

# Impact of Fine Particulate Matter (PM<sub>2.5</sub>) Exposure During Wildfires on Cardiovascular Health Outcomes

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**Background**—Epidemiological studies investigating the role of fine particulate matter (PM<sub>2.5</sub>; aerodynamic diameter <2.5 μm) in triggering acute coronary events, including out-of-hospital cardiac arrests and ischemic heart disease (IHD), during wildfires have been inconclusive.

**Methods and Results**—We examined the associations of out-of-hospital cardiac arrests, IHD, acute myocardial infarction, and angina (hospital admissions and emergency department attendance) with PM<sub>2.5</sub> concentrations during the 2006–2007 wildfires in Victoria, Australia, using a time-stratified case-crossover study design. Health data were obtained from comprehensive health-based administrative registries for the study period (December 2006 to January 2007). Modeled and validated air exposure data from wildfire smoke emissions (daily average PM<sub>2.5</sub>, temperature, relative humidity) were also estimated for this period. There were 457 out-of-hospital cardiac arrests, 2106 emergency department visits, and 3274 hospital admissions for IHD. After adjusting for temperature and relative humidity, an increase in interquartile range of 9.04 μg/m<sup>3</sup> in PM<sub>2.5</sub> over 2 days moving average (lag 0–1) was associated with a 6.98% (95% CI 1.03% to 13.29%) increase in risk of out-of-hospital cardiac arrests, with strong association shown by men (9.05%, 95% CI 1.63% to 17.02%) and by older adults (aged ≥65 years) (7.25%, 95% CI 0.24% to 14.75%). Increase in risk was (2.07%, 95% CI 0.09% to 4.09%) for IHD-related emergency department attendance and (1.86%, 95% CI: 0.35% to 3.4%) for IHD-related hospital admissions at lag 2 days, with strong associations shown by women (3.21%, 95% CI 0.81% to 5.67%) and by older adults (2.41%, 95% CI 0.82% to 5.67%).

**Conclusion**—PM<sub>2.5</sub> exposure was associated with increased risk of out-of-hospital cardiac arrests and IHD during the 2006–2007 wildfires in Victoria. This evidence indicates that PM<sub>2.5</sub> may act as a triggering factor for acute coronary events during wildfire episodes. (*J Am Heart Assoc.* 2015;4:e001653 doi: 10.1161/JAHA.114.001653)

**Key Words:** coronary disease • heart arrest • ischemic heart disease • particulate matter • wildfires

Cardiovascular disease (CVD) continues to impose a heavy burden worldwide in terms of illness, disability, and premature death.<sup>1</sup> The most common form of cardiovascular disease is coronary heart disease (CHD), also known as

ischemic heart disease (IHD). Acute myocardial infarction (AMI) and cardiac arrest are frequent manifestations of CHD. Epidemiological studies have investigated the role of fine particulate matter air pollutant (PM<sub>2.5</sub> median aerodynamic diameter <2.5 μm) in triggering acute IHD events, including cardiac arrest<sup>2–19</sup>; however the findings from these studies have been inconclusive. The updated American Heart Association scientific statement specifically characterized PM<sub>2.5</sub> exposure as a modifiable factor that contributes to CVD mortality and morbidity.<sup>20</sup> A meta-analysis<sup>21</sup> also concluded that fine particulate matter is a risk factor for acute cardiac events.

One of the most important sources of PM<sub>2.5</sub> air pollution is from wildfire (bushfire) smoke exposure.<sup>22–24</sup> Smoke from wildfires disperses widely and affects large portions of the population away from the fire source.<sup>25</sup> PM<sub>2.5</sub> levels are significantly elevated during wildfire episodes<sup>26,27</sup> and can exceed levels set by regulatory bodies (World Health Organization air quality guidelines<sup>28</sup> for PM<sub>2.5</sub>:10 μg/m<sup>3</sup> annual

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mean, 25  $\mu\text{g}/\text{m}^3$  daily mean). It has been hypothesized for a long time that  $\text{PM}_{2.5}$  is particularly toxic because of its capacity to penetrate deep into the lungs and to induce systemic inflammatory and oxidative stress responses.<sup>4,20,29–31</sup> This effect could potentially trigger a cascade of pathophysiological events in the body and lead to a variety of manifestations of CHD, including chronic atherosclerosis and angina, plaque instability, and rupture, typically following myocardial infarction and cardiac arrest.<sup>4,20,32–37</sup>

The objective of this study was to investigate the association between  $\text{PM}_{2.5}$  exposure from wildfire smoke and cardiovascular health outcomes. In particular, we aimed to investigate the effects on out-of-hospital cardiac arrests, hospital admissions, and emergency department (ED) visits for cardiovascular end points (IHD, AMI, angina) during the 2006–2007 wildfire episode in Victoria, Australia. We used modeled air exposure data to estimate wildfire-related  $\text{PM}_{2.5}$  levels. Modeling enabled wider coverage of affected areas, especially rural or regional areas that had no air-quality monitors. There is very limited understanding of the health impacts of wildfire smoke exposure on communities in such areas.

## Methods

### Health and Population Data

We received deidentified information on the health outcomes from 3 large administrative data sets in Victoria. Out-of-hospital cardiac arrests were identified from the Victorian Ambulance Cardiac Arrest Registry (VACAR), which captures data on all cardiac arrest patients attended by ambulance personnel (prehospital setting) in Victoria. VACAR is one of the largest prehospital cardiac arrest registries in the world.<sup>38</sup> The registry is based on internationally recognized data variables and definitions.<sup>39</sup> Hospital admissions (unscheduled visits) and ED visits for cardiovascular end points were obtained from the Victorian Admitted Episodes Dataset (VAED) and the Victorian Emergency Minimum Dataset (VEMD), respectively. Both VAED and VEMD are comprehensive administrative data sets maintained by the health department of Victoria documenting deidentified demographic and clinical information on ED visits and hospital admissions from hospitals in Victoria. Deidentified information included event date, home postcode, age, sex, event location (eg, house, work, street), principal diagnosis according to the International Classification of Diseases, version 10 (ICD-10) codes for CVD conditions (ICD-10AM, I00 to I99), and a unique event identifier.

Victoria is a second most populous state in southeast Australia. According to the Australian Bureau of Statistics, the estimated resident population of Victoria in 2006 was 5.1 million. Approximately 3.6 million people resided in metro-

politan Melbourne, and 1.5 million resided in rural or regional areas. We included people from both metropolitan and rural or regional areas of Victoria (those whose residential postcodes fell within the boundary of the state of Victoria). We included only people aged  $\geq 35$  years because adverse cardiovascular events such as cardiac arrest in younger people are mainly due to nonischemic causes (eg, structural abnormalities such as cardiomyopathy, congenital heart defects, inherited rhythm disorders [eg, long QT syndrome]).<sup>40</sup>

### Study Period

The study period included 2 months of intense wildfires in Victoria (December 1, 2006, to January 31, 2007). Landscape, climate (mild moist winters followed by hot dry summers), vegetation (dry eucalypt forests, vast grasslands), and protracted droughts make Victoria one of the most fire-prone regions in the world. The 2006–2007 wildfire was the longest running collection of fires that burned  $\approx 1$  million hectares of land in Victoria and lasted for  $>60$  days. This wildfire event was characterized by a few highly active fire days interspersed with days of low fire activity. The air quality during this period was substantially diminished, with elevated surface concentrations of  $\text{PM}_{2.5}$  found for most of the wildfire event. The maximum daily (24-hour) concentration of  $\text{PM}_{2.5}$  measured during the wildfire event was  $\approx 100 \mu\text{g}/\text{m}^3$ . This concentration greatly exceeded the allowable air-quality standards for  $\text{PM}_{2.5}$  set by regulatory bodies worldwide (in Australia, the advisory standard is 25  $\mu\text{g}/\text{m}^3$  for a 24-hour period; in the United States, it is 35  $\mu\text{g}/\text{m}^3$  for a 24-hour period).

The long duration of these wildfires led to widespread smoke dispersion over a wide geographic area. A large population was exposed to smoke from these fires for a long period of time. This provided us with a unique opportunity to investigate acute health impacts in the community.

### Air Pollution Data

Smoke dispersion modeling for the 2006–2007 Victorian wildfire was undertaken using the atmospheric dispersion model called The Air Pollution Model (TAPM) coupled with a chemical transport model.<sup>41</sup> The modeling technique was developed by scientists from the Commonwealth Scientific and Industrial Research Organization (CSIRO) Marine and Atmospheric Research organization located in Victoria. The chemical transport model is a 3-dimensional model with the capability of modeling the emission, transport, chemical transformation, and deposition of gaseous and aerosol species. It predicts regional air quality from a defined inventory of pollutant sources.

For meteorology, the chemical transport model used the synoptic weather model predictions for Australia provided by

the Bureau of Meteorology and downscaled by TAPM to the region of interest. Dynamic downscaling generates high-resolution meteorological fields within a regional area from lower resolution continental or global data from numerical weather models. Downscaling reliably predicted the meteorological parameters at the required spatial resolution (9×9 km) for this study. Of the many meteorological variables, temperature and humidity were among those most accurately predicted. The accuracy of the air pollution model for downscaling temperature and humidity has been presented in numerous papers and reports.<sup>41–43</sup>

For this study, the TAPM–chemical transport model was configured with a complete emissions inventory that included industrial, domestic, transportation, and natural sources of aerosol in addition to smoke from the wildfire event. Of these sources, however, only wildfires contributed significant amounts of PM<sub>2.5</sub> above the natural background concentration (5 to 10 µg/m<sup>3</sup>). Mean daily surface PM<sub>2.5</sub> concentrations were computed for each 9×9-km cell in an 80×80 grid domain centered on Melbourne. This covered all Victoria except for small areas at the extreme eastern and western boundaries. Model validation, accuracy, and spatial variation have been tested extensively and discussed in detail elsewhere.<sup>44–46</sup> Model accuracy was confirmed by comparing the modeled PM<sub>2.5</sub> values with observed PM<sub>2.5</sub> at all stations of the Victorian Environmental Protection Authority pollution-monitoring network during the wildfire event.<sup>44,46</sup> The correlation coefficient between daily predicted PM<sub>2.5</sub> and daily observed PM<sub>2.5</sub> concentrations was >0.5.

The daily observed PM<sub>2.5</sub> data were obtained either directly from TEOMs (tapered element oscillating microbalance; Thermo Fisher Scientific) located at the monitoring stations or from surrogate aerosol observations. For monitoring stations that were not equipped with PM<sub>2.5</sub> TEOMS, the backscattering coefficient was obtained from nephelometers located at each station. For this study, a very high correlation was found between PM<sub>2.5</sub> and backscattering coefficient ( $r^2=0.966$ ). This enabled PM<sub>2.5</sub> to be estimated with a high level of confidence when monitoring stations were not equipped with PM<sub>2.5</sub> TEOMS.

Comprehensive observations of smoke composition (including aerosol chemical composition, plume aging, and secondary aerosol formation) were also made at the CSIRO air-quality monitoring station in Melbourne during the wildfire event. Size, characterization, and chemical composition of smoke aerosol are also detailed in a report by Meyer et al.<sup>47</sup> Both the aerosol composition and the detailed trajectory analysis confirmed that the only significant source of PM<sub>2.5</sub> during the pollution events was the wildfires. The smoke aerosol was composed of organic content, inorganic carbon content, mineral ion content, and anhydrous sugar levoglucosan. Levoglucosan is a unique tracer for wood burning and is produced in high concentrations in biomass smoke.<sup>22</sup> PM<sub>2.5</sub>

contribution from other nonwildfire sources (eg, industry, transportation, sea salt, windblown dust) during this wildfire period was negligible. The smoke composition during biomass combustion was relatively consistent and stable and did not change significantly over a 24-hour time period.<sup>47</sup>

Modeled daily average temperature, relative humidity, and ground-level PM<sub>2.5</sub> for the study period were matched by postcodes.

## Statistical Analysis

A time-stratified case-crossover study design<sup>48–50</sup> was applied to investigate the association between wildfire-related PM<sub>2.5</sub> air pollutant and cardiovascular health outcomes using conditional logistic regression models. In this study design, the PM<sub>2.5</sub> exposure on the day of the health event (eg, out-of-hospital cardiac arrest; case day) was compared with PM<sub>2.5</sub> exposure on several nonevent days (referent; control days). The referent exposure days were selected by time-stratified sampling and were matched for day of the week, month, and year of the health event (eg, exposure on the day of an event on Monday in January was compared with exposures on all other Mondays in January). This resulted in 3 or 4 control periods for each case period. Because the matching referent periods were close in time and on the same day of the week as the event day, this study design automatically controlled for time-dependent risk factors such as day of the week and monthly, seasonal, and long-term trends.<sup>51–53</sup> Moreover, because the persons who experienced the health event also served as their own controls, time-independent factors such as age, sex, smoking, socioeconomic status, preexisting health conditions, and other individual risk factors were controlled for with this approach.<sup>48,52,54</sup>

The primary outcome measures in our study were CVD end points: out-of-hospital cardiac arrests, hospital admissions, and ED visits for IHD (ICD 10-AM, I20 to I25, I46, I49), AMI (I21), and angina (I20). The primary exposure measure was modeled wildfire-derived PM<sub>2.5</sub> (daily average) concentrations. We also included daily average temperature and relative humidity as confounding variables. We conducted a subgroup analysis by age group (35 to 64 years, ≥65 years) and by sex. Various lag periods were also investigated: lag 0 (exposure concentrations on the day of event), lag 1 (exposure concentrations 1 day before the event), lag 2 (exposure concentrations 2 days before the event), and 2-day lagged moving average (lag 0 to 1: averages of exposure concentrations on the day of the event and exposure concentrations 1 day before the event). The analysis of different lag periods was performed individually. The models were adjusted for lag 0 to lag 2 of temperature and relative humidity.

The overall results are presented as an increase in interquartile range for daily average PM<sub>2.5</sub> concentrations and the associated percentage change in the risk of CVD end

points after controlling for temperature and relative humidity at various lag periods.

The data were analyzed using the statistical package Stata (version 12.1; StataCorp). *P* values <0.05 were considered statistically significant.

## Ethics

The study was approved by Monash University human research ethics committee.

## Results

The descriptive characteristics for out-of-hospital cardiac arrests and IHD events (ED visits and hospital admissions) are shown in Table 1. Of the 457 cases of out-of-hospital cardiac arrests during the study period, the largest percentage was for patients aged  $\geq 65$  years (67%), and most were male (67%) rather than female (33%). Of the 2106 cases of ED attendance for IHD, the largest percentage was for patients aged  $\geq 65$  years (62%), and most were male (63%) rather than female (37%). Of the 3274 cases of hospital admissions for IHD, the largest percentage was for those aged  $\geq 65$  years (64%), and most were male (64%) rather than female (36%). The ED attendance data also indicated 788 cases of AMI and 1131 cases of angina, and hospital admissions data indicated 1554 cases of AMI and 1534 cases of angina. Table 2 provides an overview of modeled daily average PM<sub>2.5</sub> concentration, temperature, and relative humidity during the study period.

## Out-of-Hospital Cardiac Arrests

An interquartile range increase in PM<sub>2.5</sub> of 9  $\mu\text{g}/\text{m}^3$  over the 2-day moving average (lag 0 to 1) was associated with an increase in risk for out-of-hospital cardiac arrests of 6.98% (95% CI 1.03% to 13.29%) after adjusting for temperature and relative humidity. An association of 4.55% (95% CI 0.54% to 8.72%) was also observed on the day of the exposure (lag 0), although this was not as strong as that observed over the 2-day exposure period. None of the other lag periods showed any association (Table 3).

### Subgroup analysis by age and sex

When we conducted the subgroup analysis by age and sex, we found those aged  $\geq 65$  years to be at higher risk by 7.25% (95% CI 0.24% to 14.75%; *P*=0.04) compared with younger participants (aged 35 to 64 years: 5.8%; 95% CI -5.04% to 17.89%; *P*=0.30) and men to be at higher risk by 9.05% (95% CI 1.63% to 17.02%; *P*=0.01) compared with women (3.19%; 95% CI -6.4% to 13.84%; *P*=0.53) (Figure 1).

**Table 1.** Descriptive Characteristics of Out-of-Hospital Cardiac Arrests and IHD Events in Victoria, Australia (December 1, 2006, to January 31, 2007)

Number of out-of-hospital cardiac arrests	457
Sex	
Male	304 (67)
Female	153 (33)
Age, y	
35 to 64	152 (33)
$\geq 65$	305 (67)
IHD	
ED visits	2106
Sex	
Male	1320 (63)
Female	786 (37)
Age, y	
35 to 64	808 (38)
$\geq 65$	1298 (62)
Hospital admissions	3274
Sex	
Male	2068 (64)
Female	1206 (36)
Age, y	
35 to 64	1180 (36)
$\geq 65$	2094 (64)

Values are number (percentage). ED indicates emergency department; IHD, ischemic heart disease.

**Table 2.** Descriptive Summary of Daily Average Air Exposure Data (Modeled, December 2006 to January 2007)

Variable	Mean	Maximum	Percentile			
			25%	50%	75%	IQR
PM <sub>2.5</sub> , $\mu\text{g}/\text{m}^3$	15.43	163.44	6.08	7.35	15.12	9.04
Temperature, °C	18.66	32.03	15.62	17.86	22.06	6.44
RH, %	59.88	87.20	51.46	61.38	68.90	17.44

IQR indicates interquartile range (values are calculated for a change in PM<sub>2.5</sub> levels from the 25th to the 75th percentile); PM<sub>2.5</sub>, particulate matter; RH, relative humidity.

## IHD

### Hospital admissions

After adjusting for temperature and relative humidity, an interquartile range increase in PM<sub>2.5</sub> of 9  $\mu\text{g}/\text{m}^3$  was associated with an increase in risk of hospital admissions for IHD by 1.86% (95% CI 0.35% to 3.44%) and for AMI by

**Table 3.** Percentage Change % (95% CI) in Risk of Out-of-Hospital Cardiac Arrests, Hospital Admissions, and ED Visits for IHD, AMI, and Angina for an IQR Increase in PM<sub>2.5</sub> by 9 μg/m<sup>3</sup> at Various Lag Days

Health Outcome	Lag 0	Lag 1	Lag 2	Lag 0 to 1
Out-of-hospital cardiac arrests	4.55 (0.54 to 8.72)	2.85 (−0.46 to 6.28)	2.88 (−0.22 to 6.09)	6.98 (1.03 to 13.29)
Hospital admission				
IHD	−1.12 (−2.67 to 0.45)	0.69 (−0.78 to 2.20)	1.86 (0.35 to 3.4)	−0.96 (−3.30 to 1.43)
AMI	−1.50 (−3.80 to 0.85)	0.41 (−1.7 to 2.6)	2.34 (0.06 to 4.67)	−1.71 (−5.15 to 1.84)
Angina	−0.93 (−3.15 to 1.30)	0.56 (−1.55 to 2.66)	0.90 (−1.22 to 2.48)	−0.72 (−4.09 to 2.10)
ED visits				
IHD	−2.10 (−4.03 to −0.12)	1.63 (−0.39 to 3.71)	2.07 (0.09 to 4.09)	−0.98 (−3.96 to 2.08)
AMI	−3.86 (−6.90 to −3.61)	2.34 (−0.75 to 5.53)	0.75 (−2.44 to 4.06)	−1.86 (−6.65 to 3.11)
Angina	−2.44 (−5.08 to 0.27)	1.54 (−1.11 to 4.26)	1.71 (−0.74 to 4.23)	−1.64 (−5.74 to 2.64)

Statistics reflect the adjustment for temperature and relative humidity. AMI indicates acute myocardial infarction; ED, emergency department; IHD, ischemic heart disease; PM<sub>2.5</sub>, fine particulate matter.

2.34% (95% CI 0.06% to 4.67%) at lag 2. No significant association was found for presentation with angina at lag 2. No other lag periods showed any association (Table 3). Although we presented our results for lag periods (lag 0, 1, 2, 0 to 1), we extended our analysis for hospital admissions to include lag periods of up to 5 days but did not find any significant effect (data not shown).

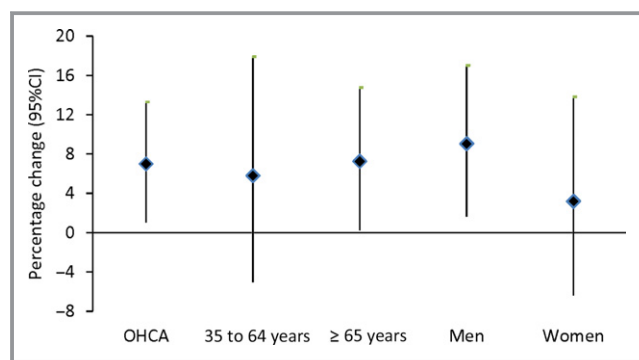
### ED visits

After adjusting for temperature and relative humidity, an interquartile range increase in PM<sub>2.5</sub> of 9 μg/m<sup>3</sup> was associated with an increase in risk of ED attendance for IHD by 2.07% (95% CI 0.09% to 4.09%) at lag 2. No association was found for either AMI or presentation with angina at lag 2. No other lag periods showed any association (Table 3).

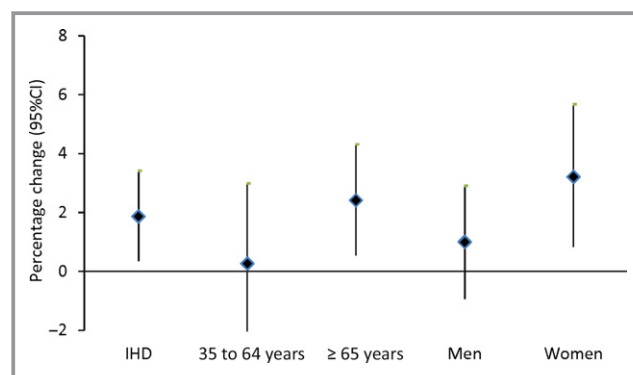
**Subgroup analysis by age and sex.** When we conducted the subgroup analysis by age and sex, we found a higher risk of IHD-related hospital admissions for those aged ≥65 years by 2.41% (95% CI 0.54% to 4.31%; *P*=0.01) compared with younger participants (aged 35 to 64 years: 0.26%; 95% CI −2.37% to 2.98%; *P*=0.84) and for women by 3.21% (95% CI 0.82% to 5.67%; *P*=0.02) compared with men (0.99%; 95% CI −0.94% to 2.9%; *P*=0.33) (Figure 2). No association by age and sex was found for ED attendance.

### Discussion

This study found a positive association between PM<sub>2.5</sub> air-pollutant exposure and acute CHD events during the



**Figure 1.** Percentage increase in risk (and 95% CI) of out-of-hospital cardiac arrests by age and by sex for interquartile range increase in PM<sub>2.5</sub> by 9 μg/m<sup>3</sup> after adjusting for temperature and relative humidity for lag 0 to 1 (lag 0 to 1: averages of exposure concentrations on the day of the event and exposure concentrations 1 day before the event). OHCA indicates out-of-hospital cardiac arrests; PM<sub>2.5</sub>, fine particulate matter.



**Figure 2.** Percentage increase in risk (and 95% CI) of hospital admission for IHD (by age and by sex) for an interquartile range increase in PM<sub>2.5</sub> by 9 μg/m<sup>3</sup> after adjusting for temperature and relative humidity at lag 2 (exposure concentrations 2 days before the event). IHD indicates ischemic heart disease; PM<sub>2.5</sub>, fine particulate matter.

2006–2007 wildfire period in Victoria. Specifically, associations were observed for out-of-hospital cardiac arrests, hospital admissions, and ED visits for IHD after 2 days of exposure to wildfire smoke at PM<sub>2.5</sub> concentrations. This association was observed mainly in older adults (aged ≥65 years), with men showing a higher risk of out-of-hospital cardiac arrests events and women showing a higher risk of IHD-related hospital admissions.

Sustained effects of wildfire smoke exposure and cumulative biological effects could be responsible for a delayed effect of PM<sub>2.5</sub> exposure on acute CHD events.<sup>55</sup> From a mechanistic point of view, exposure to PM<sub>2.5</sub> from wildfire smoke 2 days before the events may amplify the pathobiological processes in the body (induce an inflammatory cascade) and lead to ischemic events, plaque rupture, and development of arrhythmias. Multiple pathways (possibly interlinked) have been postulated<sup>4,17,20,34–36,56,57</sup> by which PM<sub>2.5</sub> could instigate adverse cardiac events including (1) induction of systemic pulmonary inflammation and oxidative stress, leading to increased levels of inflammatory markers (eg, C-reactive protein, prothrombotic and inflammatory cytokines); (2) direct translocation into blood, leading to increase in blood viscosity, thrombus formation, plaque erosion, and rupture and acceleration of the atherosclerotic process; and (3) dysregulation of the cardiac autonomic system (increase in heart rate and decrease in heart rate variability), leading to arrhythmias and cardiac arrests. Some of these potential mechanisms, however, must be seen as somewhat speculative.

A convincing explanation of how wildfire-related PM<sub>2.5</sub> air pollutants might induce different biological responses to non-wildfire-related PM<sub>2.5</sub> remains an area of research. It is conceivable that the difference in the magnitude of the inflammatory response could occur because of variation in the duration and intensity of exposure to particulate matter.<sup>20</sup> Unlike PM<sub>2.5</sub> derived from urban pollution, wildfire-related PM<sub>2.5</sub> concentrations can become extreme with variations in the duration of exposure to smoke events.<sup>25,58</sup> The difference in biological response could also be due to the variation in the chemical composition of particulate matter. Some studies have suggested that the chemical components present in PM<sub>2.5</sub> pollutant (eg, transition metals) from urban pollution can catalyze an oxidative stress reaction in the lungs, leading to inflammatory lung injury and arrhythmias.<sup>5,59–61</sup> In contrast, a study by Weggser et al<sup>30</sup> (using mouse bioassay) showed that PM<sub>2.5</sub> from wildfires was particularly toxic to the lungs, especially to the alveolar macrophages, compared with PM<sub>2.5</sub> exposure from urban pollution. This finding requires further understanding.

Other less known and studied possibilities for the delayed impact of wildfire PM<sub>2.5</sub> exposure could be due to behavioral, cultural, social, and environmental conditions that determine

a person's use of health services during such extreme events.<sup>62</sup> Similar to respiratory health points, the CVD health points at various lags may be influenced by individual perceptions and decisions to seek medical care during wildfire episodes.<sup>63</sup> People may delay deciding to go to the hospital, for example, until symptoms become too severe during the wildfire event.<sup>55</sup> This important possibility needs further exploration.

Only a limited number of studies to date have investigated the effect of fine particulate matter exposure on out-of-hospital cardiac arrests. These studies<sup>6,16–19</sup> reported an increase in the risk of out-of-hospital cardiac arrests by 4% to 10% for an increase in PM<sub>2.5</sub> concentrations by 5 to 10 µg/m<sup>3</sup>, and this is consistent with our findings. Nonetheless, it is noted that some studies have not shown an increase in implantable cardioverter-defibrillator discharges, which typically reflect occurrences of life-threatening ventricular arrhythmias at times of significant air pollution.<sup>64–66</sup>

Only a few epidemiological studies have investigated cardiovascular health impact and exposure to wildfire smoke-related particulate matter.<sup>55,58,63,67–72</sup> Most studies investigated the impact on IHD-related hospital admissions and found null or inconsistent results.<sup>55,58,63,67–70</sup> In contrast, numerous studies have investigated the association between cardiovascular health impact and exposure to particulate matter pollutants from urban sources (eg, vehicular emissions).<sup>20</sup> Studies have reported a 2% to 20% increase in risk of acute IHD-related morbidity for a 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> levels.<sup>3,4,7,11,31,73</sup>

Some challenges are involved in investigating the health impacts of wildfire smoke exposure. Wildfires are episodic and short-lived events; therefore, the brief periods of PM<sub>2.5</sub> exposure may not be enough to detect all but the most sensitive health outcomes.<sup>74</sup> Moreover, many wildfire smoke-affected areas (especially rural or regional areas) do not have routine air-quality monitoring programs. Consequently, exposure assessment is challenging in these areas.<sup>75</sup> Our study is unique in 3 respects: (1) use of spatially resolved PM<sub>2.5</sub> air pollutant data obtained from a novel air-quality modeling technique, (2) wildfire PM<sub>2.5</sub> estimates derived from areas with lack of monitoring facilities (eg, rural or regional areas outside a major city), and (3) extensive and long duration of a wildfire event with widespread PM<sub>2.5</sub> particulate dispersion affecting a large population.

Given that the burden of CHD remains high globally (CHD accounts for 64% of all CVD deaths) and is predicted to remain so for the next 20 years,<sup>76</sup> further research is required to understand the role of wildfire-related PM<sub>2.5</sub> as a triggering factor for acute CHD events. Our findings contribute to this important area of research.

We found people aged ≥65 years were at higher risk for cardiac events due to PM<sub>2.5</sub> exposure, similar to the findings

observed in other studies.<sup>6,16,55,63,67,70</sup> Given that older adults may already suffer from multiple comorbidities including atherosclerosis (often asymptomatic), exposure to PM<sub>2.5</sub> may attenuate any underlying IHD, thereby triggering potentially fatal coronary events.<sup>2</sup>

Similar to our findings, 2 studies showed that men had a higher risk of out-of-hospital cardiac arrests due to PM exposure.<sup>16,19</sup> The reason for different outcomes between men and women is still unclear. It has been suggested that women suffer cardiac arrests half as often as men of the same age.<sup>77</sup> Pathobiological processes other than atherosclerosis (eg, coronary vasospasm, valvular heart disease) may also be more common in women.<sup>78</sup> Limited studies have shown women to be at increased risk of CHD morbidity due to PM exposure.<sup>79–82</sup> This is consistent with our findings, in which we observed women to be at increased risk of IHD. Although the evidence is sparse, it has been hypothesized that hormonal alteration, increase in inflammatory biomarkers (eg, C-reactive protein), poor coronary circulation due to microvascular coronary dysfunction (more plaque erosion and distal embolization, small arterial size), and endothelial dysfunction in women may be factors contributing to female-specific ischemic disease.<sup>83</sup> Concentrations of the inflammatory biomarker C-reactive protein are also known to increase due to PM exposure.<sup>20,84,85</sup> This could explain the increase in risk of IHD in women during wildfire episodes, when PM<sub>2.5</sub> levels are significantly high. Difference in acute cardiac events between men and women during wildfire smoke exposure is an area needing further research.

The main strength of our study was the use of novel modeling techniques to estimate air exposure data during the wildfire period. Modeled data had an advantage in that they provided fine temporal and spatial resolution and wider coverage of areas with no monitoring facilities, especially rural or regional Victoria. This is in contrast to studies using monitored data, in which exposure information is obtained only from limited areas (in and around the monitors). This means that the monitored data might not adequately represent the smoke impact in areas that lack monitoring facilities (rural or regional areas), thereby limiting the ability to detect associations that might be present.<sup>86</sup>

Another important strength of this study was that the majority of the PM<sub>2.5</sub> pollutant included in the air pollution model was derived from wildfires. This allowed us to directly analyze the contribution of smoke-sourced PM<sub>2.5</sub> levels to increased risk of CHD events. The wide spread and long duration of the 2006–2007 wildfire event provided us with an opportunity to assess the health impacts of protracted exposure to uncontaminated biomass combustion. In Australia, air-quality exceedance in rural areas is associated mostly with biomass combustion from either domestic wood burning or wildfires.<sup>27,47,87</sup> In these areas, most pollution events are

biomass combustion aerosol largely uncontaminated from other pollutant types. Moreover, towns are widely separated, and for the most part, the air quality is determined by local pollutant sources (particularly domestic wood heaters); advection of pollutant plumes from other towns or cities is rare. The exception is smoke plumes from wildfires. Consequently, Australian cities and especially regional areas provide a rare test bed for investigating the impacts of biomass combustion aerosol uncontaminated by other anthropogenic sources of PM<sub>2.5</sub>.

We used comprehensive statewide health data sets to obtain information relevant for the purposes of the study. Access to health information from such large registries further reduced the risk of selection bias and strengthened case ascertainment.

A limitation of our study was the lack of information on personal risk factors such as socioeconomic status, smoking, obesity, and underlying health conditions; however, the case-crossover study design controls for confounding factors because the participants serve as their own controls.<sup>48</sup> We also lacked data on indoor PM<sub>2.5</sub> concentrations during wildfire episodes. Research has shown that during major wildfires, the impact of outdoor air quality on indoor air quality can be severe.<sup>27</sup> Although we did not adjust for the coarser fraction of particulate matter air pollutant (PM<sub>10</sub>) in the study, the bulk of the PM<sub>10</sub> emitted during wildfires is PM<sub>2.5</sub>.<sup>22,88</sup> On average, 87% of PM<sub>10</sub> due to wildfires consists of PM<sub>2.5</sub>.<sup>89</sup> A strong positive correlation has been observed between wildfire PM<sub>10</sub> and PM<sub>2.5</sub> ( $r=0.9$ ).<sup>47</sup> We also performed many tests that could have resulted in increased probability of obtaining spurious associations. We acknowledge that we were unable to account for repeated health events because we obtained only deidentified health data.

Robust evidence-based research is required to fill the knowledge gaps that currently exist in this important area of public health. Novel air exposure–modeling techniques to improve forecasting, effective spatial coverage, and health impact assessment of at-risk groups (eg, women, children, and older adults) are areas of significant need. Moreover, health impacts of wildfire smoke exposure in rural or regional communities remain largely unknown and urgently require understanding. Pathophysiology and pathways that trigger acute cardiac events due to PM<sub>2.5</sub> exposure (short and long term) remains speculative and need further evidence. Importantly, the variation in PM<sub>2.5</sub> exposure (duration and intensity) from wildfire episodes and from urban air pollution on cardiovascular health end points requires understanding. Detailed analysis of chemical composition of wildfire particulates is also needed to understand toxicity of source-specific fractions of PM<sub>2.5</sub> on clinical outcomes. Information is currently insufficient to determine a safe PM<sub>2.5</sub> exposure threshold during wildfire episodes below which there are no adverse

health impacts. Improvement in the understanding of these priority areas is needed so that effective and timely public health strategies can be developed and implemented to reduce the burden of disease during wildfire events. This will have further implications for setting appropriate air-quality standards, enhancing health care infrastructure, and improving timely risk communication and health advice during wildfires.

The results from our study suggest that PM<sub>2.5</sub> exposure from wildfire smoke may be an important determinant of out-of-hospital cardiac arrest and IHD (ED visits and hospital admissions) and that susceptible persons such as older adults may be at higher risk during such extreme events. Given the increased incidence and frequency of wildfires recently and the increased number of people at risk of smoke exposure, future research is required to investigate the role of fine particulate matter exposure from wildfire smoke in triggering acute coronary events. The knowledge and evidence resulting from such research will inform policy and practice and help build capacity in the understanding and management of adverse cardiovascular health impacts in vulnerable communities during wildfire episodes.

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## Disclosures

None.

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## Impact of Fine Particulate Matter (PM<sub>2.5</sub>) Exposure During Wildfires on Cardiovascular Health Outcomes

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