent extension of fire beyond the burn area; Patrol – Monitor the burn edge to prevent breakaways, suppress spot fires, and extinguish overlooked hot spots; Supervision- Oversee the burn on the fireground to determine lighting patterns (e.g. selection and spacing of line or spot ignition techniques, orientation of ignition direction to terrain features, wind direction etc), assess for requirements of overnight and next day patrolling. Description of protective eyewear: Goggles: provide a sealed fit on the face using a foam or rubber gasket around the edges with elastic straps as headbands and ventilation gaps on the frame for air exchange; Face Shield: strong optically transparent visor attached to helmets which protects the eyes and face from flying debris; Full face respirator: sealed full-face mask with respiratory filters for particulate matter.Tasks performed and protective eyewear used by participant 24 & 25 was not available as these participants did not return for measurements after exiting the fireground.

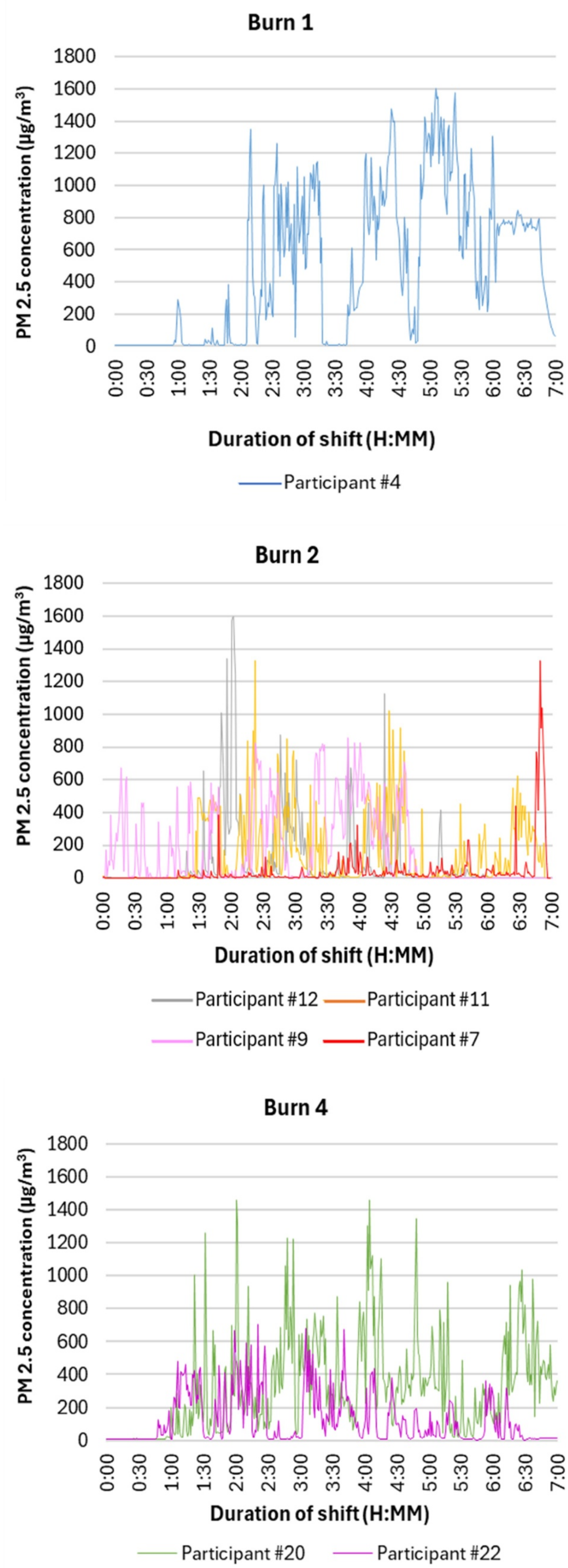

Figure 2. PM2.5 concentrations recorded with personal monitoring devices (Trolex XD1+) worn by seven wildland firefighters at three prescribed burns near Sydney Australia between August 2023 and May 2024.

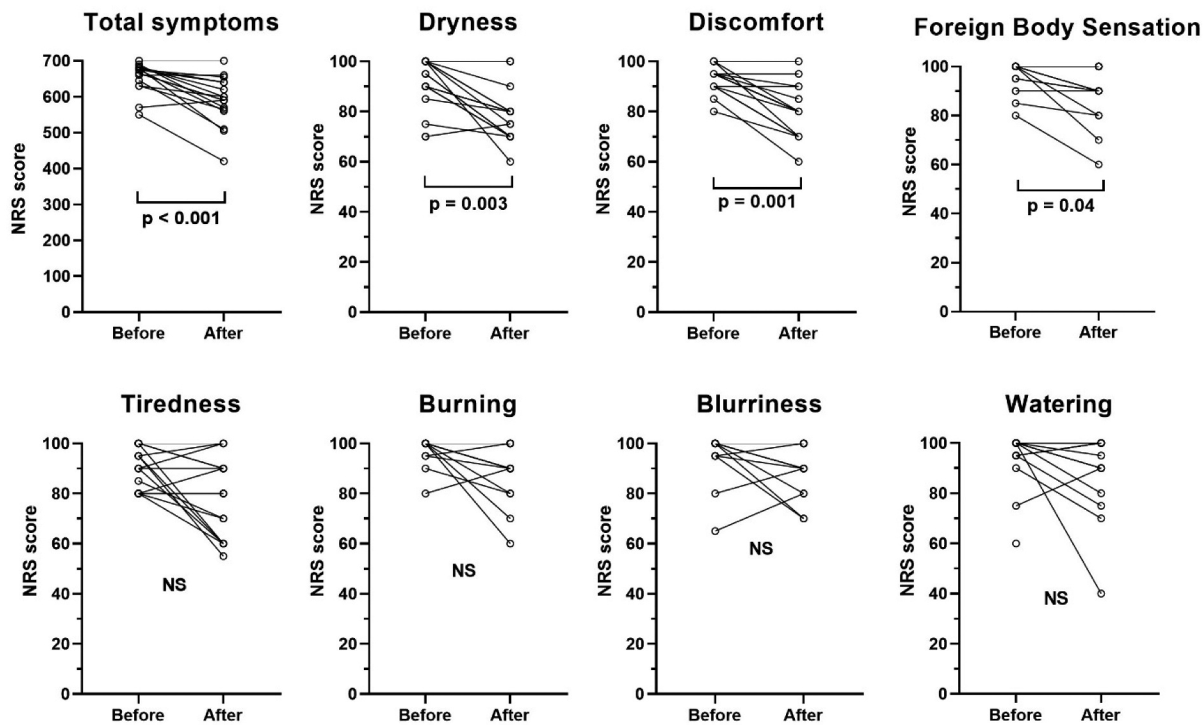

Figure 3. Eye surface symptoms scores (numerical rating scale) reported by wildland firefighters immediately before (n = 19) and after (n = 17) prescribed burns.

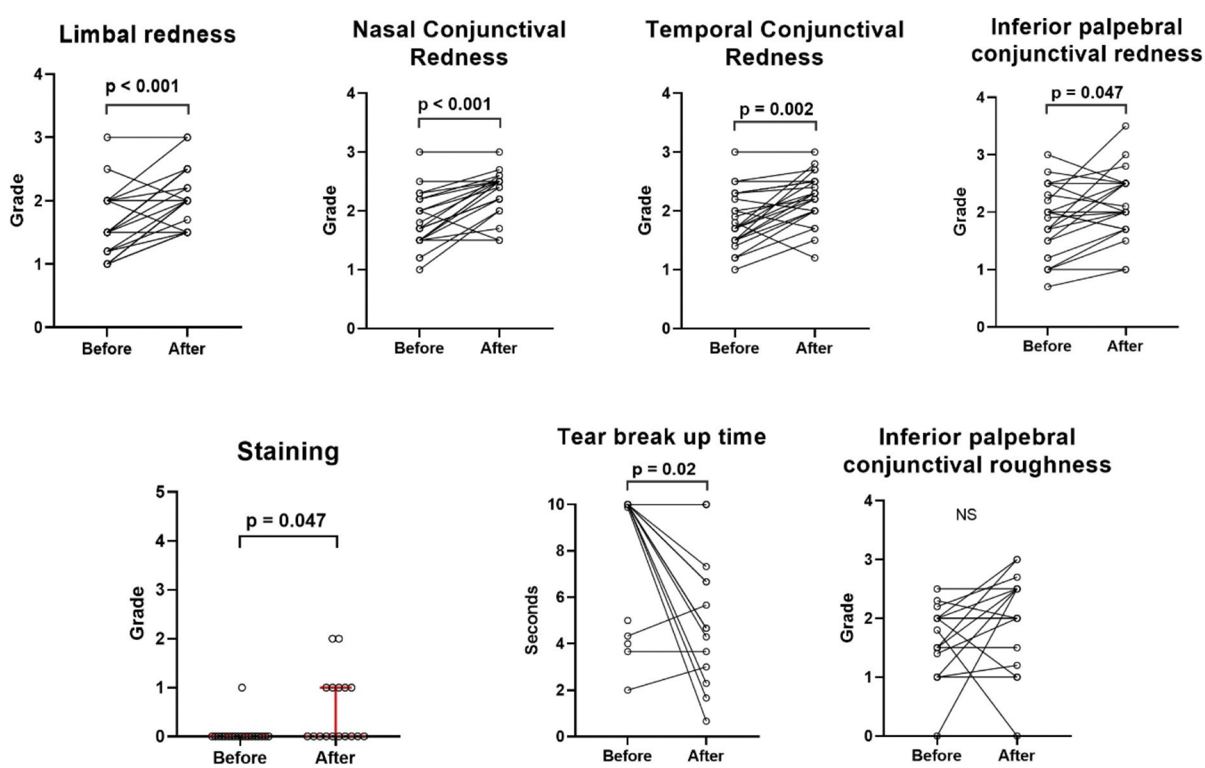

Figure 4. Eye surface signs measured in wildland firefighters immediately before and after prescribed burns. Redness grades for limbus, nasal and temporal bulbar conjunctiva, and inferior palpebral conjunctiva (n = 23). Tear break up time, staining, and inferior palpebral conjunctival roughness (n = 17). Red lines (staining) indicate median and interquartile range.

PM2.5 exposure

PM2.5 concentrations recorded from personal monitors worn by firefighters at the prescribed burns are presented in Figure II. The mean (± SD) PM2.5 concentration at Burn 1, 2 and 4 was 480.2 ± 457 μg/m^3, 130.2 ± 220.6 μg/m^3 and 216.5 ± 249.8 μg/m^3. Monitoring devices were unavailable for use at burn 3.

All firefighters were positioned upwind of smoke for at least half of their shift, while 9 (40%) were upwind for more than 70% of their shift (Figures 2-4).

Eye symptoms

Total eye symptoms ($p < 0.001$), discomfort ($p = 0.001$), dryness ($p = 0.003$) and foreign body sensation ($p = 0.039$) were more intense after the burns, while the change in eye tiredness, burning, watering and blurriness was not significant ($n = 17$, Figure III, Supplementary table S1). Similarly, dryness and discomfort intensity measured with IOSS increased from a median score of 0.5 (IQR: 0–1), to 2 (IQR: 1.25–3.5) after the burn ($n = 6$, $p = 0.013$).

Eye signs

VA did not significantly change, with median VA of 0 (0–0.02) before and 0.02 (0–0.12) after the burn ($p = 0.052$).

Soot particles were observed in the tear film and on the eyelid margin of five participants and on the nose and eyebrows of two participants. Tear stability (tear break up time) was reduced ($p = 0.02$, Figure IV, Supplementary table 2), and fluorescein staining was increased after the burn ($p = 0.047$, Figure IV, Supplementary table 2). For two participants, staining was present on the nasal and temporal conjunctiva but not the cornea.

Limbal redness increased after the burn ($p < 0.001$), as did redness of the nasal and temporal bulbar conjunctiva ($p < 0.001$ and $p = 0.002$, respectively, Figure IV), and the inferior palpebral conjunctiva ($p = 0.047$, Figure IV). Roughness of the inferior palpebral conjunctiva did not change significantly (Figure IV).

Eye surface staining, inferior palpebral roughness and tear break up time could not be reliably evaluated on the six participants at Burn 2 because the staging area was outdoors, and the ambient light did not allow clear visualisation of cobalt fluorescence from the eye surface.

Protective eyewear and alleviation of symptoms

The protective eyewear used by participants for most of their firefighting shift is shown in Table 1. Of 23 participants, 13 (56%) used sunglasses and seven (30%) used goggles for at least half of their shift. Four (17%) participants wore no protective eyewear for at least half of their shift.

One participant (#16) washed their eyes with bottled water 2 hours after starting the shift due to foreign body sensation in the right eye. At the completion of the shift, rinsing of eyes with sterile saline was conducted on three participants and ocular lubricant and prednisone eye drops were instilled in 2 and 3 participants, respectively (Table 1).

Tear analysis

Due to occupational time constraints tear collection could be attempted for only 20 of 23 participants. Of these, only six pre- and post-burn tear samples were analysable due to technical difficulties and low tear volume. Notably, only 5uL of tears was collected in eight of the post-tear samples and ELISA was not feasible for these samples. No significant difference in tear IL-1β concentration was found after shift in the six samples that were analysed (before: 92.4 ± 31.6 pg/ml, after: 92.6 ± 22 pg/ml, $p = 0.98$).

Discussion

This is the first field study to demonstrate that wildfire smoke exposure has a detrimental impact on eye surface physiology and clinical signs. A worsening of eye discomfort, dryness and foreign body sensation reported by wildland firefighters immediately following a shift of prescribed burning was accompanied by increased eye surface staining, limbal and conjunctival hyperaemia and decreased tear film stability.

In this study, symptoms were assessed using the IOSS questionnaire in Burn 1 changing to the NRS in Burns 2–4 as this assessed other eye surface symptoms identified by this group's concurrent research which surveyed Australian wildland firefighters on the occurrence of eye symptoms during occupational smoke exposure (Jaiswal et al. 2024). The increased symptoms of eye discomfort, dryness and foreign body sensation after the burns in this study are consistent with the findings of that survey where eye irritation, dryness and soreness were commonly reported (Jaiswal et al. 2024). Eye symptoms such as burning eyes, dryness and irritation are also common following exposure to fresh smoke generated from the burning of organic matter such as wood, cow dung in open cookstoves (Romieu et al. 2009; Das et al. 2017; Aung et al. 2018).

The increased staining and worsening of tear stability point to eye surface damage occurring with wildland firefighting. These changes may indicate damage to corneal and conjunctival epithelial cells and alterations to meibum quality and reduced meibomian gland function (Ward 2008). This aligns with the reduced tear stability and altered tear lipid release found after short-term exposure to tobacco smoke (Rummenie et al. 2008). Furthermore, the increased redness at the corneal limbus and the bulbar and palpebral conjunctiva is suggestive of an inflammatory response presumably to the particles and gases of wildfire smoke. Conjunctival hyperaemia results from dilation of the conjunctival microvasculature and is part of the inflammatory response to external eye surface irritants (Singh et al. 2021). Increased bulbar conjunctival redness has commonly been reported following short-term exposure to smoke from natural vegetation and biomass burns (Jaiswal et al. 2022, 2024).

With the small sample size and the challenges associated with tear sample collection at the fireground, this study was unable to determine whether an inflammatory tear film response accompanied the observed adverse eye surface clinical changes in wildland firefighters. It is noteworthy that for the six participants in whom tear analysis could be conducted, the baseline tear IL-1β levels (range 58.8–143.4 pg/ml) were markedly higher than those reported for healthy individuals elsewhere (Lam et al. 2009, Nakamura et al. 1998). This elevated tear IL-1β may be a residual effect from burns attended earlier than the 72 hours prior to participation, which was the exclusion criteria for this study.While wildfire smoke exposure can increase tear IL-1β levels (Jaiswal et al. 2024), the duration of cytokine elevation and length of time required to recover following such exposure remains largely unknown and should be investigated in a longitudinal study design to monitor for cumulative effects. One study found that 5 minutes of cigarette smoke exposure increased pro-inflammatory tear IL-6 concentrations for at least 24 hours (Rummenie et al. 2008). To overcome limitations of ELISA and low tear volume analysis found in this study, cytometric bead arrays could be trialled as these have yielded reliable results with as little as 4 μL of tears (Chen et al. 2024). Alternatively, flush tear collection may be able to yield higher tear volume without compromising cytokine detection. With this method, a small amount of saline or buffer is instilled into the eye before diluted tears are immediately collected (Markoulli et al. 2011). Finally, Schirmer strips, which are thin strips of absorbent paper that are inserted in the lower eyelid, are another possible method of tear collection that may be suitable for field studies and should be trialled (Yang et al. 2024). Moreover, although numerous clinical tests which were shown feasible in the field were conducted in this study, corneal esthesiometry may warrant inclusion in any future research as measuring corneal sensitivity may provide additional insights into the neuroinflammatory processes that possibly underpin smoke-related effects on the eye surface.

Goggles and full-face respirators, which seal against the face and provide maximum protection to the eye surface from gases and particles in smoke, were used by only eight (35%) participants for most of their shift. Of concern also is that six (26%) participants either wore no eye protection or used a faceshield (visor-like device attached to helmets) which was unlikely to have protected the eye surface from gases and particulate matter released during the burns. Evidence-based updates of protective eyewear protocols may be warranted to guide wildland firefighters in selecting and using the most appropriate eye protection for varying operational conditions. However, it is noteworthy that firefighters' preference for sunglasses over goggles in this study is consistent with reports of goggles being difficult to use continuously on a fireground due to poor fitting along with sweating and subsequent fogging of lenses that reduces visibility and affects operational capability (Jaiswal et al. 2024). Personalised fitting along with use of anti-fog coatings in protective eyewear may improve use of goggles on the fireground.

Based on NPWS policy, sunglasses used by the firefighters on the fireground should comply with Australian standards 1337 and 1338.2 :1992 (Department of Climate Change, Energy and Water 2024), which describe eye protections for industrial use and filters used in eye protection against ultraviolet radiation, respectively. However, unlike goggles, sunglasses do not completely seal around the eyes and thus may allow smoke particles and gases to contact the eye surface. A sub-group analysis of the best and least effective forms of protective eyewear used (goggles [$n = 4$] compared to none, spectacles or face shield [$n = 6$] for more than 50% of the shift) revealed no significant differences in the change in clinical signs or symptoms between groups. Another form of protective eyewear that may fully isolate the eye surface from smoke is self-contained breathing apparatus (compressed air cylinder that supplies clean air into a full-face respirator) (Dudziński et al. 2024; Teixeira et al. 2025). However, their use is not recommended for wildland firefighters as the apparatus' weight can limit mobility on the fireground (Navarro dubose et al. 2024). Air purifying full face respirators without cylinders however, are more suitable as they are portable and contain cartridges to filter gases and particulates (National Urban Security Technology Laboratory). These were used by only two firefighters in this study for 50% or less duration of their shift. As a result, their effectiveness in mitigating adverse eye surface effects from smoke exposure could not be evaluated.

The small proportion of participants (5 of 23) who received clinical intervention in the form of ocular lubricant or corticosteroid eyedrops are unlikely to have presented to eyecare practitioners for management of their symptoms or signs. This is consistent with our survey of wildland firefighters that identified that only 18% seek professional healthcare advice for eye symptoms experienced in occupational settings (Jaiswal et al. 2024). Fire agencies could however develop and incorporate protocols for the prevention and management of eye injuries in wildland firefighters in their guidelines.

The range of PM2.5 concentration found on the fireground in this study was comparable to wildfires in Australia and other prescribed burns in USA (Reisen et al. 2011; Adetona et al. 2011, 2022). Future studies should also measure firefighters' exposure to toxic gases including formaldehyde, acrolein, and carbon dioxide (Materna et al. 1992; Reisen and Brown 2009; De Vos et al. 2009; Reisen et al. 2011; MacSween et al. 2020), as these are present in high concentrations in fresh smoke and may contribute to the adverse eye surface effects observed in this study. Formaldehyde and acrolein are known to cause eye irritation and can increase inflammatory mediators in the tear film while carbon dioxide exposure has been associated with bulbar conjunctival redness and conjunctival epithelial damage (Podlekareva et al. 2002; Alabi and Simpson 2019; Vazquez-Ferreiro et al. 2019).

While recognising the logistic and environmental challenges associated with conducting field studies on the fireground, this assessment of firefighters provided a unique opportunity to measure the impacts of what is likely to become increasingly common occupational smoke exposure on the eye surface. An unavoidable feature of this field study approach was that the environmental conditions (e.g. visible atmospheric smoke and smell at the staging area) and the presence of peri-ocular and facial soot on participants faces made it impossible to conduct a masked study. High ambient lighting outdoors may also have limited the sensitivity of eye surface staining and tear stability assessments which are usually conducted in dim lighting in clinical settings. Alternative methods for measuring tear break-up time such as using portable equipment with smartphone-attached lenses and LED flashlights should be evaluated for their feasibility and accuracy in outdoor measurements (Vidas Pauk et al. 2019; Zhang et al. 2023). Another limitation was that the study was not powered to detect a change in the levels of tear inflammatory cytokine IL-1β. Hence, this study was unable to confirm whether the clinical changes observed are accompanied by changes in inflammatory tear markers.

Conclusion

This is the first study to demonstrate that wildfire smoke at prescribed burns adversely affects eye surface physiology of wildland firefighters causing eye discomfort and alike symptoms with increased eye redness and reduced tear film stability. Although a tear inflammatory response was investigated, findings were exploratory only due to constraints in feasibility. The significance of these findings remains uncertain but should be of concern given the large workforce involved and that the clinical findings were consistent with a possible inflammatory response. A prudent approach might focus on strategies to protect the eye surface from smoke exposure and mitigate smoke-induced damage. This will benefit not only wildland firefighters but also the general community whose exposure to poor air quality from wildfires is increasing worldwide.

Acknowledgements

This work was supported by a postgraduate scholarship awarded by Natural Hazards Research Australia and University of New South Wales Postgraduate Award to Sukanya Jaiswal. The authors would like to acknowledge Dr Felipe Aires at NSW National Parks and Wildlife Service for facilitating access to the prescribed burns and Mr Ali Alghamdi for assistance in data collection. The authors would also like to thank Seqirus and AFT Pharmaceuticals for in-kind supply of eyedrops and Active Environmental Solutions Australia for loaning PM2.5 monitoring devices.

This research was presented at the International Association for Wildland Fires Fire and Climate conference on 18 April 2024 in Melbourne, Australia and the Australian and New Zealand National Council for fire and emergency services (AFAC) conference on 02 September 2024 in Sydney, Australia.

Author attributions

SJ: Conceptualization, Investigation, Writing – Original Draft, Formal analysis. **BG**: Conceptualization, Methodology, Resources, Writing – Review & Editing, Supervision. **HD**: Investigation. **MM**: Investigation, Writing – Review & Editing, Supervision. **IJ**: Conceptualization, Investigation, Writing – Review & Editing, Supervision.

No authors utilized Artificial Intelligence in any stages of the hypothesis, data collection, data evaluation or manuscript preparation.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

Artificial intelligence statement

Artificial intelligence was not utilised at any stage during research development & design, data collection or manuscript preparation.

Data availability statement

The data that support the findings of this study are available from the corresponding author, SJ, upon reasonablerequest.

Ethical disclosure

The study was approved by the University of New South Wales Human Research Ethics Committee (Project ID 230169) and was conducted in accordance with the tenets of Declaration of Helsinki.

References

Adetona AM, Adetona O, Gogal Jr RM, Diaz-Sanchez D, Rathbun SL, Naeher LP. 2017. Impact of work task-related acute occupational smoke exposures on select proinflammatory immune parameters in wildland firefighters. J Appl Psychol Occupational Environ Me. 59(7):679–690. doi: 10.1097/JOM.0000000000001053.

Adetona AM, Adetona O, Chartier RT, Paulsen MH, Simpson CD, Rathbun SL, Naeher LP. 2022. Differences in fine particle exposure and estimated pulmonary ventilation rate with respect to work tasks of wildland firefighters at prescribed burns: a repeated measures study. Ann Work Exposures Health. 66(8):985–997. doi: 10.1093/annweh/wxac037.

Adetona O, Dunn K, Hall DB, Achtemeier G, Stock A, Naeher LP. 2011. Personal PM2. 5 exposure among wildland firefighters working at prescribed forest burns in southeastern United States. J Educ Chang Occupational Environ Hygiene. 8(8):503–511. doi: 10.1080/15459624.2011.595257.

Adetona O, Reinhardt TE, Domitrovich J, Broyles G, Adetona AM, Kleinman MT, Ottmar RD, Naeher LP. 2016. Review of the health effects of wildland fire smoke on wildland firefighters and the public. Inhal Toxicol. 28 (3):95–139. doi: 10.3109/08958378.2016.1145771.

Alabi EB, Simpson TL. 2019. Conjunctival redness response to corneal stimulation. Optometry Vision Sci. 96 (7):507–512. doi: 10.1097/OPX.0000000000001398.

Amster ED, Fertig SS, Baharal U, Linn S, Green MS, Lencovsky Z, Carel RS. 2013. Occupational exposures and symptoms among firefighters and police during the Carmel forest fire: the Carmel cohort study. Isr Med Assoc J. 15 (6):288–292.

Aung TW, Baumgartner J, Jain G, Sethuraman K, Reynolds C, Marshall JD, Brauer M. 2018. Effect on blood pressure and eye health symptoms in a climate-financed randomized cookstove intervention study in rural India. Environ Res. 166:658–667. doi: 10.1016/j.envres.2018.06.044.

Australasian Fire and Emergency Service Authorities Council (AFAC). 2015. National guidelines for prescribed burning operations: case study 2 – burning young silvertop ash regrowth forests in NSW. Report for National burning Project – subproject 4. Victoria: Melbourne.

Barnett MJ, Doroudgar S, Khosraviani V, Ip EJ. 2022. Multiple comparisons: to compare or not to compare, that is the question. Res Soc Administrative Pharm. 18(2):2331–2334. doi: 10.1016/j.sapharm.2021.07.006.

Boga A, Stapleton F, Briggs N, Golebiowski B. 2019. Daily fluctuations in ocular surface symptoms during the normal menstrual cycle and with the use of oral contraceptives. Ocul Surf. 17(4):763–770. doi: 10.1016/j.jtos.2019.06.005.

Bron A, Evans V, Smith J. 2003. Grading of corneal and conjunctival staining in the context of other dry eye tests. Cornea. 22(7):640–650. doi: 10.1097/00003226-200310000-00008.

Chen Y, Mallem K, Asbell PA, Ying GS. 2024. A latent profile analysis of tear cytokines and their association with severity of dry eye disease in the dry eye assessment and management (DREAM) study. Sci Rep. 14(1):526. doi: 10.1038/s41598-024-51241-1.

Das I, Jagger P, Yeatts K. 2017. Biomass cooking fuels and health outcomes for women in Malawi. Ecohealth. 14 (1):7–19. doi: 10.1007/s10393-016-1190-0.

David S, Geoffrey N. 2011. Correction for multiple testing: is there a resolution? Chest. 140(1):16–18. doi: 10.1378/chest.11-0523.

Department of Environment and Climate Change. 2024. Environment and water, *fire management manual 2024-25 policy and procedures for fire management*. New South Wales: Environment and Heritage Department of Climate Change, Energy, the Environment and Water.

De Vos AJ, Reisen F, Cook A, Devine B, Weinstein P. 2009. Respiratory irritants in Australian bushfire smoke: air toxics sampling in a smoke chamber and during prescribed burns. Archiv Environ Contam Toxicol. 56(3):380–388. doi: 10.1007/s00244-008-9209-3.

Dudziński Ł, Czyżewski Ł, Panczyk M. 2024. Assessment of parameters reflecting the reactivity of the autonomic nervous system of Polish firefighters on the basis of a test in a smoke chamber. Front Public Health. 12:1426174. doi: 10.3389/fpubh.2024.1426174.

Gallanter T, Bozeman WP. 2002. Firefighter illness and injuries at a major fire disaster. J Prehospital Emerg Care. 6 (1):22–26. doi: 10.1080/10903120290938724.

Jaiswal S, Jalbert I, Schmid K, Tein N, Wang S, Golebiowski B. 2022. Smoke and the eyes: a review of the harmful effects of wildfire smoke and air pollution on the ocular surface. Environ Pollut. 15:119732. doi: 10.1016/j.envpol.2022.119732.

Jaiswal S, Jalbert I, Olsen N, Burnett A, Golebiowski B. 2024. Blinded by smoke: wildfire smoke exposure and eye irritation in Australian wildland firefighters. Ocul Surf. 34:381–291. doi: 10.1016/j.jtos.2024.09.001.

Jaiswal S, et al. 2024. Wildfire smoke induces ocular surface inflammation and tear film changes in a human experimental model. Submitted to Translational Vision Science and Technology.

Lam H, Bleiden L, De Paiva CS, Farley W, Stern ME, Pflugfelder SC. 2009. Tear cytokine profiles in dysfunctional tear syndrome. Am J Ophthalmol. 147(2):198–205. e1. doi: 10.1016/j.ajo.2008.08.032.

MacSween K, Paton-Walsh C, Roulston C, Guérette E-A, Edwards G, Reisen F, Desservettaz M, Cameron M, Young E, Kubistin D, et al. 2020. Cumulative firefighter exposure to multiple toxins emitted during prescribed burns in Australia. Exposure Health. 12(4):721–733. doi: 10.1007/s12403-019-00332-w.

Markoulli M, Papas E, Petznick A, Holden B. 2011. Validation of the flush method as an alternative to basal or reflex tear collection. Curr Eye Res. 36(3):198–207. doi: 10.3109/02713683.2010.542867.

Materna BL, Jones JR, Sutton PM, Rothman N, Harrison RJ. 1992. Occupational exposures in California wildland fire fighting. Am Ind Hyg Assoc J. 53(1):69–76. doi: 10.1080/15298669291359311.

Nakamura Y, Sotozono C, Kinoshita S. 1998. Inflammatory cytokines in normal human tears. Curr Eye Res. 17 (6):673–676. doi: 10.1080/02713689808951242.

National Urban Security Technology Laboratory. Respiratory protection wildland firefighting. USA: System Assessment and Validation for Emergency Responders (SAVER); 2022. https://www.dhs.gov/sites/default/files/2022-08/22_0817_st_saver_technote_wildland_fire_respirators.pdf.

Navarro KM, Kleinman MT, Mackay CE, Reinhardt TE, Balmes JR, Broyles GA, Ottmar RD, Naher LP, Domitrovich JW. 2019. Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality. Environ Res. 173:462–468. doi: 10.1016/j.envres.2019.03.060.

Navarro KM, West MR, O'Dell K, Sen P, Chen I-C, Fischer EV, Hornbrook RS, Apel EC, Hills AJ, Jarnot A, et al. 2021. Exposure to particulate matter and estimation of volatile organic compounds across wildland firefighter job tasks. Environ Sci Technol. 55(17):11795–11804. doi: 10.1021/acs.est.1c00847.

Navarro DuBose K, Fent K, Swan R, Tarley J. 2024. NIOSH science blog. Centers for Disease Control and Prevention. https://blogs.cdc.gov/niosh-science-blog/2024/04/29/wildland-ff-webinar/.

Papas EB, Keay L, Golebiowski B. 2011. Estimating a just-noticeable difference for ocular comfort in contact lens wearers. Invest Ophthalmol Visual Sci. 52(7):4390–4394. doi: 10.1167/iovs.10-7051.

Podlekareva D, Pan Z, Kjærgaard S, Mølhave L. 2002. Irritation of the human eye mucous membrane caused by airborne pollutants. Int Arch Occup Environ Health 75(5):359–364. doi: 10.1007/s00420-001-0308-y.

Reisen F, Brown SK. 2009. Australian firefighters' exposure to air toxics during bushfire burns of autumn 2005 and 2006. Environ Int. 35(2):342–352. doi: 10.1016/j.envint.2008.08.011.

Reisen F, Hansen D, Meyer CM. 2011. Exposure to bushfire smoke during prescribed burns and wildfires: firefighters' exposure risks and options. Environ Int. 37(2):314–321. doi: 10.1016/j.envint.2010.09.005.

Rodney R, Swaminathan A, Calear AL, Christensen BK, Lal A, Lane J, Leviston Z, Reynolds J, Trevenar S, Vardoulakis S, et al. 2021. Physical and mental health effects of bushfire and smoke in the Australian capital territory 2019–20. Front Public Health. 9:682402. doi: 10.3389/fpubh.2021.682402.

Romieu I, Riojas-Rodríguez H, Marrón-Mares AT, Schilmann A, Perez-Padilla R, Masera O. 2009. Improved biomass stove intervention in rural Mexico: impact on the respiratory health of women. Am J Respir Crit Care Med. 180 (7):649–656. doi: 10.1164/rccm.200810-1556OC.

Rummenie VT, Matsumoto Y, Dogru M, Wang Y, Hu Y, Ward SK, Igarashi A, Wakamatsu T, Ibrahim O, Goto E, et al. 2008. Tear cytokine and ocular surface alterations following brief passive cigarette smoke exposure. Cytokine. 43 (2):200–208. doi: 10.1016/j.cyto.2008.05.011.

Rural and Land management group. Bushfire glossary. Australasian Fire Authorities Council (AFAC). 2012. http://www.afac.com.au/docs/corporate/bushfire-glossary.pdf?sfvrsn=4%3E

Shusterman D, Kaplan JZ, Canabarro C. 1993. Immediate health effects of an urban wildfire. West J Med. 158(2):133.

Singh RB, Liu L, Anchouche S, Yung A, Mittal SK, Blanco T, Dohlman TH, Yin J, Dana R. 2021. Ocular redness–I: etiology, pathogenesis, and assessment of conjunctival hyperemia. Ocul Surf. 21:134–144. doi: 10.1016/j.jtos.2021.05.003.

Squire B, Cathy C, Raby S. 2011. Medical events during the 2009 los angeles county station fire: lessons for wildfire EMS planning. Prehospital Emerg Care. 15(4):464–472. doi: 10.3109/10903127.2011.598607.

Swiston JR, Davidson W, Attridge S, Li GT, Brauer M, van Eeden SF. 2008. Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. Eur Respir J. 32(1):129–138. doi: 10.1183/09031936.00097707.

Teixeira J, Bessa MJ, Delerue-Matos C, Sarmento B, Santos-Silva A, Rodrigues F, Oliveira M. 2025. Human exposure to polycyclic aromatic hydrocarbons during structure fires: concentrations outside and inside self-contained breathing apparatus and in vitro respiratory toxicity. Environ Pollut. 373:126112. doi: 10.1016/j.envpol.2025.126112.

Terry RL, SCHNIDER CM, HOLDEN BA, Cornish RU, Grant TI, Sweeney DE, LA HOOD DO, BACK A. 1993. CCLRU standards for success of daily and extended wear contact lenses. Optometry Vision Sci. 70(3):234–243. doi: 10.1097/00006324-199303000-00011.

Vazquez-Ferreiro P, Carrera Hueso FJ, Alvarez Lopez B, Diaz-Rey M, Martinez-Casal X, Ramón Barrios MA. 2019. Evaluation of formaldehyde as an ocular irritant: a systematic review and meta-analysis. Cutan Ocul Toxicol. 38 (2):169–175. doi: 10.1080/15569527.2018.1561709.

Vidas Pauk S, Petriček I, Jukić T, Popović-Suić S, Tomić M, Kalauz M, Jandroković S, Masnec S. 2019. Noninvasive tear film break-up time assessment using handheld lipid Layer examination instrument. Acta Clin Croat. 58(1):63–71. doi: 10.20471/acc.2019.58.01.09.

Ward KW. 2008. Superficial punctate fluorescein staining of the ocular surface. Optometry Vision Sci. 85(1):8–16. doi: 10.1097/OPX.0b013e31815ed756.

Wolffsohn JS, Arita R, Chalmers R, Djalilian A, Dogru M, Dumbleton K, Gupta PK, Karpecki P, Lazreg S, Pult H, et al. 2017. The ocular surface. Ocul Surf. 15(3):539–574. doi: 10.1016/j.jtos.2017.05.001.

Wu C, Adetona O, Song C. 2021. Acute cardiovascular responses of wildland firefighters to working at prescribed burn. Int J Hyg Envir Heal. 237:113827. doi: 10.1016/j.ijheh.2021.113827.

Wu C-M, Adetona A, Song C, Naeher L, Adetona O. 2020. Measuring acute pulmonary responses to occupational wildland fire smoke exposure using exhaled breath condensate. Archiv Environ Occup Health. 75(2):65–69. doi: 10.1080/19338244.2018.1562413.

Wu C-M, Song CC, Chartier R, Kremer J, Naeher L, Adetona O. 2021. Characterization of occupational smoke exposure among wildland firefighters in the Midwestern United States. Environ Res. 193:110541. doi: 10.1016/j.envres.2020.110541.

Wuebbles DJ, Fahey DW, Hibbard KA, Arnold JR, DeAngelo B, Doherty S, Easterling DR, Edmonds J, Edmonds T, Hall T, et al. 2017. Climate science special report: fourth national climate assessment (NCA4). Volume I. https://www.globalchange.gov/reports/climate-science-special-report-fourth-national-climate-assessment-nca4-volume-i.

Yang L, Jin X, Hu S, Yu P, Wang X. 2024. Evaluating the efficacy of the diluted Schirmer method for tear collection in dry eye syndrome patients. Curr Eye Res. 49(12):1223–1230. doi: 10.1080/02713683.2024.2380446.

Zhang X, Shen J, Kang Z, Chen A, Cao Q, Xue C. 2023. Clinical observation of tear film breakup time with a novel smartphone-attachable technology. BMC Ophthalmol. 23(1):204. doi: 10.1186/s12886-023-02932-2.