Personal strategies to mitigate the effects of air pollution exposure during sport and exercise: a narrative review and position statement by the Canadian Academy of Sport and Exercise Medicine and the Canadian Society for Exercise Physiology

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ABSTRACT
Air pollution is among the leading environmental threats to health around the world today, particularly in the context of sport and exercise. With the effects of air pollution, pollution episodes (e.g., wildfire conflagrations), and climate change becoming increasingly apparent to the general population, so has its impact on sport and exercise. As such, there has been growing interest in the sporting community (i.e., athletes, coaches, and sports science and medicine team members) in practical personal-level actions to reduce the exposure to and risk of air pollution. Limited evidence suggests the following strategies may be employed: minimizing all exposures by time and distance, monitoring air pollution conditions for locations of interest, limiting outdoor exercise, using acclimation protocols, wearing N95 face masks, and using antioxidant supplementation. The overarching purpose of this position statement by the Canadian Academy of Sport and Exercise Medicine and the Canadian Society for Exercise Physiology is to detail the current state of evidence and provide recommendations on implementing these personal strategies in preventing and mitigating the adverse health and performance effects of air pollution exposure during exercise, while recognizing the limited evidence base.

INTRODUCTION

Health benefits and physiological responses to exercise and sport are well known.[1] Climate change, characterized by more extreme, more frequent, and longer-lasting exposures to environmental threats, has the potential to alter typical physiological responses to, and known health benefits of exercise.[2] For example, exercise-induced elevations in ventilation, core temperature, blood flow, and an upregulation of the metabolism may catalyse harmful effects of inhaled pollutants when exposed to poor air quality. Increased inhaled doses, deposition of pollutants in the respiratory tract, and faster circulation of absorbed particles and gases within the systemic circulation can affect nearly all organs, impact exercise performance, and, in the worst case, harm athletes' health.[3–6]

Joint investigations in the United States of America (Medicare), Canada (MAPLE), and Europe (ELAPSE) show that air pollution exposure at all levels, even low concentrations, affects health.[7–9] As a result, in September 2021, the World Health Organization (WHO) released drastically reduced new thresholds for key ambient pollutants.[10] More research is needed to fully describe the health risks and possibly modified benefits of exercise in air pollution and their effects on athletic performance.[4–6] As training and competitions at venues with increased air pollution exposures are becoming more common,[11] strategies to protect athletes' health and to enable them to achieve their best possible athletic performance need to be developed. The purpose of this position statement is to provide evidence-informed recommendations on personal strategies to prevent or mitigate adverse health and performance effects of air pollution exposure during exercise.

AIR POLLUTION COMPONENTS, SOURCES, AND HEALTH EFFECTS

Air pollution is a complex mixture of gases and particles.[10,12] Athletes' health effects attributed to air pollution mixtures are heterogeneous and influenced by the toxicity of the respective individual components, which vary over space and time. Below, biological, chemical, and physical characteristics of particulate matter (PM), ozone (O_3), nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), and volatile organic compounds (VOCs), the pollutants with the largest public health relevance, are described, and their most common sources listed. For each pollutant, the best understood effects on physiological systems relevant for athletic performance are briefly summarized. However, although individual pollutants are discussed in this article, synergies between individual components may exist for which there are little data. Common air pollutant abbreviations are listed in Table 1 for reference and the WHO's air quality guidelines are presented in Figure 1.

Table 1 Air pollutant abbreviations

Abbreviation	**Meaning**
CO	Carbon monoxide
DE	Diesel exhaust
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_3	Ozone
PM	Particulate matter
PM_{10}	Thoracic particles (PM with nominal mean aerodynamic diameter ≤ 10 µm)
$PM_{2.5}$	Fine particles (PM with nominal mean aerodynamic diameter ≤ 2.5 µm)
SO_2	Sulphur dioxide
SO_x	Sulphur oxides
TRAP	Traffic-related air pollution
UFP (or $PM_{0.1}$)	Ultrafine particles (PM with nominal mean aerodynamic diameter ≤ 0.1 µm)
VOCs	Volatile organic compounds

Particulate matter

PM is a complex mixture of solid particles and liquid droplets comprising various acids, organic chemicals, metals, pollen, and small particles of soil, dust, or carbon.[13] Particles can be directly emitted from a source, such as construction sites, unpaved roads, fields, smokestacks, or fires. However, the majority of PM forms in the atmosphere in complex reactions from chemicals such as sulphur dioxide (SO_2) and NO_x, pollutants emitted from power plants, industrial zones, and motorized transport. The composition, size, shape, and concentration of particles define their potential for health threats.[13] The smaller the particle, the greater the likelihood that it will penetrate more deeply into the airways, deposit in the respiratory tract, and impair health.[13] Three categories are typically used to classify PM based on their diameter: PM ≤ 10 µm (PM_{10}), PM ≤ 2.5 µm ($PM_{2.5}$), and PM ≤ 0.1 µm ($PM_{0.1}$) which are often referred to as ultrafine particles (UFP). Exposure to PM is associated with negative effects on respiratory and cardiovascular health, including alterations in respiratory symptoms (e.g., wheeze), lung function, oxidative stress, inflammation, heart rate (HR), blood pressure (BP), and cognition.[13]

Ozone

O_3 is a highly reactive form of oxygen (O_2).[14] Ground-level O_3 is created by chemical reactions between NO_x and VOCs in the presence of sunlight. Industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapours, and chemical solvents are major sources of NO_x and VOCs.[14] Due to its association with UV radiation, O_3 levels are often increased during hot, sunny weather. As such, high O_3 and high ambient temperatures often coincide. In recent years, global exposure to O_3 has increased,[15] reflecting an increased emission of O_3 precursors, such as NO_x, coupled with warmer temperatures, resulting from climate change. O_3 is associated with respiratory disease independent of PM exposure.[14] Symptoms provoked by O_3 exposure include cough, sore or scratchy throat, pain on deep inspiration, and difficulty breathing.[14] In those with pre-existing respiratory disease who are sensitive to ozone, symptoms may be dramatically worsened, and the frequency of asthma attacks increased, with a decrease in asthma control with regular medication.[14]

Nitrogen oxides

NO_x are highly reactive chemicals that contribute to the generation of smog, a brown haze often seen above cities when NO_x and VOCs react with sunlight, and acid rain, the product of NO_x, SO_2, water, and O_2.[16,17] NO_x is formed primarily from the release of nitrogen contained in fuel during combustion or through natural events such as forest fires or volcanic eruptions.[16] Combined with other compounds in the atmosphere, such as ammonia, nitrate becomes an important contributor to the secondary formation of $PM_{2.5}$ and O_3.[13,14] Exposures to high NO_2 concentrations are associated with aggravated respiratory symptoms including coughing, wheezing, and difficulty breathing.[16] Longer exposures to elevated NO_2 concentrations may contribute to the pathogenesis of asthma and increase the susceptibility to respiratory infections.[16]

Sulphur oxides

SO_2 belongs to the family of SO_x gases.[18] Over 90% of SO_x emissions are released in the form of SO_2, a colourless gas with a distinct sulphurous pungent odor. It originates from the sulphur contained in raw materials such as coal, oil, and metal-containing ores during combustion and refining processes.[19] As aforementioned, dissolved in water vapour in the air, SO_2 forms acids (sulphuric acid and sulphate) and interacts with other gases and particles to form sulphates that can be harmful, particularly to the respiratory tract.[18] SO_2 irritates the eyes, mucous membranes, skin, and respiratory tract.[19] Asthmatics appear to be particularly affected by SO_x, with significant decreases in forced expiratory volume in one second (FEV_1) and forced vital capacity (FVC), which can be aggravated further by exercise.[20]

Carbon monoxide

CO is a product of incomplete combustion of hydrocarbon-based fuels and presents as a colourless, odourless, tasteless, but poisonous gas.[21] The most common sources of CO emissions are vehicles, wood industry, residential wood heating, and forest fires. Following the inhalation of CO, it rapidly diffuses across the alveolar membrane and binds reversibly to haemoglobin with a 200-fold greater affinity than O_2 to form carboxyhaemoglobin.[16] Carboxyhaemoglobin inhibits the blood's capacity to carry O_2 to organs and tissues, resulting in tissue hypoxia and impaired exercise performance.[22] Organs primarily targeted by CO poisoning are the central nervous system and the heart. Maximum cardiac output and maximal arteriovenous difference are lowered with CO in the bloodstream, decreasing maximum oxygen uptake ($\dot{V}O_2max$) and work output.[23] The relationship between CO exposures and respiratory health outcomes is unknown. Common symptoms of CO poisoning are confusion, nausea, headache, dizziness, fatigue, and drowsiness. CO poisoning can impact the ability to perform complex tasks and reduce exercise capacity, visual perception, and manual dexterity.[16,24]

Volatile organic compounds

VOCs refer to all compounds with high vapour pressure and low water solubility and are often components of petroleum fuels, hydraulic fluids, paint thinners, and dry-cleaning agents [25]. They are also emitted from diesel exhaust (DE). When combined with NO_x, they react to form ground-level O_3. In the outdoors, VOCs create smog under certain conditions. The health effects of VOCs depend on the nature of the VOCs, the concentration and duration of exposure, respectively. Benzene and formaldehyde, two better researched VOCs, are listed as human carcinogens.[26] Long-term exposure to VOCs can cause damage to the liver, kidneys, and central nervous system. Short-term exposure to VOCs can cause eye and respiratory tract irritation, headaches, dizziness, visual disorders, fatigue, loss of coordination, allergic skin reactions, and nausea.[26]

INTERSECTION OF AIR POLLUTION EXPOSURE AND EXERCISE

Exposure Pathways

Exposure pathways of humans to air pollutants include inhalation, ingestion, dermal absorption, and non-conventional routes, such as absorption through the eyes.[27] The primary route of exposure for most vapours, gases, and particles is inhalation. Once inhaled, chemicals are either exhaled or deposited in the respiratory tract. If deposited, damage can occur through direct contact with tissue or diffusion through the lung-blood interface into the bloodstream on a systemic level. Once in contact with tissue in the upper respiratory tract or lungs, chemicals may induce effects ranging from simple irritation to severe tissue damage. Substances absorbed into the blood are circulated and distributed to organs, where they have the potential to cause further impairment. In the context of exercise, exposure to air pollution via inhalation is of particular interest. Increases in minute ventilation ($\dot{V}E$), airway airflow patterns, and transitions from nasal to oral breathing are considered to increase the dose of air pollutants reaching and depositing into more distal parts of the respiratory tract.[28,29] Indeed, Daigle *et al*.[30] reported a 4.5-fold higher deposition of UFPs in the respiratory tract following four 15-min long exercise bouts ($\dot{V}E = 38.1\pm9.5$ L/min) with 15-min long rest breaks in between compared to rest only ($\dot{V}E = 9.0\pm1.3$ L/min). Furthermore, para-athletes may have individual factors that affect their air pollution exposure. For example, in high-level spinal cord injury,[31] expiratory muscle weakness and larger residual volumes may put these athletes at a greater risk for PM accumulation due to larger dead space ventilation (i.e., diminished air flow and exchange).

Effects on General Health

Long-term effects appear to vary by pollutant, with O_3 having the most convincing interaction with exercise.[4] For example, long-term physical activity in high O_3 environments results in an increased risk of asthma in children.[32] However, in adults, a large study from Denmark with relatively low exposures to NO_2 reported no interaction effects between air pollution exposure and physical activity levels on mortality, incidence of asthma, chronic obstructive pulmonary disease, and myocardial infarction.[33–35] Two other studies in adults showed a protective effect of physical activity against adverse health effects of air pollution on premature mortality and impaired lung function.[36,37] In summary, a recent mapping review confirmed previous findings that the health benefits of physical activity generally outweigh the health risks of air pollution in healthy individuals;[5] however, insufficient evidence is available for athletes whose training volumes are very high, making them a population group that needs to be studied further. In this position statement, we propose evidence-informed strategies to mitigate the deleterious health and performance effects of air pollution during training and competition.

METHODS

A steering committee (MSK, AH, SK) initially convened and determined the objectives of the position statement. The committee then identified and invited an expanded panel of experts with clinical and/or academic experience in exercise and air pollution. The panel, consisting of an elite athlete and experts in sports medicine, family medicine, pulmonology, epidemiology, exercise physiology, and parasport, was carefully selected to ensure a diverse and balanced perspective. MEDLINE, Embase, Cochrane Central Register of Controlled Trials, SPORTDiscus, and the Agricultural and Environmental Science Database were searched for peer-reviewed publications related to air pollution, exercise, and strategies preventing or mitigating effects of air pollution. We excluded publications focusing on people with respiratory or cardiovascular conditions, with the exception of asthma and exercise-induced bronchoconstriction (EIB) given their prevalence in athletic populations.[38] No date restrictions were applied, and a final search was conducted on March 1, 2022. The reference lists of the included studies were hand searched for potentially missed articles. An example search strategy is available in online supplemental appendix 1. Given the limited evidence base identified in a preliminary search, as well as the necessity to incorporate expert experiential perspectives, a narrative review was selected in lieu of a systematic review. Due to the paucity in insufficient published evidence, Grading of Recommendations, Assessment, Development and Evaluations (GRADE)[39] and other consensus methodologies were not applied. The steering committee appraised the literature and compiled the initial draft. The draft was subsequently reviewed by the extended panel of experts. The final version of the position statement was approved by all authors and the Canadian Academy of Sport and Exercise Medicine and Canadian Society for Exercise Physiology board of directors. A summary of the results and recommendations is provided (Figure 2 and Figure 3).

EXERCISE INTENSITY

The inhaled dose of air pollution (i.e., concentration×ventilation×time) generally increases with exercise intensity due to a proportional increase in $\dot{V}E$.[40] As such, given the known dose-response relationship between air pollution and health outcomes,[10] an increase in exercise intensity could theoretically augment the health and performance effects of air pollution. Indeed, public health agencies generally recommend the curtailment or complete avoidance of intense activities during periods of poor air quality.[41] Nevertheless, limited evidence suggests the contrary.

To our knowledge, only one study has investigated the differential responses to low- and high-intensity exercise performed in high levels of PM. In a double-blinded crossover trial, 18 recreationally active males performed two 30-min exercise bouts while exposed to high concentrations of DE (300 µg/m^3 of $PM_{2.5}$): once at a low-intensity (30% $\dot{V}O_2$peak) and once at a high-intensity (60% $\dot{V}O_2$peak).[42–44] Interestingly, low- and high-intensity cycling in high levels of DE did not produce differences in respiratory function or inflammation, autonomic function, norepinephrine, circulating NO_x, and systemic inflammation.[42–44] Even more surprisingly, the authors found that even though low-intensity exercise under DE exposure significantly increased $\dot{V}E$, $\dot{V}O_2$, carbon dioxide production, and the O_2 cost of exercise compared to filtered air, no exposure effect was found for the high-intensity cycling bout.[45] One relevant study has been conducted comparing two modalities of exercise designed to deliver similar inhaled doses of O_3 in 10 competitive male runners: a moderate 1-hour continuous exercise bout at $\dot{V}E$ = 80 L/min and one with a succession of 30-min warm-up and 30-min competition intensity ($\dot{V}E$ = 112 L/min).[46] The decrement in lung function was comparable between bouts, indicating that the higher intensity did not exacerbate the O_3 effect. Taken together, the results of these laboratory studies do not support the premise that increased exercise intensities potentiate the adverse effects of air pollution. While further research is warranted, the goal at present is not to specifically avoid high-intensity efforts *per se*, but rather to reduce the total inhaled dose over the course of the bout.

Summary

- Aim to minimize the total inhaled dose (i.e., the product of air pollution concentrations, ventilation rate, and duration of the exercise bout) of air pollution during an exercise bout.

REDUCING EXPOSURE BY TIME AND DISTANCE

A fundamental strategy is to distance oneself from air pollution by time and distance. Pollution exposure varies considerably over time across all time frames from hours to months. Within-day variations can be large and are affected by local factors such as weather (e.g., wind, ambient temperature, precipitation), traffic patterns, topography, and the built environment.[47] Since ground-level O_3 is generated in response to ultraviolet light, O_3 levels typically peak in the afternoon, whereas particulate levels seem to peak in the evening, returning to baseline levels early the next morning.[13,48] Thus, in the absence of extraordinary factors, early in the morning is usually a low pollution time of day. At the other end of the timescale, there are seasonal variations in pollution as well. For example, certain regions of the world have strong seasonal variations in pollution, such as wildfire season in Western North America and haze season in Southeast Asia. Although these seasonal pollution events can last days or weeks, changes in wind, weather, and geography can lead to local variations in exposure which can be used to choose a training location that minimises exposure.

Location is also key when considering air pollution exposure. In general, urban sites have poorer air quality than rural sites, although significant environmental events (e.g., wildfires) can alter this relationship. Within urban areas, pollution exposure is extremely variable and small changes in location by individuals can lead to significant reductions in air pollution exposure. For example, it is clear that levels drop significantly within a small distance from major traffic arteries and many pollutants (e.g., CO, PM, NO_x) reach background levels by 400 metres from a major road;[49] that is, the levels of air pollution that would occur in the absence of anthropogenic emissions. Of course, concentration-distance relationships vary with air pollutants, with some pollutants (e.g., O_3) exhibiting less spatial variability in urban environments.[14] Nonetheless, individuals are encouraged to physically distance themselves as much as possible from significant sources of air pollution. For example, cycle or walking commuters should consider using smaller streets and greenways when safe to do so, whereas outdoor workouts should plan to take place towards the centre of green spaces. It must be considered, however, that for some exercisers of differing abilities (e.g., wheelchair athletes), relocating an exercise session and accessing green spaces on short notice may pose additional challenges.

Summary

- While highly variable, air pollution levels are generally lowest early in the morning. Athletes may also consider participating in events when local seasonal events (e.g., wildfires, haze) are less likely.

- Athletes are encouraged to physically distance themselves from sources of air pollution, such as major roads and highways, and towards green spaces.

MONITORING AIR POLLUTION LEVELS

To optimize the timing and location of exercise, a good understanding of current and forecasted pollution levels is key. This can be achieved by using services that provide current and future air pollution conditions for locations of interest. Local government websites and apps provide trustable data. For example, in Canada, the following government site provides good quality real-time data with reasonable granularity in terms of location: https://weather.gc.ca/airquality/pages/index_e.html. These websites and apps even have utility when planning the location for outdoor exercise. In larger urban centres, conditions are typically monitored at multiple locations, so users can compare different locations within an urban agglomeration to determine where the pollution is at its lowest. Once the general region for activity is determined, then the individual can choose the precise location of activity based on local factors (e.g., towards the centre of green spaces and away from local sources of pollution).

Air quality indices, aggregate measures characterizing air pollution concentrations present at a given moment in time, and their associated health risks are reported by many public health authorities to raise awareness of current local air pollution levels.[50] However, different indices may be used between countries, reflecting different pollutants of interest, air quality standards, and an overall lack of international consensus. Consequently, caution is warranted in directly comparing different air quality indices. In Canada, the reported Air Quality Health Index (AQHI) was developed to reflect the additive effects of NO_2, O_3, and $PM_{2.5}$.[50] In older adults exercising outdoors in rural and urban settings, the AQHI has been demonstrated to be predictive of acute subclinical adverse cardiorespiratory effects (e.g., decrease in heart rate variability, increased oxidative stress, decrease in FEV_1).[51–53]

It must be acknowledged that most websites and indices generally rely on networks of fixed-site monitoring stations or remote sensing techniques that are designed to estimate population-wide exposures for regulatory purposes.[54] While capable of providing accurate, long-term air quality data, monitoring stations have high construction costs and consequently, are sparsely distributed and rarely situated near locations of interest in respect to exercise and sport. In other words, the data may be nonspecific to an individual athlete's environmental context and incapable of providing actionable, hyperlocal, time-resolved data. World Athletics has begun important work in this area, deploying air pollution sensors inside main athletics stadia to provide local measurements.[54,55] Alternatively, low-cost, wearable air pollution sensors present a potentially promising method to determining exposure levels.[56] These sensors can theoretically overcome the spatial and temporal limitations of fixed-site station-derived air pollution estimates, providing athletes with the ability to independently acquire immediate and hyperlocal exposure data to quickly modify behaviour before or during a workout. While there has been a rapid proliferation of such devices in recent years, many devices still lack sufficient third-party validation. An objective sensor evaluation is provided by the South Coast Air Quality Management District in California (http://www.aqmd.gov/aq-spec/sensors). This group evaluates the performance of low-cost sensors against gold-standard reference instruments and publishes their findings online. We do not recommend or endorse any specific sensors at this time.

Summary

- Minimize air pollution exposure by monitoring current and forecasted levels of air pollution for locations of interest using trusted sources (e.g., local government websites).
- Affordable, wearable air pollution sensors theoretically allow for the timely assessment of personal air pollution levels. However, the performance of such sensors may be highly variable.

INDOOR EXERCISE AS AN ALTERNATIVE

Moving an exercise bout indoors may be an alternative to reduce exposure when ambient pollution is high. However, the unintended consequence may be increased exposures to indoor air pollutants. Consequently, the effectiveness of this strategy is dependent on the ratio of indoor-outdoor air pollution concentrations. In the discussion below, we will focus on several factors that influence this ratio, including the types and sources of air pollutants, degree of infiltration, and available building ventilation.[57]

Indoor types and sources of air pollutants have been shown to vary greatly depending on the type of sporting facility. For example, while PM, CO, and NO_2 levels may be of particular concern in ice hockey arenas or skating rinks due to the use of propane- or gasoline-powered ice resurfacing machine (e.g., Zambonis), VOC concentrations may be of special concern in fitness centres given the frequent use of disinfectants.[3,58] In general, some common sources of air pollution in sporting environments include ice resurfacing machines, dust, moulds, cleaning agents, paints, disinfectants, air fresheners, candles, climbing chalk, and snowboard/ski wax. For a comprehensive overview of the relevant types and sources of air pollutants in indoor sporting environments, we refer to a recent review by Salonen *et al.*[58]

Indoor air quality is also influenced by the surrounding outdoor air pollution by means of natural building ventilation and infiltration (i.e., exchange of air pollutants between indoor and outdoor environments via cracks and leaks in a building).[57] For example, Weichenthal *et al.* conducted a crossover study in healthy women and compared the cardiovascular responses to cycling in outdoor or indoor settings.[59] Similar $PM_{2.5}$ between indoor and outdoor environments was reported, attributed to the presence of open windows.[59] Similarly, another study found high concentrations of $PM_{2.5}$ in an elementary school gym in Prague, which authors theorized as penetration of traffic-related air pollution (TRAP) from a nearby traffic-dense street.[60] Thus, in some buildings, the action of closing doors and windows could reduce the exchange of air, and subsequently, lower concentrations of indoor pollutants. However, the trade-off is potentially 'trapping' more air pollutants originating from indoor sources. Portable air cleaners (PAC) and central heating, ventilation, and air conditioning (HVAC) systems with built-in filters (e.g., high-efficiency particulate arrestance [HEPA] filters) present promising solutions, despite a paucity of evidence on changes in health outcomes from their use.[61]

Nevertheless, when the ratio of indoor-outdoor air pollutant concentrations is favourable (e.g., indoor air quality exceeds outdoor air quality), limited evidence suggests that exercising indoors may confer physiological benefits. Several studies in healthy adults have shown that compared to indoor environments with air cleaned via a HEPA filter, exercising while breathing ambient air characterized by high levels of TRAP can impair glucose metabolism, increase systemic inflammation, and attenuate post-exercise hypotension.[62–65] In another study of older adults in Brazil, a greater improvement in glycaemia, brain-derived neurotrophic factor, and cognitive function was observed following 12 weeks of aerobic training in an indoor environment, relative to an outdoor urban park.[66]

Summary

- When ambient air pollution concentrations are high, it may be favourable to relocate an exercise bout indoors after considering the indoor air quality and potential co-exposures (e.g., indoor temperatures).
- Indoor air quality can also be improved by controlling indoor sources of air pollution, optimizing ventilation, and using portable air cleaners fitted with HEPA filters.

ACCLIMATION

Acclimating to air pollution may be a viable performance strategy in certain populations (i.e., high-performance athletes). Multiple small laboratory studies involving consecutive daily short-term exposures to O_3 during exercise have investigated the acclimation effect in respect to respiratory function and symptom responses. In general, these studies involved healthy adults or those with mild asthma intermittently exercising at light intensities while exposed to high concentrations of O_3 (~200-

500 ppb) for ~2 hours on 4-5 consecutive days.[67,68] In these studies, post-exercise FEV_1 was worse with the initial two days of O_3 exposure, before gradually improved with consecutive daily exposures, such that FEV_1 on the last days of O_3 exposure was similar to levels observed following an exercise bout in filtered air.[67,68] However, this acclimation appears to persist for less than a week.[68,69] One study examined the potential effects on performance outcomes, finding that after four consecutive days of 350 ppb O_3 exposure, performance time and $\dot{V}O_2$peak were no different than in the filtered air condition;[70] however, there is likely significant inter-individual variability in response.

The O_3 acclimation effect may be, in part, concentration-dependent.[71] In one modelling study using a dataset of over 650,000 performance outcomes from outdoor collegiate athletes, those who experienced the greatest O_3-induced detriment in performance were exposed to the lowest levels of O_3 seven days before their event; this supports a potential acclimation effect dependent on exposure over several days.[72]

The potential for acclimation to other pollutants in relation to exercise is less clear. In one study involving 16 male, collegiate athletes performing two consecutive days of maximal exercise tests while exposed to high levels of PM (~340,000 particles/cm^3), no acclimation effect was observed.[73] Only a single study was found to examine the effects of four consecutive daily exposures to NO_2 during exercise: decrements in FEV_1, FVC, and antioxidant status was observed following the first day of exposure, but the magnitude of the decrements decreased following the fourth day.[74] Nonetheless, the dose of NO_2 used was several times larger than ambient levels.

In summary, O_3 appears to be the pollutant with the most potential for acclimation. The findings must be interpreted cautiously, given the very high O_3 levels, limited endpoints and very low-intensity exercise used. It must therefore be acknowledged that the use of an O_3 acclimation protocol remains speculative until the safety and real-world effectiveness of such a strategy can be properly assessed.

Summary

- Laboratory studies suggest that exposure to high levels of ozone on multiple, consecutive days may allow athletes to acclimate to the deleterious pulmonary effects of ozone.
- Athletes should be aware that the safety and effectiveness of an ozone acclimation protocol, in the context of sport and performance, has yet to be directly tested outside of laboratory settings.

EXPOSURE PRIOR TO COMPETITION

Exposure to air pollution before an exercise bout may have cardiorespiratory and performance implications, even when the exercise itself is performed in optimal air quality. This is an important practical question, as athletes and exercisers are likely exposed to higher levels of air pollution during their travel to a sporting environment. For example, while bus commuting generally makes up <5% of one's day, it can contribute between 11%-70% of one's daily exposure to certain traffic-related pollutants.[75] For the purpose of this discussion, we refer to 'pre-exercise' as the exposure to air pollutants hours prior to an exercise bout, whereas 'acclimation' refers to intentional multi-day protocols involving short-term exposures to high levels of air pollution.

Two studies investigating the cardiorespiratory and performance effects of pre-exercise exposure have been conducted using controlled laboratory conditions, exposing participants to high levels of DE at 300 µg/m^3 of $PM_{2.5}$. In one study involving eight endurance-trained males, 60 min of resting exposure to DE prior to exercise increased exercise HR, and attenuated exercise-induced bronchodilation. However, performance on a 20-km cycling time trial was not affected.[76] In the second study, constant load cycling performed 2.5 hours following a 2-hour resting pre-exercise exposure to DE impaired exercise tolerance, ventilatory responses, and dyspnea in 11 healthy, older adults.[77]

Minimizing pre-exercise air pollution exposure is therefore recommended. For example, for organized sports involving team buses, individuals should avoid meeting in semi-closed transport hubs or leaving the bus running while waiting for the passengers to board. Alternatively, when possible, travel should be avoided altogether. While en route to training or competition, athletes can also minimize air pollution exposures by closing vehicle windows, turning on air conditioning, and using cabin air filters. Outside of training or competition in high particulate air pollution, a mask that effectively filters particles may be beneficial.

Summary

- Minimize exposure to air pollution during transportation to exercise facilities by closing vehicle windows, turning on air conditioning, and using cabin air filters.

RESPIRATORS AND FACE MASKS

When exposures cannot be avoided, a face mask that reduces the inhalation of air pollutants can be considered. The effectiveness of a face mask is dependent on the pollutant, type of filter or adsorbent material, ability to correctly don the mask, and quality of face seal. Not all users will be able to achieve an optimal seal with a single mask given varying facial characteristics (e.g., masks certified for adults may not fit children properly). The protection conferred by the cloth and surgical masks that have become commonplace during the COVID-19 pandemic is inconsistent given the inability to form a tight seal, allowing pollutants to flow through the path of least resistance via gaps in the face seal, rather than the filter itself.[78]

Surprisingly, research into the health and performance effects of masks in the context of air pollution is lacking. Langrish *et al*. found a beneficial BP and autonomic effect from wearing an N95 face mask during a 2-hour walk. However, participants wore masks for 24 hours on the day before and the day of the study (for a total of 48 hours), limiting generalizability.[79] In a recent double-blinded, randomized study, wearing an N95 face mask during a 2-hour walk had beneficial effects on lung function, airway oxidative stress, and systemic inflammation, relative to a sham mask.[80] Among children, wearing an N95 mask designed for paediatric populations while briskly walking was found to be comfortable and safe.[81] In the only study investigating the use of carbon-infused masks to protect against O_3, improvements in lung function were observed compared to a sham mask, but discomfort and breathing difficulties were also reported.[82]

Although recent meta-analyses found wearing an N95 face mask during exercise had minimal physiological and performance effects,[83] they are not universally tolerated during exercise. Therefore, given the paucity of studies investigating the health and performance effects of wearing a face mask during moderate-to-vigorous intensity exercise in a highly polluted environment, we do not specifically recommend wearing a face mask during moderate-to-vigorous exercise. Nonetheless, athletes in high PM environments may consider the use of a properly fitted N95 face mask prior to and following training and competition to minimize the potential adverse effects of pre-exposure.

Summary

- Athletes in environments characterized by high levels of PM may consider wearing a face mask that has been verified to remove ≥ 95% of airborne particles (i.e., N95, KN95, FFP2) when outside of training or competition. Cloth and surgical masks are not recommended given the variability in forming tight face seals, undermining their effectiveness.
- Face mask efficacy is dependent on: 1) wearing it correctly, 2) ensuring proper fit via a user seal check, and 3) maintaining and replacing the mask after saturation.

MEDICATIONS

EIB is a respiratory disorder that is particularly prevalent in athletic populations, which is of concern, given asthmatics may be prone to acute exacerbations brought on by air pollution.[38] Common first- and second-line medications include inhaled β_2-agonists (e.g., salbutamol/albuterol, salmeterol), inhaled corticosteroids, anticholinergics, and leukotriene receptor antagonists (e.g., montelukast).[38] As air pollution contributes to EIB by exacerbating oxidative stress and inflammatory pathways, it has been hypothesized that these medications may be effective prophylactic medications. However, the available research is limited, and each medication likely has different effects and may work differently according to the pollutant. On the contrary, concerns have also been raised over asthma medications potentially proving counterproductive by facilitating the deposition of pollutants further down the bronchial tree via bronchodilation. Indeed, recent work in mice has demonstrated exacerbations in O_3-induced respiratory inflammation with combined long-acting β_2-agonists and glucocorticoid use.[84]

In two double-blinded, placebo-controlled trials involving competitive, non-asthmatic athletes exposed to O_3, salbutamol did not attenuate the effects of O_3 on lung function, symptoms, or exercise performance.[85,86] In a recent study exposing young adults with EIB to high DE concentrations, pre-exercise salbutamol use induced bronchodilation, reduced the work of breathing, but did not affect dyspnea, micro- or macro-vascular function, or HR, when compared to filtered air.[87,88] Use of the long-acting β_2-agonist salmeterol in adults with asthma exposed to SO_2 improved decrements in pre- to post-exercise change in FEV_1 and symptoms.[89] Some studies do suggest that montelukast use, at least under well-controlled conditions, may be effective at attenuating SO_2- and PM-induced bronchoconstriction, respiratory inflammation, and endothelial dysfunction.[90–92]

Taken together, there is currently no evidence to suggest that asthma medications can aggravate the acute effects of air pollution exposure during exercise. Likewise, there is also no support for using these medications in non-asthmatics or increasing the dose in asthmatics exercising in high pollution conditions. Limited evidence suggests montelukast or salmeterol use may have vascular and respiratory benefits under certain conditions, but there is no evidence that these changes translate into ergogenic benefits. However, prior to the prescription of montelukast, a shared decision-making process must be undertaken to evaluate the risk-benefit trade-off, given montelukast's risk for serious adverse neuropsychiatric events.[93] In summary, patients with asthma or EIB should continue to use asthma medications as prescribed and avoid increasing medication doses prior to exercising in a polluted environment. As always, athletes must remain in compliance with current anti-doping regulations regarding any medication use (https://www.wada-ama.org/en/prohibited-list).

Summary

- Asthma medications do not appear to mitigate or aggravate the effects of air pollution exposure during exercise.
- Athletes with asthma and/or EIB should continue to pharmacologically control their conditions, with the dose and frequency as prescribed.
- Practitioners must remain aware and up to date with organisation-specific anti-doping regulations.

SUPPLEMENTS

Much research examines the interaction between supplements and pollution, given that multiple air pollutants (e.g., PM, O_3) exert their adverse cardiorespiratory effects by augmenting oxidative stress levels.[94] However, relatively few studies have explored the potential role of antioxidant supplementation in modulating the health and performance effects of air pollution exposure during exercise; exercise is known to improve cardiorespiratory fitness levels by favourably influencing one's antioxidant capacity, which may potentially offset the pro-oxidative effects of air pollution.[94]

In two ecological studies following healthy, amateur Dutch cyclists during the summer, antioxidant supplementation had a prophylactic effect against acute O_3-induced decrements in lung function. In the first trial, ambient O_3 levels were negatively associated with post-exercise FVC, FEV_1, peak expiratory flow; 12 weeks of daily β-carotene, vitamin E, and vitamin C (starting one week before measurements) modified this relationship.[95] Findings were replicated in a second larger trial involving 38 cyclists: a 100 $\mu g/m^3$ O_3 (~51 ppb) exposure reduced FEV_1 and FVC by 95 ml and 125 ml, respectively, and daily antioxidant supplementation attenuated these reductions.[96] However, variability exists between studies, with one double-blinded trial finding no improvements in O_3-induced respiratory inflammation or symptoms, despite a significant attenuation in lung function,[97] and another reporting no protection whatsoever in terms of lung function and inflammation.[98] In the only study examining performance effects, using antioxidant supplementation in trained runners did not affect average speed, HR, perceived exertion, or total time on an 8-km time trial performed in 100 ppb O_3.[99]

The benefits of antioxidant supplementation are less clear in the context of TRAP. A one-time red-orange juice supplementation 2.5 hours prior to a Yo-Yo intermittent recovery test blunted TRAP-induced increases in post-exercise HR, systolic BP, skeletal muscle damage, and lipid peroxidation.[100] However, despite authors reporting reductions in $\dot{V}O_2$peak from TRAP exposure, no effect modification from the red-orange juice supplementation was observed.[100] In summary, while recognizing significant variability between studies, it appears that antioxidant dietary supplementation with 250-650 mg of vitamin C and 75-100 mg of vitamin E, and 25 mg of β-carotene for at least one week prior to exercising in a high O_3 environment may reduce O_3 effects, especially in those with inadequate dietary intake.

Summary

- For at least one week prior to exercising in an environment with high O_3 levels, athletes may consider consuming 250-650 mg of vitamin C and 75-100 mg of vitamin E, and 25 mg of β-carotene.

CONCLUSION

Air pollution is of particular importance in the context of sport, with athletes generally inhaling larger doses of air pollutants in both acute and chronic settings. While the health, well-being, and performance effects of exercising in air pollution have yet to be fully elucidated, the health effects of air pollution are well documented and substantial. Changes in national policies are necessary to create long-lasting changes, but evidence-informed and practical personal-level strategies offer athletes a major tool in reducing the exposures to and effects of air pollution. Based on the reviewed literature and the perspectives of the panel of authors, athletes may minimize air pollution exposures outside of training and competition by monitoring concentrations, exercising in the morning or in locations when seasonal events are less likely, minimizing pre-exercise and intra-transport exposures, wearing face masks, and optimizing antioxidant consumption. Athletes with asthma and/or EIB should continue to use medications as prescribed by their physicians. Consecutive multi-day exposures to ozone prior to competition may also attenuate the pulmonary effects of ozone pollution. During exercise, athletes should aim to minimize the total inhaled dose of air pollution and maximize distances from significant sources of air pollution (e.g., major traffic arteries).

The contents of this statement should be interpreted in the context of its limitations. Foremost is the uncertainty and limited primary evidence base underscoring the provided recommendations. As expected, the literature search identified relatively few relevant research studies for each strategy, with some completely lacking high-quality, randomized controlled studies designed to specifically investigate their efficacy. Moreover, while systematic methodologies were employed during the literature search, a narrative approach was necessary due to the limited primary evidence base and methodological heterogeneity. To employ a truly personalized approach to mitigating the impact of air pollution in sport and exercise, further research investigating the different complex components of exercise (e.g., frequency, intensity, modality, and duration) and air pollution (e.g., type, sources, concentrations, and mixtures) is warranted. We did not identify any studies investigating the long-term efficacy of any strategies on 'hard' clinical or performance endpoints either. There is also a distinct lack of diversity in the evidence base regarding sport type and competition level—most were performed in young, healthy adults employing a cycling, running, or walking model.

This statement was intended to raise public awareness of and provide guidance around a growing area of concern in the sport and exercise field. The benefits and harms of each strategy remain, to a degree, uncertain. Future well-designed randomized controlled trials are necessary to further validate the efficacy of each strategy in optimizing the health and performance of athletes. In all situations, this statement should not supplant clinical judgement, and a shared, informed decision-making process should be undertaken prior to the adoption of any interventions.

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