Why cardiologists should be interested in air pollution

H C Routledge, J G Ayres, J N Townend

Despite major improvements in air quality resulting from increasingly stringent legislation, there remains a strong association between daily mortality and current levels of air pollution. Growing epidemiological evidence suggests that many, perhaps the majority, of these deaths are caused by cardiovascular disease.

Urban air pollution is primarily derived from fossil fuel combustion and consists of both gaseous and particulate matter (PM) (table 1). Airborne particles are complex mixtures of elemental carbon, organic carbon compounds, and reactive components such as transition metals, metal oxides, acid condensates, sulfates, and nitrates. The particles believed to be most deleterious to health are those with an aerodynamic diameter of less than 10 μm (PM$_{10}$) although increasingly attention has focused on the ultrafine component (PM$_{2.5}$ and PM$_{0.1}$), which can penetrate deep into the gas exchange region of the lung. Sulfur dioxide is largely derived from industrial sources while nitrogen dioxide and carbon monoxide are both vehicle derived. Ozone is an oxidant gas formed by the action of ultraviolet light on oxides of nitrogen and hydrocarbon fragments in vehicle emissions. All have been implicated in time series analyses as causes of adverse cardiovascular health effects (tables 1 and 2).

**ACUTE CARDIOVASCULAR EFFECTS**

Examination of epidemiological data shows that while the relative risk for pollution related death is greater for respiratory than for cardiovascular causes, because of the size of the population at risk, the number of deaths is in fact greater for cardiovascular diseases (table 2). Although effect sizes vary greatly between studies, meta-analyses of the time series data suggest that an increase in fine particulate pollution of 10 μg/m$^3$ is associated with an increase in total mortality of 1.8% and cardiovascular mortality of about 1.4%. Similar conclusions can be drawn from data on hospital admissions for cardiovascular disease (table 3). Findings from a London time series analysis were consistent with 1 in 50 mortality for deaths caused by heart failure, myocardial infarction, and stroke were all increased significantly in the polluted compared with the control areas. Notably, arrhythmia admissions were increased by 50% compared with the periods before and after the smog. More recently Hoek and colleagues studied associations between daily variations in air pollution and specific cardiovascular causes of death in the Netherlands over eight years. Effect sizes were significant for total cardiovascular mortality and deaths caused by myocardial infarction and other ischaemic heart disease, but were more pronounced (three times higher) for deaths caused by heart failure and arrhythmia.

A panel study carried out by Peters and colleagues adds further weight to the hypothesis that an increase in cardiac arrhythmia contributes to the rise in mortality associated with increases in ambient pollution levels. In 100 patients with implantable cardioverter-defibrillators in Boston in the USA, episodes of defibrillation were related to daily air pollution. The frequency of defibrillator discharges was...
Table 1  Sources of urban air pollution

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>London annual hourly average 1996</th>
<th>Maximum daily UK value 1996</th>
<th>EPAQS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur dioxide (ppb)</td>
<td>8</td>
<td>201</td>
<td>100 (over 15 minutes)</td>
</tr>
<tr>
<td>PM$_{10}$ (µg/m$^3$)</td>
<td>30</td>
<td>380</td>
<td>50 (24 hour mean)</td>
</tr>
<tr>
<td>Ozone (P8)</td>
<td>16</td>
<td>121</td>
<td>50 (8 hour running average)</td>
</tr>
<tr>
<td>Nitrogen dioxide (P8)</td>
<td>28</td>
<td>205</td>
<td>150 (1 hour mean)</td>
</tr>
<tr>
<td>Carbon monoxide (ppm)</td>
<td>1.4 (roadside)</td>
<td>15.8 (roadside)</td>
<td>10 (8 hour running average)</td>
</tr>
</tbody>
</table>

EPAQS, Expert Panel on Air Quality Standards (Department for Environment, Food and Rural Affairs); PM$_{10}$, particulate matter with an aerodynamic diameter of less than 10 µm.

Table 2  Time series analyses of pollutants causing adverse cardiovascular health effects

<table>
<thead>
<tr>
<th>Time series study</th>
<th>Geographic area</th>
<th>Pollutants</th>
<th>CVS mortality effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wichmann 1985$^1$</td>
<td>West Germany 1985</td>
<td>SO$_2$</td>
<td>8% † mortality during smog</td>
</tr>
<tr>
<td>Schwartz 1990$^2$</td>
<td>London 1958–1972</td>
<td>TSP</td>
<td>6% † CVS mortality (15% † admissions)</td>
</tr>
<tr>
<td>Kinney 1991$^4$</td>
<td>Los Angeles County 1970–1979</td>
<td>Particle, O$_3$, NO$_2$</td>
<td>Strongly associated with daily CVS mortality</td>
</tr>
<tr>
<td>Schwartz 1992$^5$</td>
<td>Philadelphia 1973–1980</td>
<td>SO$_2$</td>
<td>5% † mortality/100 µg †</td>
</tr>
<tr>
<td>Dockery 1992$^6$</td>
<td>6 US cities</td>
<td>Fine particles, sulfates</td>
<td>Association between cardiopulmonary mortality and level of pollution in city</td>
</tr>
<tr>
<td>Schwartz 1994$^7$</td>
<td>Philadelphia death certificates 1973–1980</td>
<td>TSP</td>
<td>RR death = 1.08 on high v low pollution day, † heart disease and stroke deaths</td>
</tr>
<tr>
<td>Schwartz 1994$^8$</td>
<td>Meta-analysis</td>
<td>TSP</td>
<td>RR death = 1.06 for 100 µg †</td>
</tr>
<tr>
<td>Anderson 1996$^9$</td>
<td>London 1987–1992</td>
<td>Black smoke</td>
<td>2.5% † daily mortality/7–19 µg/m$^3$ †</td>
</tr>
<tr>
<td>Ponka 1998$^{10}$</td>
<td>Helsinki 1987–1993</td>
<td>PM$_{10}$</td>
<td>4.1% † CVS mortality/10 µg/m$^3$ †</td>
</tr>
<tr>
<td>Zmirou 1998$^{11}$</td>
<td>10 European cities</td>
<td>Black smoke</td>
<td>RR CVS mortality 1.02/50 µg/m$^3$ †</td>
</tr>
<tr>
<td>Ostro 1999$^{12}$</td>
<td>Bangkok 1992–1995</td>
<td>PM$_{10}$</td>
<td>2% † CVS mortality/10 µg/m$^3$ †</td>
</tr>
<tr>
<td>Samet 2000$^{13}$</td>
<td>20 U cities 1987–1994</td>
<td>PM$_{10}$</td>
<td>† Rate of CVS/respiratory mortality, 0.68% for each † PM$_{10}$ of 10 µg/m$^3$</td>
</tr>
<tr>
<td>Kwon 2001$^{14}$</td>
<td>Seoul 1994–1998</td>
<td>PM$_{10}$, SO$_2$, CO, ozone, NO$_2$</td>
<td>Weak associations</td>
</tr>
<tr>
<td>Katsuyanagi 2001$^{15}$</td>
<td>29 European cities APHEA 2</td>
<td>PM$_{10}$</td>
<td>† Rate of CVS/respiratory mortality 0.6% for each † PM$_{10}$ of 10 µg/m$^3$, effect size greater in elderly, with high NO$_2$, or in cold climates</td>
</tr>
</tbody>
</table>

APHEA, Air Pollution and Health: a European approach; CCF, congestive cardiac failure; CVS, cardiovascular system; IQR, interquartile range; RR, relative risk; TSP, total suspended particles.

Table 3  Hospital admissions for cardiovascular disease

<table>
<thead>
<tr>
<th>Time series study</th>
<th>Geographic area</th>
<th>Pollutants</th>
<th>Effect on CVS admissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwartz 1995$^{16}$</td>
<td>Michigan 1986–1989</td>
<td>PM$_{10}$, CO</td>
<td>† Ischaemic heart disease admissions (RR 1.018 IQR † PM$<em>{10}$ and with heart failure (RR 1.024 /IQR † PM$</em>{10}$ and 1.022/IQR † CO))</td>
</tr>
<tr>
<td>Burnett 1995$^{17}$</td>
<td>Ontario 1983–1988</td>
<td>Particulate sulfates</td>
<td>† CVS admission/13 µg/m$^3$ †</td>
</tr>
<tr>
<td>Morris 1995$^{18}$</td>
<td>7 US cities 1986–1989</td>
<td>CO</td>
<td>† Heart failure admissions (RR 1.10–1.37/10 ppm † )</td>
</tr>
<tr>
<td>Wordley 1997$^{19}$</td>
<td>Birmingham 1992–1994</td>
<td>PM$_{10}$</td>
<td>Risk of respiratory (2.4%) or cerebrovascular (2.1%) admission for 10 µg/m$^3$ †</td>
</tr>
<tr>
<td>Schwartz 1997$^{20}$</td>
<td>Tuscan 1997</td>
<td>PM$_{10}$</td>
<td>2.75% † CVS admission/IQR †</td>
</tr>
<tr>
<td>Burnett 1997$^{21}$</td>
<td>10 Canadian cities 1981–1991</td>
<td>SO$_2$</td>
<td>† CVS mortality/100 µg/m$^3$ †</td>
</tr>
<tr>
<td>Burnett 1997$^{22}$</td>
<td>Toronto 1992–1994</td>
<td>SO$_2$, CO</td>
<td>† CVS mortality 1.020/IQR † CO</td>
</tr>
<tr>
<td>Polaniecki 1997$^{23}$</td>
<td>London 1987–1994</td>
<td>Black smoke</td>
<td>2.5% myocardial infarction admissions attributable, associated with angiography admissions</td>
</tr>
<tr>
<td>Schwartz 1999$^{24}$</td>
<td>Eight US counties 1988–1990</td>
<td>NO$_2$</td>
<td>Associated with arrhythmia admissions</td>
</tr>
</tbody>
</table>

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significantly correlated with increased PM$_{10}$ and PM$_{2.5}$, with a lag time of two days, and with nitrogen dioxide on the previous day. In patients with at least 10 interventions to treat ventricular arrhythmia, the odds of a discharge tripled with an increase in nitrogen dioxide from the 5th to 95th centile and increased by 60% for an equivalent rise in PM$_{2.5}$.

The relation between air pollution and myocardial infarction has recently been strengthened by the findings of the determinants of myocardial infarction onset study. This multicentre, case crossover investigation suggested that a transient increase in the concentration of fine particles (increase of 25 $\mu$g/m$^3$ PM$_{2.5}$)—still below current air quality standards—was associated with an increased risk (odds ratio 1.48) of myocardial infarction within 1–2 hours. In addition high 24 hour concentrations of fine particles were associated with an increased risk (odds ratio 1.69) of myocardial infarction. The results at the two separate time periods were independent and additive suggesting the possibility of two, possibly independent, mechanisms.

**POTENTIAL MECHANISMS**

Epidemiology has clearly shown a link between increases in particulate air pollution and deaths and admissions caused by heart failure, myocardial infarction, and arrhythmia. To show that these associations are causal, plausible mechanisms of action are required. Several hypotheses have been proposed, and evidence is accumulating in support of two possibly interlinked mechanisms by which low concentrations of particles in inspired air may have adverse cardiovascular effects. Inhalation and interstitialisation of fine particles may provoke an inflammatory response in the lungs with the consequent release into the circulation of prothrombotic and inflammatory cytokines. A systemic acute phase response of this nature would put people with coronary atheroma at increased risk of plaque rupture and thrombosis. Secondly, exposure to PM may have an adverse effect on cardiac autonomic control, leading to an increased risk of arrhythmia in susceptible patients.

**INFLAMMATION AND COAGULATION**

A systemic inflammatory response to particulate air pollution was initially suggested in 1995 by Seaton and colleagues who postulated that such a response may precipitate acute coronary events as a result of an increase in blood coagulability. The relation between systemic inflammation and adverse coronary events both in patients with coronary artery disease and in the general population is now well established. The analysis of stored blood samples from the subjects of large epidemiological studies has provided evidence for a systemic inflammatory response to air pollutants. Both plasma viscosity and C reactive protein concentration increased in association with high levels of particulate pollution in studies involving nearly 4000 healthy adults. During an air pollution episode, the odds of observing C reactive protein concentrations above the 90th centile increased threefold, and the odds ratio for plasma viscosity above the 95th centile of the distribution was 3.6. These associations suggest that pulmonary injury as a result of pollution may lead to a systemic inflammatory response. The pulmonary insult initiating such a sequence of events has been shown by exposure studies at both the cellular and animal level. Fine particles have been shown to be able to penetrate the alveolar epithelium, causing local inflammation and oxidative stress. Human bronchial epithelial cells exposed to combustion derived particles in vitro release proinflammatory cytokines such as interleukin 6, interleukin 8, and tumour necrosis factor $\alpha$. Cytokine production in these models is preceded by activation of the transcription factor nuclear factor $\kappa$ B and is inhibited by the free radical scavenger N-acetyl-L-cysteine.

In animals, ambient PM$_{10}$ samples collected and then administered by intratracheal instillation have enabled closer investigation of the properties of particles that are responsible for causing an inflammatory response. The degree of oxidative stress and the release of cytokines have consistently been found to be related to size, surface area, and the transition metal content of particles. The oxidant and proinflammatory properties of particles remain an active area of research, while the systemic and cardiac consequences of this pulmonary injury are now also being examined experimentally. In healthy human volunteers, increases in neutrophils and platelets in the peripheral blood have been found following acute exposure to diesel exhaust, in association with an increase in inflammatory cells and expression of endothelial adhesion molecules in bronchial biopsies. In hyperlipidaemic rabbits, exposure to PM$_{10}$ caused bone marrow stimulation, with an increase in circulating polymorphonuclear leucocytes. In addition, atherosclerotic lesions in these animals displayed characteristic features of instability (thin plaque caps, presence of inflammatory cells, fewer smooth muscle cells) when compared with lesions in non-exposed controls.

Recently, the assumption that local pulmonary inflammation following pollution exposure is the sole trigger of the systemic inflammatory response has been challenged. Ultrafine carbon particles radiolabelled with 99 m technetium were found to pass rapidly into the systemic circulation following inhalation. Accumulation in the liver, perhaps by Kupffer cells, suggests that inflammation in response to pollution may be initiated at extrapulmonary sites. Animal and human challenge studies should further clarify the nature of the proinflammatory and procoagulant cytokine responses to inhalation of specific pollutants.

**CARDIAC AUTONOMIC CONTROL**

Disturbances in the control of heart rate and rhythm in response to particulate pollution were originally suggested by two observational studies. Increases in heart rate in nearly 3000 subjects were observed during a pollution episode in Central Europe in January 1985. In a panel study in Utah, pulse rate (and the likelihood of the pulse rate being increased) were positively associated with levels of PM$_{10}$ on the preceding one to five days. An increase in resting heart rate suggests either reduced vagal or increased sympathetic cardiac control and is recognised as an independent risk factor for total cardiovascular mortality and sudden death. The mechanisms by which abnormal autonomic control influence prognosis are not proven, but there is strong animal evidence that increased sympathetic and reduced vagal control results in an increased susceptibility of ischaemic myocardium to ventricular fibrillation. Thus, these two observational studies provide a plausible link between exposure to particulate pollution and sudden cardiac death in susceptible people.

Experimental animal evidence also supports the hypothesis that the cardiac autonomic nervous system is susceptible to the adverse effects of air pollution. In dogs with partially ligated coronary arteries exposed to concentrated ambient particles through tracheostomy, heart rates rose with increasing PM$_{10}$ exposure and cardiac autonomic control measured by heart rate variability (HRV) was altered. Decreased HRV reflects impaired vagal cardiac control and is an independent predictor of cardiac death in patients with established heart disease such as myocardial infarction and chronic heart failure. Analysis of ambulatory ECG recording from seven elderly subjects during particulate pollution episodes from a steel mill showed consistent negative...
associations between pollution and same day measures of HRV. In two further groups of elderly patients, the risk of a person having low HRV was significantly increased on high PM$_{2.5}$ days. In an occupational study, the limitations in estimating personal exposure from regional monitoring were overcome by the use of personal exposure monitors in a cohort of 40 boilermakers. A significant negative association was found between 4 hour PM$_{2.5}$ exposure and 24 hour standard deviation of normal to normal RR intervals, a standard index of HRV. Experimental laboratory exposure to sulfur dioxide in humans has also recently been shown to exert significant adverse effects on HRV.

Exactly how inhalation of pollutants and, in particular, fine particles can exert such effects on the cardiac autonomic nervous system remains to be elucidated. Animal work has shown that stimulation of nasopharyngeal, upper, and lower airway receptors can mediate powerful neural influences on the cardiovascular system. Alternatively, and in keeping with the inflammatory hypothesis, inhaled particles may indirectly promote an autonomic stress response as a result of cytokine release.

These two mechanistic hypotheses in combination may thus explain the observed acute effects of air pollution on cardiovascular morbidity and mortality. In susceptible people, pollution may increase the likelihood of plaque rupture, promote ischaemia, and increase the vulnerability of ischaemic or failing myocardium to lethal arrhythmia (fig 1).

**CHRONIC EFFECTS**

The long term effects of air pollution exposure on the cardiovascular system are more difficult to determine but a small number of studies has highlighted potentially important associations. Two large prospective cohort studies have found associations between long term exposure to fine PM and cardiopulmonary mortality. In the US six cities study involving over 8000 subjects, the effects of air pollution on mortality were estimated while controlling for other risk factors. Over a 16 year follow up period, city specific cardiopulmonary mortality rates were found to be associated with the average concentrations of particulate pollutants in each city. The American Cancer Society found an association between fine particulate and sulfur oxide pollution and cardiopulmonary mortality after a six year follow up in over 500,000 adults. Each 10 $\mu$g/m$^3$ increase in fine particulate air pollution was associated with a 6% increase in risk of cardiopulmonary mortality. Most recently in a study from the Netherlands a consistent association was found between long term exposure to traffic related pollution and cardiopulmonary mortality. Living near a major road and hence being exposed to the highest levels of both black smoke and nitrogen dioxide was associated with a relative risk of cardiopulmonary mortality of 1.95.

The association between long term pollution exposure and cardiovascular death may also be explained by the inflammatory properties of fine particles. In addition to the relation
between acute cardiac events and inflammatory stimuli, there is growing evidence of the importance of inflammation in the atherogenic process itself.56 Markers of inflammation such as C reactive protein can predict long term cardiovascular mortality in apparently healthy subjects.57 In patients undergoing diagnostic coronary angiography, serological evidence of multiple exposure to infectious agents is related to the extent of atherosclerosis and to long term prognosis.58 Although this awaits supportive experimental evidence, one may hypothesise that, in a similar manner to cigarette smoking, repeated exposure to pollutants would contribute to a chronic inflammatory state, increasing the propensity to atherogenesis.

FUTURE RESEARCH
The unpredictable nature of coronary artery disease remains a problem that concerns all cardiologists. Patients with chronic stable angina have a low annual rate of clinical events, but sudden death and acute coronary syndromes including acute myocardial infarction can present without warning both in patients with established disease and in apparently healthy people. Surprisingly little attention has been paid to environmental factors that may influence levels of inflammation and autonomic tone and thus cardiovascular risk. The role of air pollution in determining inflammatory or oxidative status and cardiac autonomic control remains to be determined, but it can be seen that the epidemiological evidence for the association of air pollution with cardiac mortality and morbidity is beyond doubt. Research already underway will throw light upon which components of air pollution are important in these respects and at what levels. The determination of possible threshold effects or ‘safe’ levels will help to establish both appropriate legal standards and the policies required for air quality control. In addition, basic research into exactly how air pollution may result in adverse cardiac events may help to improve our understanding of the triggers of plaque rupture and arrhythmia. Further clinical studies are required but cellular and molecular studies in the field of atherosclerosis and arrhythmia should assess the impact of environmental factors such as air pollution.

References

A 38 year old man without any symptoms was referred to our hospital for examination of a heart murmur. There were signs of right ventricular overload on the ECG. Doppler echocardiographic measurements demonstrated a maximum pressure gradient of 105 mm Hg across the right ventricular outflow tract. Lung perfusion scanning demonstrated reduced tracer uptake in the right lung. Although we initially suspected pulmonary thromboembolism, the computed tomographic angiography revealed severe luminal stenosis and a solid mass arising from the right ventricular outflow tract extending into both left and right pulmonary arteries (see fig), which are atypical findings for pulmonary thromboembolism. The morphological characteristics detected by computed tomography suggested the diagnosis of pulmonary artery sarcoma. After intraoperative pathologic examination of the frozen section confirmed the diagnosis of pulmonary artery sarcoma, radical resection and reconstructive surgery using a cryopreserved homograft were performed. The patient received postoperative radiotherapy and chemotherapy, and has remained well over the subsequent 10 months.

Pulmonary artery sarcoma is extremely rare and has a poor prognosis. The diagnosis is difficult and often initially misdiagnosed as pulmonary thromboembolism. It has been reported that a mean survival is only 1.5 months after diagnosis without surgical intervention. Early diagnosis and aggressive surgical treatment are the only ways of effecting a cure. Computed tomography may offer adequate information on the extent of a neoplasm, which helps us to differentiate a pulmonary artery sarcoma from pulmonary thromboembolism.

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