Dietary antioxidants and environmental stress

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Air is one of our most important natural resources; however, it is also in the front line for receiving environmental pollution. Air quality decreased markedly following the industrial revolution, but it was not until the great London Smog in 1952 that air quality made it onto the political agenda. The introduction of the Clean Air Act in 1956 led to dramatic decreases in black smoke and SO2 concentrations over the next two decades, as domestic and industrial coal-burning activities ceased. However, as these improvements progressed, a new threat to public health was being released into the air in ever-increasing quantities. Rapid motorisation of society from the 1960s onwards has led to the increased release of atmospheric pollutants such as tiny particles (particulate matter of <10μm in aerodynamic diameter) and oxides of N, and the generation of the secondary pollutant O3. These primary and secondary traffic-related pollutants have all proved to be major risks factors to public health. Recently, oxidative stress has been identified as a unifying feature underlying the toxic actions of these pollutants. Fortunately, the surface of the lung is covered with a thin layer of fluid containing a range of antioxidants that appear to provide the first line of defence against oxidant pollutants. As diet is the only source of antioxidant micronutrients, a plausible link now exists between the sensitivity to air pollution and the quality of the food eaten. However, many questions remain unanswered in relation to inter-individual sensitivity to ambient air pollution, and extent to which this sensitivity is modified by airway antioxidant defences.

Antioxidants: Oxidative stress: Air pollution: Lung function: Vitamins

Abbreviations: FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; PM, particulate matter; RTLF, respiratory-tract lining fluid.

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has shifted from the traditional sources of pollution in the energy and industrial sectors to traffic-related pollution. These new pollutants broadly fall into primary source pollutants such as oxides of N and particulate matter (PM) and secondary photochemical pollutants such as O₃ (see Table 1). Although all these pollutants are bad for public health, the effects of PM particularly have caught the attention of researchers in the last decade. Two USA-based studies have been primarily responsible for this increased profile, as they have both provided convincing evidence that the concentration of PM in air is related to life expectancy (Dockery et al. 1993; Pope et al. 1995). Importantly, the decrease in life span is estimated to be 1–2 years, which is large when compared with other environmental risk factors related to mortality. As a consequence of this work and a number of follow-up studies (Abbey et al. 1999; Dockery, 2001; Pope et al. 2002), air pollution is attracting increasing attention from both the political and scientific communities. As a result of increased awareness of the problem, weather forecasts in newspapers and on television now warn the public when poor air quality threatens, whilst free government telephone numbers can be used to obtain more detailed information. When air quality is poor, sensitive individuals such as asthmatics are advised to avoid strenuous exercise, particularly outdoor exercise. Clearly, any form of exercise increases the breathing rate and hence the amount of (contaminated) air that is entering the lung.

Although legislation has been introduced in the UK, across Europe and in the USA to control traffic emissions, pollution still exists and its eventual resolution will require substantial change in the attitudes of many individuals and all governments. In the meantime, the impact of traffic-generated air pollutants will probably be present for several decades. For those in the public health arena who have to deal with the problem it is clear that the current science base does not provide an adequate understanding of the impact of traffic-related pollutants on health. Considerably more work is therefore required before a firm understanding of the mechanisms underlying pollution-induced effects on human health is obtained.

The effects of air pollution

Inhalation of pollutants at concentrations encountered during typical episodes induces a range of symptoms in patients with established respiratory conditions and even in some healthy subjects (Koren et al. 1989; Devlin et al. 1991; Schelegle et al. 1991; Aris et al. 1993). For example, breathing only slightly elevated concentrations of O₃ (120–240 µg/m³) results in a range of respiratory symptoms in a small percentage (10–20) of the healthy population (Mudway & Kelly, 2000). Symptoms include decreased lung function, increased airway hyper-reactivity and pulmonary inflammation. Those individuals with pre-existing conditions such as asthma and chronic obstructive pulmonary disease generally experience an exacerbation of their symptoms. Similarly, NO₂ arising from traffic outdoors and gas appliances indoors results in a time-dependent inflammatory response in the lung (Sandstrom et al. 1991).

Epidemiological studies have consistently reported associations between particulate air pollution, especially PM <10 µm in aerodynamic diameter, and adverse health effects, increasing morbidity and mortality (Samet et al. 2000). However, it is by no means clear how exposure to PM, typically as low as 30 µg/m³, can produce these health effects and which components of PM mediate them. Although epidemiological evidence suggests that it is the fine (PM of 0.1–2.5 µm in aerodynamic diameter) or ultrafine (PM of <0.1 µm in aerodynamic diameter) fraction that contains the toxic components, there is no general agreement. Moreover, the wide spectrum of disease end points (from cardiovascular death to an asthma attack) suggests that more than one component may be driving the health effects.

Air pollution and oxidative stress

The three traffic-related pollutants causing most concern include the primary pollutants NO₂ and PM of <10 µm, and the secondary pollutant O₃. All these pollutants are toxic to the lung, and in ambient air they usually coexist in varying combinations. Although the properties of these pollutants vary markedly, they all have one common feature, which is that they can cause oxidative stress. Oxidative stress is a relatively new term in biology that was introduced by Sies (1991) to describe non-lung phenomena. However, the concept is a global one and can relate to events occurring in any tissue. Oxidative stress is a situation in which the prooxidant–antioxidant balance is disturbed. This imbalance can occur when the generation of oxidant molecules, or free radicals, exceeds the available antioxidant defences (for an overview of the distribution of intracellular and extracellular antioxidant defences in the lung, see Fig. 1). The damage arising from aberrant free radical activity is often loosely referred to as oxidative stress, and it is characterised by the presence of increased

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Source</th>
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<tbody>
<tr>
<td>NO₂</td>
<td>Combination of fossil fuels from stationary sources: heating; power generation; motor vehicles</td>
</tr>
<tr>
<td>O₃</td>
<td>Strong oxidising agent formed in the air through a complex series of reactions involving sunlight (UV radiation) on NO₂ and hydrocarbons</td>
</tr>
<tr>
<td>Particulate matter (PM)</td>
<td>Mixture of solid and liquid particles of various sizes suspended in air: coarse fraction (2.5–10.0 µm), mechanically produced and natural PM: fine fraction (0.1–2.5 µm), small PM, may be formed from gaseous reactions; ultrafine fraction (&lt;0.1 µm), formed by nucleation resulting from condensation reactions</td>
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Table 1. Types and sources of airborne pollutants
cellular concentrations of oxidised lipids, proteins and nucleic acids. Many of these oxidation products become ineffective; for example, many enzymes become inactivated following oxidation. Of the three ambient air pollutants of primary concern: NO₂ is a free radical, as it contains unpaired electrons in its outer electron orbital; O₃, although not a free radical, is a powerful oxidant, second only to F₁ in redox potential; much of the PM carries on its surface metal and organic contaminants that are capable of generating free radicals (Kelly, 2003).

On entering the lung, ambient pollutants do not come into direct contact with respiratory epithelial cells, but rather their first contact is with the fluid layer that covers the respiratory epithelium, the respiratory-tract lining fluid (RTLF; Fig. 2). Thus, the responses observed following exposure to ambient pollutants are thought to be mediated through oxidation reactions occurring within this fluid–air–lung interface (Pryor, 1994). In the case of O₃, and to a lesser extent NO₂, because of its low solubility and high reactivity (Medinsky & Bond, 2001), these reactions appear to be confined to the RTLF. As a result, little O₃ is thought to react directly with the underlying cells. Instead, its toxicity is transmitted to the respiratory epithelium by secondary oxidation products formed by the direct ozonisation of RTLF lipids (Pryor et al. 1995). These species trigger the underlying cells to elaborate inflammatory signals (Kafouri et al. 1999), resulting in airway neutrophilia with ensuing tissue injury. Particulate pollution can, in contrast, cross the RTLF layer; however, it is likely that in making the transition the oxidative nature of the particle surface will be changed as a result of reactions with components of the RTLF (Kelly, 2003).

**Antioxidants and normal lung function**

Opposing the formation of cytotoxic species in the RTLF is a network of antioxidants: ascorbate (van der Vliet et al. 1999), urate (Peden et al. 1990), reduced glutathione (Cantin et al. 1987), α-tocopherol (Mudway et al. 2001), extracellular superoxide dismutase (Mudway et al. 2001) and glutathione peroxidase (Avisser et al. 1996). All these antioxidants are free-radical scavengers, but many (ascorbate and urate) also function as sacrificial targets for O₃, reacting rapidly with this oxidant to limit its interaction with RTLF lipids and proteins (Pryor et al. 1995). It has been proposed that the composition and quantity of antioxidants within the RTLF might therefore represent an important determinant of an individual’s responsiveness to O₃ (Kelly et al. 1995). Indeed, there is evidence (discussed later, see p. 582) that increased antioxidant intake may protect against the effects of air pollution.

Both the extracellular compartment (RTLF) and the intracellular components of the lung are well endowed with antioxidant defences (Fig. 1). Whilst there is evidence to suggest that good lung function is associated with diets rich in fruits and vegetables (Britton et al., 1995), there is little data linking basal pulmonary or blood antioxidant levels to an individual’s responsiveness to oxidant gases under controlled conditions (Blomberg et al. 1999; Mudway et al. 2001). It is, however, conceivable that boosting the plasma concentrations of these antioxidants above the normal range could have a protective effect, if this strategy results in augmented RTLF antioxidant concentrations.

Interest in dietary antioxidants first arose in the area of lung disease in the 1980s, with the suggestion from retrospective observational studies that individuals with low intakes of dietary antioxidants have decreased lung function. Studies by Cohen and colleagues (Tockman et al. 1986; Morabia et al. 1989) indicated that dietary retinol levels are an important predictor of lung function, in that individuals with higher retinol intakes tend to have better lung function. Schwartz & Weiss (1990), reporting the findings of the National Health and Nutrition Examination Survey study, observed that the dietary intake of vitamin C is positively associated with a measure of lung function (forced expiratory volume in 1 s; FEV₁). Strachan et al. (1991) found that smokers with high intakes of fresh fruit and fruit juice have a higher FEV₁ than those with a low intake of these foods. In the Zutphen study (Miedema et al. 1993) it was shown that fruit intake is inversely related to the incidence of chronic non-specific lung disease, but there is no association with the estimated intakes of several antioxidants, including β-carotene, vitamin C and Se. In the MORGEN study (the monitoring project on risk factors and health in The Netherlands) it was found that a high intake of vitamin C and β-carotene, but not vitamin E, is associated with a higher FEV₁ and forced vital capacity (total volume expired; FVC) than a low intake of these antioxidants, suggesting that these nutrients do have a protective effect on lung function (Grievink et al. 1998).

In addition to these epidemiological studies, there are a number of cross-sectional studies in which associations have been made between blood concentrations of dietary antioxidants and lung function and/or respiratory symptoms. Taylor et al. (1986) have reported that patients with chronic obstructive pulmonary disease who have an abnormal FEV₁:FVC have decreased plasma antioxidant levels. The findings of the National Health and Nutrition...
Examination Survey II study (Schwartz & Weiss, 1994) suggest that both bronchitis and wheeze are negatively associated with serum vitamin C levels. Ness et al. (1996) have reported that plasma vitamin C concentration correlate with both FEV1 and FVC in men but not women. More recently, Mudway et al. (2000) have shown that FEV1 is not influenced by vitamin C supplementation in healthy vitamin C-replete subjects.

As outlined earlier, a growing body of evidence links the intake of vitamins and provitamin \( \beta \)-carotene with lung function; i.e. a high intake of these dietary components is associated with higher FEV1 and FVC than low intakes, presumably as a result of improved antioxidant reserves to deal with the inevitable increases in reactive oxygen species. This scenario has been demonstrated in patients with cystic fibrosis who, because of decreased production of pancreatic juices, are unable to efficiently breakdown and absorb fat-soluble vitamin antioxidants such as vitamins E and A (Bye et al. 1985; Homnick et al. 1993). This problem, along with recurrent airway infections and increased neutrophil activity, means that patients with cystic fibrosis endure regular bouts of increased oxidative stress (Brown & Kelly, 1994). Moreover, as both lung function and antioxidant status decline with age in patients with cystic fibrosis (Brown et al. 1996), it is possible that these two events are linked, although no long-term prospective studies have yet addressed this interesting possibility. Encouragingly, short-term intervention studies have shown that high-dose antioxidant supplementation (/d; 200 mg vitamin E, 300 mg vitamin C, 25 mg \( \beta \)-carotene, 90 \( \mu \)g Se, 500 \( \mu \)g vitamin A) improves the antioxidant status of patients with cystic fibrosis, which appears to be linked with an improvement in lung function.

**Air pollution and antioxidant intake**

In support of the proposed benefit from increased antioxidant intake, recent field studies have demonstrated that increased intakes of nutritional antioxidants can reduce the magnitude of lung function decrements in subjects exposed to high \( O_3 \) doses both occupationally (shoe cleaners in Mexico City; Romieu et al. 1998) and recreationally (Dutch cyclists; Grieveink et al. 1999). In these studies it was observed that prolonged periods of supplementation (75 mg vitamin E, 650 mg vitamin C, 15 mg \( \beta \)-carotene daily for 1.5 months in the Mexico City study; 100 mg vitamin E, 500 mg vitamin C daily for 15 weeks in the Dutch cyclist study) are associated with protection against average \( O_3 \) backgrounds of 67.3 \( \mu \)g/m\(^3\) and 38.5 \( \mu \)g/m\(^3\) respectively. Notably, major \( O_3 \) episodes were only recorded in the Mexico City study, with numerous hourly episodes >110 \( \mu \)g/m\(^3\).

Corroboration for these findings has been provided in a number of controlled chamber studies. Chatham et al. (1987) have reported protection against \( O_3 \)-induced (600 \( \mu \)g/m\(^3\) for 2 h, with intermittent exercise) decrements in FVC in subjects receiving a daily supplement of 528 mg vitamin E, 650 mg vitamin C, 15 mg \( \beta \)-carotene daily for 1-5 months in the Mexico City study; 100 mg vitamin E, 500 mg vitamin C daily for 15 weeks in the Dutch cyclist study) are associated with protection against average \( O_3 \) backgrounds of 67-3 \( \mu \)g/m\(^3\) and 38-5 \( \mu \)g/m\(^3\) respectively. Notably, major \( O_3 \) episodes were only recorded in the Mexico City study, with numerous hourly episodes >110 \( \mu \)g/m\(^3\).
decrements was observed. A recent (double-blind) study has examined a fuller range of response end points in two groups of sixteen subjects exposed to \(O_3\) at 800 \(\mu g/m^3\) for 2 h while exercising at a ventilation rate of 201/min per \(m^2\) following placebo and vitamin supplementation (250 mg vitamin C, 33 mg vitamin E and a 370 g (12 oz) vegetable cocktail rich in carotenoids daily for 14 d; Samet et al. 2001). In this study a small yet significant blunting of the \(O_3\)-induced decrement in \(FEV_1\) (\(P = 0.05\)) was observed in the supplemented group with a similar trend (\(P = 0.06\)) observed in the FVC response. No protection against \(O_3\)-induced airway inflammation was reported. In this study subjects were initially placed on a restricted-antioxidant diet for 7 d before entering the placebo or vitamin predosing period, such that their initial vitamin C, vitamin E, and \(\beta\)-carotenoid concentrations were low (group means of 34.2, 13.3 and 1.4 \(\mu mol/l\) respectively). In field studies in which protection has been observed as early as blood antioxidant levels, when measured, have been at the upper end of the normal range (Grievink et al. 1998, 1999; Romieu et al. 1998). Whilst these studies have examined responses in healthy subjects, a recent study by Trenga et al. (2001) has addressed whether vitamin supplementation (500 mg vitamin C and 264 mg vitamin E daily for 4 weeks) would protect asthmatics against \(O_3\)-induced (120 \(\mu g/m^3\) for 45 min, with mild exercise) lung function decrements and following subsequent provocation with \(SO_2\) (100 and 250 \(\mu g/m^3\)). No difference between the pre- and post-\(O_3\) lung function decrements (FVC, \(FEV_1\), forced expiratory flow (25th–75th percentile) and positive expiratory flow) was observed between the supplement and placebo groups. Similarly, no difference was observed in the lung function decrement after \(SO_2\). Indeed, overall responses actually appeared to be larger in the vitamin-receiving group. In each of these studies statistical power is limited both by small group sizes and the fact that subjects do not act as their own controls. Further, although chamber studies have reported protection against \(O_3\) with vitamin supplementation the end points in which protection was seen are not consistent, and the magnitude of the protective effect is small.

Although it has recently been hypothesised that low antioxidant intake may result in accelerated loss of lung function with ageing (Kelly, 2003), few studies have explored whether there is a relationship between antioxidant intake and lung function in childhood. Cook et al. (1997) have reported a positive association between \(FEV_1\) and the frequency of fresh fruit consumption and a weak association with green vegetable and salad consumption. As they found no association between \(FEV_1\) and serum vitamin C concentration, they concluded that other micronutrient antioxidants derived from these foods are more important than ascorbic acid. More recently, Gilliland et al. (2003) have reported that low intakes of antioxidant vitamins are associated with deficits in pulmonary function in both boys and girls participating in the Children’s Health Study in California. Importantly, the deficits amongst boys with asthma are large enough to be clinically significant. Gilliland et al. (2003) have suggested that low antioxidant intake during childhood may contribute to the risk of developing obstructive lung disease during adulthood, as well as increased morbidity and mortality associated with low \(FEV_1\).

In conclusion, the air breathed contains many products of human activity that pose important challenges to the health of the population. Atmospheric oxidative pollutants in particular pose an important challenge to the maintenance of normal lung function. Gaseous air pollutants, such as \(O_3\), are thought to play a role in the causation and aggravation of asthma and allergic responses that are increasingly prevalent in children. Although still under active discussion, many investigators now believe that oxidative stress plays a central role in the impact of air pollutants such as \(O_3\) and PM. Oxidative stress, by definition, is an imbalance between oxidants and antioxidants. As many antioxidants are derived from the food eaten, increased attention is being paid to the quality of the diet, and how this strategy may help protect the population from an oxidising environment.

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