Sports Med (2014) 44:223–249
DOI 10.1007/s40279-013-0108-z

REVIEW ARTICLE

The Health Effects of Exercising in Air Pollution

Luisa V. Giles · Michael S. Koehle

Published online: 1 November 2013

Abstract The health benefits of exercise are well known. Many of the most accessible forms of exercise, such as walking, cycling, and running often occur outdoors. This means that exercising outdoors may increase exposure to urban air pollution. Regular exercise plays a key role in improving some of the physiologic mechanisms and health outcomes that air pollution exposure may exacerbate. This problem presents an interesting challenge of balancing the beneficial effects of exercise along with the detrimental effects of air pollution upon health. This article summarizes the pulmonary, cardiovascular, cognitive, and systemic health effects of exposure to particulate matter, ozone, and carbon monoxide during exercise. It also summarizes how air pollution exposure affects maximal oxygen consumption and exercise performance. This article highlights ways in which exercisers could mitigate the adverse health effects of air pollution exposure during exercise and draws attention to the potential importance of land use planning in selecting exercise facilities.

1 Introduction

Physical inactivity poses a significant health risk to individuals as it increases the likelihood of developing heart disease, type 2 diabetes mellitus, cancer, and stroke [1, 2]. It is estimated that physical inactivity is the fourth most common cause of mortality and contributes to 3.2 million deaths annually [3]. Many of the most accessible forms of exercise, such as walking, cycling, and running often occur outdoors. Globally, 52 % of people live in urban centers, and in the developed world this figure approaches 78 % [4]. This means that exercising outdoors may increase exposure to urban air pollution. Therefore, the purpose of this review is to summarize the health effects of exercising in air pollution, with a focus on particulate matter (PM), ozone, and carbon monoxide, as these pollutants are likely to cause adverse health effects in urban exercisers.

A literature search using PubMed, Google Scholar, and EMBASE was performed. Text word searches of article titles and abstracts were conducted using search terms relevant to exercise and air pollution. Combinations of the following primary key words were used in the searches: *ozone, particulate matter, particulate, diesel exhaust, gasoline, carbon monoxide, exercise, physical activity,* and *exertion*. The use of 'wild cards' where appropriate captured variants on terms (e.g., exerci* to capture exercise, exercising). The literature search was last performed in April 2013. There was no restriction of searches to specific time/date ranges. Studies that directly examined the interactive effects of exercise and air pollution were included.

2 Introduction to Air Pollution and Health

Air pollution can be present as either gases or particles, and is emitted directly from a source (primary) or formed in the atmosphere (secondary) [5]. Ambient (outdoor) air quality guidelines for each of the pollutants detailed below can be found in Table 1.

L. V. Giles (✉) · M. S. Koehle
School of Kinesiology, University of British Columbia, 210-6081 University Blvd, Vancouver, BC V6T 1Z1, Canada
e-mail: luisagiles@gmail.com

M. S. Koehle
Division of Sports Medicine, University of British Columbia, Vancouver, Canada

Table 1 World Health Organization air quality guidelines

Pollutant	Averaging period		
	Annual	24 h	8 h
$PM_{2.5}$	10 μg/m^3	25 μg/m^3	
PM_{10}	20 μg/m^3	50 μg/m^3	
Ozone			50 ppb
Carbon monoxide			9 ppm

PM particulate matter, *ppb* parts per billion, *ppm* parts per million, *PM_{10}* PM with a mean aerodynamic diameter of 10 μm or less, *$PM_{2.5}$* PM with a mean aerodynamic diameter of 2.5 μm or less

2.1 Particulate Matter (PM)

PM is a mixture of solid and liquid components, of varying sizes and chemical compositions. Sources of PM include wood and fossil fuel combustion, incense and candle burning, as well as the oxidation of gases emitted from automobiles and power plants, and natural sources such as wind-blown dust and wildfires [5]. Estimated annual $PM_{2.5}$ concentrations in many North America cities may be below 20 μg/m^3 [6]. Twenty-four-hour averages in Canada and California exceeded 30 and 65 μg/m^3, respectively, for 2 % of the year [5]. In contrast, in Beijing, acute episodes of high air pollution can result in 24-h $PM_{2.5}$ concentrations that exceed 250 μg/m^3 [7].

PM is typically categorized by its aerodynamic diameter; this differs from its geometric diameter as it takes into account the behavior of the particle in air. The aerodynamic diameter takes into account factors such as particle density, size, and shape, which play a key role in deposition in the respiratory tract and associated health effects. PM is grouped into three size fractions (Table 2), all of which are smaller than the diameter of a human hair.

PM exposure is associated with respiratory and cardiovascular conditions such as myocardial infarction, stroke, atherosclerosis, bronchitis, and asthma [8–13]. Three proposed pathways in which PM exposure leads to cardiovascular disease involve (1) pulmonary oxidative stress and inflammation, (2) perturbation of the autonomic nervous system, and (3) translocation of PM or its constituents into the circulation. Collectively, these pathways may result in systemic oxidative stress and inflammation, platelet aggregation, vasoconstriction, endothelial dysfunction, increased blood pressure, heart rate, arrhythmia potential and coagulation, decreased heart rate variability, and the potential to cause atherosclerotic progression and plaque vulnerability [14].

Table 2 Size fractions of particulate matter

Name	Acronym	Description
Coarse PM	$PM_{2.5–10}$	PM with a mean aerodynamic diameter between 2.5 and 10 μm
Fine PM	$PM_{2.5}$	PM with a mean aerodynamic diameter of 2.5 μm or less
Ultrafine PM	$PM_{0.1}$	PM with a mean diameter of 0.1 μm or less

PM particulate matter

2.2 Ozone

Ground level ozone is a secondary gaseous pollutant that forms by chemical reactions in the atmosphere involving nitrogen dioxide, sunlight, and hydrocarbons [5]. Mean 1-h maximum concentrations in North America and Europe can approach 100 parts per billion (ppb) [5]. However, in cities such as São Paulo and Mexico City, concentrations may exceed 200 ppb for several days [5]. Many monitoring locations in the USA can often exceed the World Health Organization 8-h ozone guideline of 50 ppb [15]. Ozone is a respiratory irritant that impairs pulmonary function and heart rate variability, causes lung inflammation airway hyper-responsiveness, and may interact with lung defense mechanisms by impairing mucociliary clearance, decreasing macrophage activity, and depleting airway antioxidant defenses [5, 16, 17].

2.3 Carbon Monoxide

Carbon monoxide is a colorless, odorless gas that is produced from the incomplete combustion of fuels containing carbon [18]. Common outdoor sources of carbon monoxide include car exhaust fumes (gasoline and diesel), stationary combustion equipment such as heating and power-generating plants, smoke from fires, and gas-powered engines [19–21]. Outdoor concentrations are highest near car exhaust, in congestion, and near traffic intersections [20]. Typical 8-h concentrations in European cities are 17 parts per million (ppm) with short peaks below 53 ppm [22].

Carbon monoxide exerts a toxic health effect through hypoxic and non-hypoxic mechanisms, and has a 210–240 times greater affinity for hemoglobin (Hb) compared with O_2. Approximately 80–90 % of absorbed carbon monoxide binds with Hb to form carboxyhemoglobin (COHb), which reduces the O_2-carrying capacity of blood, leading to tissue hypoxia [19, 21, 23, 24]. Carbon monoxide exposure may also result in a pro-oxidant cellular environment [25], and affect mitochondrial respiratory chain components, leading to an attenuated energy production, causing cellular injury or dysfunction [26].

3 Air Pollution Exposure with Different Modes of Transport

Research examining the microenvironment implies that the mode of transport can affect exposure to air pollution. This becomes important when considering passive travel to an

exercise location and active travel such as cycle commuting. Much of the work has focused on PM exposure, and suggests that cyclists traveling in bicycle lanes in major urban centers may be exposed to more $PM_{2.5}$ than pedestrians [27–29]. Gaseous pollutants follow a similar pattern to that of PM, with cyclists being more exposed than pedestrians [30]. Such differences in exposure are likely attributable to the proximity of cyclists to traffic, and may be easily mitigated through choosing a cycling route with less traffic or by appropriate land-use planning that separates bicycle lanes from traffic. While there are differences in pollutant exposure between cyclists and pedestrians, they are small and whether such differences result in health effects is unclear.

For those travelling to an exercise location it is important to consider that car and bus passengers can receive similar or higher exposures than if walking or cycling, and fuel type may affect this exposure [29, 31]. The health effects of exposure to air pollution are discussed further below, but given that exposure to $PM_{2.5}$ prior to exercise can increase exercise heart rate [32], and that time spent in traffic is associated with a post-exposure myocardial infarction risk [33], it is important for individuals and exercise professionals to consider how travel to training and competition could affect health and exercise performance.

4 How Exercise May Increase Susceptibility to Air Pollution

During exercise a number of physiologic changes occur that could exacerbate the effects of air pollution on health. These include alterations in breathing, pollution dose, and nasal defenses. At submaximal exercise levels (at a power output of approximately 100 W or ventilation of approximately 35 L/min), breathing switches from predominantly nasal to predominantly oral [34]. This transition causes the nasal filtration system to be bypassed, potentially increasing pollutant dose, which may exacerbate the health effects of air pollution.

When exercise begins, minute ventilation (V_E) increases; additionally, exercise increases the proportion of ultrafine particles (UFP, Table 2) that deposit in the airways and are not exhaled (deposition fraction; 0.6 at rest, 0.8 during exercise) [35, 36]. Compared with rest, the increased deposition fraction and V_E with exercise can collectively lead to a 3- to 4.5-fold increase in the total number of particles deposited in the airways during light exercise, and a 6- to 10-fold increase during high-intensity exercise [36, 37]. The total deposition of particles tends to be greater in men compared with women and children [37]. The greater total deposition with exercise may enhance the adverse effects of air pollution. However, the balanced net relationship between particles and health during exercise becomes less clear when one considers that 2.5 h following PM exposure during exercise, retention of PM within the lung is less, and estimated bronchial clearance is greater than with rest [38]. Breathing frequency and V_E influence the uptake of ozone and carbon monoxide; therefore, for the same concentration of pollutant the amount inhaled that could lead to health effects would be greater [39–41]. Strenuous exercise impairs nasal mucociliary clearance and reduces nasal cilia beat frequency [42, 43]. The impairment of respiratory defenses may increase the dose of air pollution during exercise, and leave an urban exerciser more vulnerable to subsequent air pollution exposure.

If one assumes that adverse health effects are proportional to the dose of pollution, one would expect this to be more likely in exercisers. However, regular exercise plays a key role in improving some of the physiological mechanisms and health outcomes that air pollution exposure may exacerbate. This problem presents an interesting challenge of balancing the beneficial effects of exercise along with the detrimental effects of air pollution upon health.

5 Pulmonary Effects of Exercise and Air Pollution

5.1 Breathing Pattern and Minute Ventilation

5.1.1 PM

Air pollutants are respiratory irritants that can alter breathing patterns during exercise by increasing breathing frequency and decreasing tidal volume [44–55]. The effects of PM exposure during exercise on the breathing pattern have not been studied, but when exposure to diesel exhaust containing high concentrations of PM with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) occurs prior to exercise, the breathing pattern during exercise is not affected [32].

5.1.2 Ozone

At submaximal intensities, with ozone exposure V_E is typically maintained; however, maximal V_E decreases in a dose-dependent manner above 150 ppb, likely due to a reduction in maximal exercise performance [56, 57]. Compared with clean air exposures, ozone exposure increases breathing frequency and decreases tidal volume during submaximal exercise [44–55], which may be mediated by C-fiber stimulation [58]. For shorter duration acute exposures (~1 h), ozone levels greater than 180 ppb similarly alter the breathing pattern [54]. However, with longer duration but acute exposures (~6.6 h), much lower concentrations (80 ppb) cause this response [45]. The World Health Organization guideline for 8-h ozone concentration is 50 ppb (Table 1), this is below the concentration that alters the breathing pattern; however, many monitoring

locations in the USA often exceed this 8-h level [15]. This situation suggests that exercising individuals may be exposed to concentrations similar to 80 ppb and thus experience alterations in their breathing patterns.

5.1.3 Carbon Monoxide

Carboxyhemoglobin-induced tissue hypoxia may be sensed by the central nervous system, and stimulate the respiratory centers to increase ventilation [19]. Ventilation following carbon monoxide administration does not appear to be affected during low-intensity exercise. Conversely, at higher exercise intensities (above the lactate threshold) V_E exponentially increases, and, the higher the %COHb, the higher the V_E for the same work rate [59]. The increase in V_E and %COHb associated with carbon monoxide exposure may initiate a feedback loop that would further increase V_E and hence %COHb. To see such changes in V_E, one requires COHb levels in excess of 11–20 % [59], this is higher than the typical %COHb of smokers and would require exposure to concentrations of 120 ppm [20]. This concentration of carbon monoxide exceeds typical indoor concentrations (<5 ppm), and ambient air quality guidelines [24], thus making this level of exposure unlikely. However, exceptions to this are indoor environments such as ice arenas where faulty resurfacing and poor ventilation may result in carbon monoxide levels up to 304 ppm [60].

5.2 Lung Function

There are currently no data assessing the effects of carbon monoxide on lung function. However, acute (hours–days) exposure to PM and ozone during exercise adversely affects lung function. Additionally, chronic (weeks–years) exposure to PM in an exercise facility adversely affects baseline lung function, and outdoor levels of ozone are associated with asthma in active children. A summary of these studies can be found in Sects. 5.2.1, 5.2.2, 5.2.3, and in Table 3.

5.2.1 PM

PM exposure may result in oxidative stress, increased bronchial responsiveness, increased airway resistance, and increased airway inflammatory cells [61, 62], each of which may impair lung function. The role of the indoor environment in impairing lung function is particularly applicable in ice arenas, where combustion related to the use of ice resurfacing equipment affects indoor air quality. In ice arenas, indoor levels of PM can be 30-fold greater than outdoors, and can increase a further 4-fold following ice resurfacing [63]. Exercising regularly over a 2 year period in ice arenas using fossil-fueled resurfacing equipment decreases baseline forced expiratory volume in 1 s (FEV_1; up to an 11 % reduction), and forced expiratory flow in the middle 50 % of expiration ($FEF_{25–75}$; up to a 22 % reduction). In the same individuals, following acute exercise in a high PM_1 (PM <1 μm) ice arena, individuals with exercise-induced asthma experience reductions in forced vital capacity (FVC, 12 %), FEV_1, (15 %), and $FEF_{25–75}$, (28 %). While these reductions are considerable, they do not differ from those in a low PM_1 environment [64], indicating that the chronic exposure during exercise training may be more important. Given that a significant number of individuals in North America, Europe, and Russia use ice arenas regularly, this presents an area that may benefit substantially from the use of non-fossil fuel ice resurfacing.

The health effects of air pollution may persist for hours following exposure. Therefore, the role of exposure prior to exercise is also important to consider. To this end, exposure to high concentration of $PM_{2.5}$ prior to exercise significantly reduces exercise-induced bronchodilation (FEV_1 change from baseline −0.2 % in 300 μg/m^3 of $PM_{2.5}$ vs. +3.5 % in air), implying that the environment prior to exercise may also affect lung function [32].

5.2.2 Ozone

Decrements in lung function following ozone exposure may be due to stimulation of bronchial C-fibers causing bronchoconstriction [65, 66]. In communities with high concentrations of ozone, the risk of children developing asthma is related to the time they spend outside, and the number of outdoor sports that they play (three or more vs. none) [10]. The risk of asthma does not hold true for communities with low concentrations of ozone [10], and genetics may play a role in this risk [67].

A large number of studies have suggested that acute ozone exposure during exercise impairs lung function including FEV_1, FVC, and $FEF_{25–75}$ [45–51, 53–56, 68–94]. These changes occur in healthy school-aged children [73], healthy male and female individuals [53, 56], competitive athletes [74, 83], and trained individuals [53, 77]. There are a smaller number of studies that do not find an effect of exposure to ozone on lung function [57, 95–100], this could be due to a combination of low-concentration or short-duration exposures, low exercise intensity, or small subject numbers within the study.

The effects of ozone on lung function are not different if the exposure occurs orally compared with oronasally [95] or nasally [85]. However, impairments in lung function are significantly greater with higher exercise ventilations compared with lower exercise ventilations [68]. The dose of ozone (concentration • V_E • time) plays an important role in affecting lung function, as there is a dose-dependent decrease in lung function with increasing levels of ozone [45, 56, 68, 70, 84, 87, 101, 102].

Table 3 Summary of studies assessing the effects of air pollution exposure during exercise on lung function

Study	Population and methods	Exposure	Exercise test	Measured outcome
Ambient exposures and mixtures				
Studies reporting significant effects				
Avol et al. [107]	$N = 158$ (57 asthmatic patients, 101 healthy; 101 M, 57 F)	Total suspended particulate 166–227 μg/m^3 Ozone 1,156–1,165 ppb vs. purified air	1 h continuous exercise (V_E 40 L/min)	Data obtained from 2 years of study yielded mixed results within asthmatic patients and healthy patients, depending upon the year. Year 1 showed significant effects on FEV_1 and FVC, year 2 did not
Avol et al. [106]	Adolescents $N = 59$ (46 boys, 13 girls)	Total suspended particulate 153 μg/m^3 Ozone 140 ppb vs. purified air	1-h continuous exercise (V_E 32 L/min)	Significant reduction in FEV_1 that did not fully return to baseline 1 h following ambient exposure
Avol et al. [105]	Children $N = 66$ (33 boys, 33 girls)	Total suspended particulate 88 μg/m^3 Ambient ozone concentration 113 ppb vs. purified air	1 h at 50 % of VO_{2max}	No significant effects between ambient air and purified air. Significant trend towards forced expiratory dysfunction (FEV_1) with increasing ambient ozone levels
Braun-Fahrlander et al. [73]	Healthy school children $N = 128$	Ambient half-hourly ozone levels (20–78 ppb)	10 min of cycling at 170 bpm	Post-exercise decrements in peak flow were associated with ozone levels
Brunekreef et al. [74]	Competitive cyclists $N = 23$ M	Mean 1-h ozone concentration during exercise training or races Mean 43.5 ppb Max 97.5 ppb	Mean exercise time 75 min, heart rate 161 bpm during training, and 176 bpm during races	Ozone levels were negatively associated with FEV_1, FVC, and PEFR, following exercise
Grievink et al. [83]	Amateur cyclists $N = 26$ (23 M, 3 F) 14 controls, 12 antioxidant supplementation	Mean ambient 8-h ozone concentration during exercise training or races: 50.5 ppb	Approximately 90 min of exercise, 154 bpm heart rate	Ozone levels were related to decreased FEV_1, FVC, and peak expiratory flow rate. Antioxidant supplementation mitigated these reductions. No repeated measures, no blinding to supplementation
Korrick et al. [86]	Healthy $N = 530$ (375 M, 155 M)	Mean ozone exposure during a hike 40 ppb	Mean hike time 8 h	2.6 % decline in FEV_1 (95 % CI 0.4–4.7; $p = 0.02$) and a 2.2 % decline in FVC (95% CI 0.8–3.5; $p = 0.003$) for each 50-ppb increment in mean ozone
Kulstrunk and Bohini [110]	Healthy $N = 16$ (10 M, 6 F)	NO_2 71 vs. 7.5 μg/m^3 (approximately 8 min)	Maximum exercise test (approximately 8 min)	FEV_1 significantly decreased (2.5–3 %) 10, 30, 60, and 120 min after exercise in city air compared with room air
McCreanor et al. [111]	Mild and moderate asthmatic patients $N = 60$ (31 M, 29 F)	$PM_{2.5}$ 28.3 vs. 11.9 μg/m^3 UFP 63,700 vs. 18,300 particles/cm^3 NO_2 142 vs. 21.7 μg/m^3	2-h walk along a busy street vs. a park	Significant reduction in % predicted FEV_1 (−6.1 vs. −1.9 %) and FVC (−5.4 vs. 1.6 %) immediately after exposure on the busy street compared with the park. Remained significant until 5 h post-exposure. Moderate asthmatic patients were more severely affected
Rundell et al. [114]	Healthy $N = 12$ M	High PM_1 vs. low PM_1 252,290 vs. 7,382 particles/cm^3	30 min of exercise at 85–90 % max heart rate	FEV_1 and $FEF_{25–75}$ significantly decreased following exercise in a high PM_1 environment compared with a low PM_1 environment

Table 3 continued

Study	Population and methods	Exposure	Exercise test	Measured outcome
Spektor et al. [93]	Healthy $N = 30$	Ozone concentrations during exercise were in the of 21–124 ppb	Each participant repeated the same exercise protocol throughout the summer V_E 20–150 L/min Duration 15–55 min	Ozone was associated with decrements in FVC at −2.1 mL/ppb, FEV_1 at −1.4 mL/ppb, $FEF_{25–75}$ at −6.0 mL/s/ppb, and FEV_1/FVC at −0.038 %/ppb
Studies reporting no significant effect				
Brauner et al. [108]	Healthy $N = 29$ (20 M, 9 F)	24 h exposure to air from a busy street UFP 10,067 vs. 235 particles/cm^3; $PM_{2.5}$ 9.7 μg/m^3 vs. particle filtered	2 × 90 min exercise at 65–70 % max heart rate conducted during the 24-h exposure	No significant effect of exposure and exercise on lung function
Girardot et al. [109]	Healthy $N = 354$ (154 M, 200 F)	Ambient daily $PM_{2.5}$ and ozone levels on the day of the hike	12.2-km hike, approximately 5 h in duration	No association between lung function and ozone or $PM_{2.5}$
Strak et al. [112]	Healthy $N = 12$ (4 M, 8 F)	High vs. low traffic route 44,094 vs. 27,813 particles/cm^3	High traffic route = 8 km Low traffic route = 7.7 km	No significant association between lung function and exposure
Timonen et al. [113]	Children with chronic respiratory symptoms $N = 33$ (18 boys, 15 girls)	Measured ambient pollution levels on the day of testing	Target load of 70–85 % max heart rate Minute 1: 60 % of the target load Minute 2: 75 % of the target load Minute 3: 90 % of the target load Minute 4–8: 100 % of the target load	PM_{10}, black smoke, NO_2, and carbon monoxide were not associated with exercise-induced bronchial responsiveness. However, air pollution levels were associated with reductions in baseline lung function
Particulate matter				
Studies reporting significant effects				
Giles et al. [32]	Cyclists $N = 8$ M	60-min exposure to diesel exhaust containing 300 μg/m^3 of $PM_{2.5}$ followed by exercise	20-km cycling time trial	Pre-exercise exposure to 300 μg/m^3 of $PM_{2.5}$ significantly reduced exercise-induced bronchodilation (FEV_1 change from baseline −0.2 % in 300 μg/m^3 of $PM_{2.5}$ vs. +3.5 % in air)
Rundell [64]	$N = 23$ F (14 ice hockey players and 9 control Nordic skiers)	2 years of training in a low PM_1 rink (electric resurfacer) then moved to a high PM_1 rink (fossil fuel resurfacer) for 2 years Controls trained in a low PM_1 environment	6-min exercise skating challenge performed pre- and post-lung function test	Two years following the move, players experienced a significant reduction in baseline measures of FEV_1 and $FEV_{25–75}$ reductions were as large as 11 and 22 %, respectively Rates of lung function decay over 4 years were significantly greater in ice hockey players than controls for FEV_1, FVC, $FEF_{25–75}$, and PEFR. Unable to investigate EIB because of the small sample size for EIB+ individuals

Table 3 continued

Study	Population and methods	Exposure	Exercise test	Measured outcome
Rundell [64]	Collegiate ice hockey players $N = 26$ M with exercise-induced asthma	Low PM_1 vs. high PM_1 ice rink 2,580 particles/cm^3 vs. 348,600 particles/cm^3	6-min maximal cycling test	FEV_1, FVC, and $FEF_{25–75}$ fell following exercise in PM. No significant difference between low PM_1 and high PM_1 conditions. Use of montelukast attenuated the fall in FVC, FEV_1, and $FEF_{25–75}$ following exercise in a high PM_1 environment, and only in $FEF_{25–75}$ in a low PM_1 environment
Ozone				
Studies reporting significant effects				
Adams et al. [70]	Healthy $N = 8$ M	200, 300 or 400 ppb 18 different protocols that elicited doses of 400, 580, 800, and 1,120 ppm/L Dose = concentration × V_E × time	Exposure time between 30 and 80 min, and exercise V_E at 33 L/min and 66 L/min	Main effect of dose on lung function, which increased with decreasing dose. Post hoc revealed significant reduction in lung function at 1,120 ppm/L dose. Protocol to elicit this dose: 300 ppb, for 60 min at V_E of 66 L/min or 400 ppb for 45 min at a V_E of 66 L/min
Adams et al. [47]	Trained distance runners $N = 10$	200 or 350 ppb for 60 min	2 exercise sessions: (1) 60-min continuous (V_E of ~80 L/min) (2) 30 min warm-up followed by 30 min at 85 % VO_{2max} (V_E 75 L/min)	Ozone significantly reduced FVC, FEV_1, and $FEF_{25–75}$ in a dose-dependent manner. No significant difference between exercise modes
Adams et al. [69]	Aerobically trained $N = 40$ (20 M, 20 F)	300 or 300 ppb of ozone plus 600 ppb of NO_2 for 1 h	1 h of cycling ($V_E = 50$ L/min for women and 70 L/min for men)	Ozone alone, and ozone plus NO_2 significantly reduced FEV_1, FVC, and $FEF_{25–75}$. Ozone plus NO_2 did not cause effects greater than ozone alone
Adams [68]	Healthy $N = 30$ (15 M, 15 F)	300 ppb for 1 h	2 sessions with exercise ($V_E = 17$ L/min/m^2 BSA or 34 L/min/m^2 BSA)	Significantly greater decrease in FVC (−12 vs. −6 %), and FEV_1 (−14 vs. −9 %) following exercise with a greater V_E vs. less V_E
Adams [45]	Healthy $N = 30$	40–120 ppb for 6.6-h exposure and exercise session	6.6 h with 50 min of exercise for each 1 h (V_E = ~30 L/min) 10 min in between allowed to pulmonary function tests to be performed	120 and 80 ppb significantly decreased FVC (~11 % and ~4 % reduction post-exposure), FEV_1 (~13 and ~4 % reduction post-exposure) vs. air, in a dose-dependent manner
Adams [46]	Healthy $N = 30$ (15 M, 15 F)	80 ppb for 6.6-h exposure and exercise session	6.6 h with 50 min of exercise for 1 h ($V_E = 36$ L/min) 10 min in between allowed for pulmonary function tests to be performed	Significant reduction in FVC (3.67–4.07 % decrease) and FEV_1 (3.51–3.64 % decrease) compared with fresh air

Table 3 continued

Study	Population and methods	Exposure	Exercise test	Measured outcome
Alfaro et al. [48]	Healthy $N = 8$ (4 M, 4 F; split into sensitive to ozone (2 M, 2 F) and non- sensitive to ozone (2 M, 2 F)	350 ppb for 1 h	60 min of exercise (V_E 50–55 L/min)	Significant reduction in FEV_1 and FVC up to 1-h post-ozone exposure in ozone-sensitive individuals
Aris et al. [71]	Healthy $N = 10$ (6 M, 4 F)	200 ppb for 2 h with exercise	Moderate exercise	26.4 % reduction in FEV_1 and 19.9 % reduction in FVC, following ozone exposure
Avol et al. [101]	Healthy $N = 50$ (42 M, 8 F)	Ambient ozone (150 ppb), 80, 160, 240, or 320 ppb in a laboratory	1 h cycling (V_E of 55 L/min)	No significant effect of 80 ppb on FEV_1 and FVC. Ambient conditions and >160 ppb caused a significant reduction in FEV_1 and FVC
Brookes et al. [49]	Aerobically trained $N = 15$ M	200 or 350 ppb for 1 h, followed by a repeat day of exposure	1 h of cycling (V_E of 60 L/min)	Significant reduction in FEV_1, FVC, and $FEF_{25–75}$ with ozone exposure vs. air. Repeat exposures may enhance this reduction
DeLucia and Adams [50]	Healthy $N = 6$ M	150 or 300 ppb for 1 h	Exercise at 25, 45 or 65 % VO_{2max}	300 ppb of ozone at 65 % VO_{2max} significantly reduced FEV_1 by 6.1 %
Dillard et al. [75]	Healthy $N = 10$	300 ppb for 1 h	1-h cycling at 50 % VO_{2max}	Significant reduction in FEV_1
Folinsbee et al. [80]	Healthy $N = 14$ M	500 ppb of ozone for 2 h performed in 4 different environmental conditions of increasing temperature (25, 31, 35, and 40 °C)	30 min of exercise at 45 % VO_{2max}. Exercise occurred between 30 and 60 min, or 60 and 90 min during the 2-h exposure	Greatest reduction in pulmonary function occurred immediately after exercise. FEV_1 and FVC drop post-exercise were 826 and 937 mL, respectively. Trend towards greater impairment with ozone and heat
Folinsbee et al. [76]	Healthy $N = 10$ M	500 ppb of ozone for 2 h performed in 4 different environmental condition of increasing temperature (25, 31, 35, and 40 °C) Additional days combined ozone with 500 ppb of NO_2	30 min of exercise at 35–40 % VO_{2max} ($V_E = 40$ L/min). Exercise occurred between 60 and 90 min during the 2-h exposure	During exposure there was a decrease in lung function. No additional effect of NO_2 combined with ozone
Folinsbee et al. [77]	Trained athletes $N = 7$ (6 M, 1 F)	210 ppb for 1 h	1 h at 75 % VO_{2max}	Significant decreases in FVC: −7 %, FEV_1: −15 %, and $FEF_{25–75}$: −18 % immediately after exercise in ozone vs. air
Folinsbee et al. [78]	Healthy $N = 22$ M	300 ppb for 2 h	3 × 30 min of exercise ($V_E = 38$ L/min). Separated by 10 min intervals to measure pulmonary function	No significant effect of ozone on lung function following the first exercise period. At 75 and 115 min of the exposure, FVC, FEV_1, and $FEF_{25–75}$ significantly decreased

Table 3 continued

Study	Population and methods	Exposure	Exercise test	Measured outcome
Folinsbee et al. [81]	Healthy $N = 10$ M	120 ppb for 6.6 h	Exercise for 50 min out of each 1 h ($V_E = 40$ L/min) 10 min in between allowed to pulmonary function tests to be performed	FEV_1 decreased throughout the exposure and by 13 % (591 mL) at the end of exposure. FVC and $FEF_{25–75}$ decreased 8.2 and 17.4 %, respectively
Folinsbee et al. [79]	Healthy $N = 17$ M	120 ppb for 6.6 h repeated on 5 consecutive days	Exercise for 50 min out of each 1 h (V_E of 39 L/min) 10 min in between allowed to pulmonary function tests to be performed	FEV_1 was significantly less on day 1 (−13 %), and day 2 (−9 %), following ozone exposure vs. air, but not on days 3, 4, and 5. Possible adaptation to ozone Airway responsiveness significantly increased following ozone vs. air
Folinsbee et al. [51]	Healthy $N = 19$ F	350 ppb for 75 min	2 × 30-min bouts of treadmill walking (V_E 40 L/min) separated by 10 min to perform pulmonary function tests	Significant decrease in FVC (13.2 %), FEV_1 (19.9 %), $FEF_{25–75}$ (29.9 %), and PEFR (22.8 %) immediately following ozone exposure. Significance persisted at 18 h post Significant increase in airway resistance immediately post and 18-h post-exposure to ozone
Gerrity et al. [82]	Healthy $N = 15$ (5 M, 10 F)	400 ppb for 1 h	1-h walking on a treadmill (V_E of 20 L/min/m^2 BSA)	Significant reduction in FVC (no change vs. 0.5 L reduction), and FEV_1 (0.02 L increase vs. 0.51 L decrease), and a significant increase in airway resistance (0.1 vs. 1.25 cm H_2O/s increase) immediately following exercise in ozone vs. air. FEV_1 and FVC were also significant 90 min post
Gibbons and Adams [53]	Aerobically trained $N = 10$ F	Filtered air vs. 150 and 300 ppb of ozone, in 24 and 35 °C (6 sessions total)	1 h at 66 % VO_{2max} (V_E 55 L/min)	At 24 °C, 300 ppb significantly reduced FEV_1 and $FEF_{25–75}$ vs. air At 35 °C, 300 ppb significantly reduced FEV_1, FVC, and $FEF_{25–75}$ vs. air and 150 ppb
Gong et al. [56]	High-level cyclists $N = 17$	120 and 200 ppb at 31 °C	1 h at 70 % VO_{2max} followed by an incremental max test	Ozone caused a 5.6 and 21.6 % reduction in FEV_1 for 120 and 200 ppb exposure, respectively
Holz et al. [94]	$N = 36$ (15 mild asthmatic patients: 5 M, 10 F; 21 non-asthmatic individuals: 10 M, 11 F)	250 vs. 125 ppb vs. filtered air for 3 h	Cycling for 15 min on and 15 min off (V_E 26 L/min)	1-h post-exposure, 250 ppb significantly reduced FEV_1, this was not seen for 125 ppb or filtered air. Both asthmatic patients and non-asthmatic individuals experienced the same degree of change. At 24 h post-exposure, lung function had returned to baseline

Table 3 continued

Study	Population and methods	Exposure	Exercise test	Measured outcome
Horstman et al. [84]	Healthy $N = 22$ M	80, 100, or 120 ppb for 6.6 h	Exercise for 50 min out of each 1 h (V_E of 39 L/min) 10 min in between allowed to pulmonary function tests to be performed	Significant decreases of −0.31, −0.30, and −0.54 L were observed with exposures to 80, 100, and 120 ppb, respectively. Significantly increased bronchial reactivity
Hynes et al. [85]	Healthy $N = 17$ (11 M, 6 F)	400 ppb for 30 min	Cycling for 30 min (V_E ~40 L/min) Participants exercise with either oral, or nasal breathing	Ozone exposure significantly reduced FVC (3.8–4.9 % reduction) and FEV_1 (5.1–6.6 % reduction). No significant difference between oral and nasal modes of exposure
Lauritzen et al. [87]	Healthy $N = 6$ F	200, 300, or 400 ppb vs. air 10 sessions total manipulating V_E and ozone to provide a varying dose. Dose = V_E × ozone concentration	1 h cycling (V_E 23, 35, or 46 L/min)	FVC, FEV_1, and $FEF_{25–75}$ significantly decreased as dose increased
Linn et al. [88]	Adults $N = 45$ (15 healthy, 30 asthmatic patients)	120 ppb for 6.5 h	6.5 h with 50 min of exercise for each 1 h (V_E ~39 L/min) with pulmonary function measured each 1 h	Significant decrease in lung function and increase in bronchial reactivity following ozone vs. air
McDonnell et al. [89]	Healthy $N = 38$ M	80 or 100 ppb for 6.6 h	6.6 h with 50 min of exercise for each 1 h with a V_E of approximately 40 L/min. 10 min in between allowed to pulmonary function tests to be performed	Significant ozone-induced decrements were observed for FVC (−0.25 L), FEV_1 (−0.35 L), and $FEF_{25–75}$ (−0.57 L/s) and significant increases were observed in airway reactivity (35 %), specific airway resistance (0.77 cm H_2O/s)
McKittrick and Adams [90]	Aerobically fit $N = 12$ M	300 ppb	3 protocols performed on different days to result in the same dose of ozone: (1) 1 h of continuous exercise (2) 2 sessions of 2 h of intermittent exercise (15-min on 15-min off, or 30-min on 30-min off)	All ozone exposures with exercise significantly decreased FVC, FEV_1, and $FEF_{25–75}$ vs. air No significant difference between exercise protocols
Messineo and Adams [54]	Healthy $N = 28$ F	180 or 300 ppb for 1 h	1 h of cycling (V_E of 45 L/min), approximately 61–67 % VO_{2max}	Significant reduction in FVC, FEV_1, and $FEF_{25–75}$ in both ozone conditions vs. air. Decrements in parameters increased with ozone concentration
Mihevic et al. [91]	Healthy $N = 14$	300 or 500 ppb for 2 h	40 min of exercise during a 2-h exposure	Significant reductions in FVC, FEV_1 from ozone exposure which were greater immediately following exercise

Table 3 continued

Study	Population and methods	Exposure	Exercise test	Measured outcome
Schelegle et al. [92]	Endurance-trained athletes $N = 10$ M	120, 180, and 240 ppb for 1 h	1 h competitive simulation final 30 min at 86 % VO_{2max}	Significant decreases in FVC (−7.8 and −9.9 %), and FEV_1 (−5.8 and −10.5 %) following 180 and 240 ppb, respectively
Schonfeld et al. [55]	Healthy $N = 40$ M (10 per group, one group per duration in between sessions)	350 ppb of ozone for 1 h	3 × 1 h of exercise with a (V_E of 60 L/min), separated by either 24, 48, 72, or 120 h	Significant decrease in FEV_1, FVC, and $FEF_{25–75}$ and increased airway resistance following ozone vs. air
Studies reporting no significant effects				
Adams et al. [95]	Healthy $N = 6$ M	400 ppb for either 75 min or 30 min to result in similar doses across different exercise levels	75 min at a V_E of 30 L/min 30 min at a V_E of 75 L/min For each condition oral vs. oronasally were compared	No significant effect on lung function
Fernandes et al. [96]	Asthmatic patients $N = 15$ (7 M, 8 F)	122 ppb for 1 h prior to exercise	6-min treadmill exercise challenge	No significant effect of exercise-induced bronchoconstriction
Gomes et al. [97]	$N = 10$ M	4 conditions 20 °C + air (control) 20 °C + 100 ppb 31 °C + air 31 °C + 100 ppb	8 km time-trial run	No significant effect on lung function
Koenig et al. [98]	Healthy patients and asthmatic patients $N = 20$ (10 per group)	120 or 180 ppb for 40 min	30 min of rest followed by 10 min of exercise	No significant effect on lung function at either concentration. Significant increase in airway resistance following 180 ppb
Krishna et al. [99]	Healthy $N = 12$ (10 M, 2 F)	200 ppb for 2 h	Cycling for 15 min on and 15 min off (V_E 30 L/min)	No significant changes in FEV_1 and FVC
Savin and Adams [57]	Healthy $N = 9$ M	150 or 300 ppb ~30 min	Maximal incremental exercise test lasting ~30 min	No significant effect on FEV_1, or FVC
Superko et al. [100]	Coronary heart disease $N = 6$ M	200 or 300 ppb for 40 min	40 min of walking on a treadmill	No significant effect on lung function

BSA body surface area; bpm: beats per minute, *CI* confidence interval, *EIB* exercise induced bronchoconstriction, *F* females, FEV_1 forced expiratory volume in 1 s, *FVC* forced vital capacity, $FEF_{25–75}$ forced expiratory flow from the mid-point of FVC, *M* males, *max* maximum, *PEFR* peak expiratory flow rate, PM_1 particulate matter with a mean diameter of 1 μm or less, $PM_{2.5}$ particulate matter with a mean diameter of 2.5 μm or less, PM_{10} particulate matter with a mean diameter of 10 μm or less, *UFP* ultrafine particulate matter, V_E minute ventilation, VO_{2max} maximal oxygen consumption, *ppm* parts per million; ppb: parts per billion

For each 50-ppb increment in mean ozone concentration during moderate exercise, there is an associated 2.6 % decline in FEV_1 and a 2.2 % decline in FVC [86]. At extremely high levels of exposure (350 ppb), even with low exercise intensities, individuals experience a significant decrease in FVC (13.2 %), FEV_1 (19.9 %), $FEF_{25–75}$ (29.9 %), and the peak expiratory flow rate (PEFR) (22.8 %) [51]. During longer duration acute exposures (6.6 h), concentrations of 80 ppb adversely affect lung function (FEV_1 reduction of ~4 %), [45, 46, 84]. Many monitoring locations in the USA often exceed this level [15]; however, it is unlikely that individuals would exercise for 6.6 h. For those with a physically active occupation this would be more likely. For shorter duration acute exposures (~1 h), ozone concentrations typically need to exceed 160 ppb to affect lung function [101]. In Europe, ambient hourly levels have reached 172 ppb [103]. However, the occurrence of such high levels is atypical, raising the issue of relevance to urban exercisers. Despite this, a few studies suggest that ambient ozone concentrations during exercise are related to decrements in lung function [73, 83, 104].

Repeat exposures to ozone on subsequent days may enhance any adverse effects on lung function [49, 79]. However, there is evidence that individuals adapt to ozone, as significant decrements in lung function are not seen on days 3, 4, or 5 of a 5-day exposure cycle [79]. Because individuals are concurrently exposed to multiple pollutants in the ambient environment, it is important to determine the additive or synergistic effects of co-exposure. However, there is no research to suggest that co-exposure of ozone and nitrogen dioxide during exercise enhances the adverse effects of ozone [69, 76].

5.2.3 Field Studies

Field studies examining the effects of acute ambient air pollution exposure during exercise on lung function are conflicting [73, 74, 83, 86, 105–113]. In healthy children, during moderate exercise in ambient air containing ozone and PM, FEV_1 is significantly decreased [106]. Likewise, decrements in PEFR correspond with ambient ozone levels following short-duration high-intensity exercise [73]. Despite one study showing a lack of effect of air pollution exposure on lung function, there appears to be a significant negative correlation between the change in FEV_1 and the inhaled dose of ozone [105]. In children with chronic respiratory symptoms, ambient air pollution exposure impairs baseline lung function, but not exercise-induced bronchial hyperresponsiveness [113].

In healthy adults, the results are also conflicting [74, 83, 86, 93, 107–112, 114]. Some studies reported adverse effects for both short-duration high-intensity and longer duration moderate-intensity exercise [74, 83, 86, 93, 110, 114]. Those with asthma are particularly sensitive to air pollution and only require moderate exercise (walking) in ambient exposure to adversely affect FEV_1 and FVC [107, 111].

As exercise protocol, duration, and air pollution exposure characteristics vary in the above studies, it is difficult to draw conclusions. However, the adverse effects are better demonstrated in vulnerable populations such as asthmatic patients and children, who may want to minimize exposure.

5.3 Lung Inflammation

Air pollution exposure causes lung inflammation, this inflammation is a step in the inflammatory cascade that may adversely affect the cardiovascular system and can cause endothelial dysfunction, coagulation, thrombosis, and oxidative stress [14]. Field and laboratory-based studies examining air pollution exposure during exercise and lung inflammation are conflicting [48, 114–124]. Ozone exposure during exercise has been investigated; however, there are no data on lung inflammation during exercise with isolated carbon monoxide or PM exposure, but there is a small amount of work on ambient PM in field studies that is discussed in Sects. 5.3.1 and 5.3.2.

5.3.1 Ozone

In animals, exposure to extremely high levels of ozone (>800 ppb) during exercise increases airway permeability [125] and oxidative stress [121], and causes lung injury [126, 127], which could lead to an influx of inflammatory cells and thus lung inflammation.

Healthy individuals may experience lung inflammation in response to ozone. Longer duration acute exposures of between 4 and 6.6 h to 80–200 ppb of ozone with exercise (V_E 40 L/min) cause acute inflammatory cell influx into the airway [128], and significantly increase airway markers of inflammation [115, 118]. The inflammatory response to shorter duration acute exposures may require higher concentrations of ozone than longer duration exposures, as exposure to 200 ppb of ozone during exercise (1 h at V_E 25 L/min/m^2 body surface area) does not alter the late inflammatory or early bronchoconstrictor response to an inhaled allergen [116]. Environmental temperature plays a role in modifying the effects of ozone on inflammation. For example, exposure to 100 ppb of ozone in a hot environment (31 °C) significantly increases nasal Clara cell protein 16 (CC16) and glutathione/protein concentration [129] compared with a cool environment (20 °C) without ozone. This response does not occur with either ozone alone or elevated temperature, highlighting a potential synergy between the two. For competing athletes, this adds another layer of complexity, particularly in locations such as Delhi

and Beijing, where both heat and high levels of pollution coexist.

Asthmatic patients experience a significantly greater inflammatory response to pollution than non-asthmatic individuals [122]. Those with moderate asthma demonstrate more inflammation than those with mild asthma [111]. Irrespective of asthma status, some individuals can be categorized as sensitive to ozone. In such a population, higher markers of inflammation in exhaled breath condensate are seen 4 h post-exposure (350 ppb), compared with controls [48].

5.3.2 Field Studies

Fraction of exhaled nitric oxide (FeNO) is a surrogate measure of airway inflammation, and would be expected to increase with air pollution exposure. The majority of studies imply that for healthy individuals, acute exercise in a high-pollution/high-traffic area is not associated with FeNO [114, 120, 124]. One field study found that there is a small but significant 1.1-ppb increase in FeNO (95 % confidence interval 0.08–2.2 ppb) per 8.7 $\mu g/m^3$ increase in $PM_{2.5}$ [123]. Given that the increase in FeNO is small, the clinical relevance of this is unclear.

The role of a chronically elevated air pollution dose, such as during repetitive training, on lung inflammation is important to consider. Training in an urban environment for 12 weeks significantly increases FeNO, where as rural individuals undergoing the same training plan do not experience this [130]. Adolescent runners who train regularly outdoors do not experience any acute changes in airway inflammation following a training session, despite 40 % of test days occurring during air quality advisories [119]. This research demonstrates the potential importance of chronic exposures to air pollution during training on lung inflammation, highlighting the potential need for improved land-use planning in selecting exercise locations.

5.4 Symptom Exacerbation and Discomfort

Increased symptoms and discomfort during exercise may increase the likelihood of terminating exercise prematurely. This is particularly important for those who are returning to, or beginning an exercise program, and for those who have cardiovascular or respiratory conditions that currently limit exercise capacity. Ozone plays a role in exacerbating respiratory symptoms; however, the role of PM and carbon monoxide is unknown.

5.4.1 Ozone

Post-exercise changes in pulmonary symptoms such as chest tightness, wheeze, and shortness of breath are associated with ozone exposure [44, 45, 48, 49, 54, 68, 74, 81, 90, 101, 107, 115, 118]. Symptoms increase with increasing ozone concentration, and exercise intensity [68, 101]. Continuous exercise leads to more symptoms than intermittent exercise despite the same effective dose [90], which may in part be related to the decrease in V_E that resulted from transitions from rest to exercise. When ozone exposure occurs in conjunction with elevated temperature [53], and if repeat exposure occurs the following day [49], symptoms may further increase.

6 Cardiovascular Effects of Exercise and Air Pollution

Ozone is known to increase the risk of cardiovascular events such as arrhythmia, myocardial infarction, and heart failure. Potential mechanisms that have been proposed include inflammation, endothelial dysfunction, oxidative stress, and interference with autonomic control of the heart [131]. However, there are currently minimal studies that assess the cardiovascular effects of ozone during exercise; the majority of studies focus on PM and carbon monoxide exposure.

6.1 Angina and Myocardial Ischemia

In those with coronary artery disease, acute exposure to PM and carbon monoxide causes myocardial ischemia and reduces the time to onset of angina (TTA). The effects of carbon monoxide on myocardial ischemia are likely related to hypoxia [132], and the effects of PM on ischemia are likely caused by endothelial dysfunction, perturbation of the autonomic nervous system, and increased coagulation [14]. There are no data regarding myocardial ischemia and angina with ozone exposure. The data for PM and carbon monoxide are summarized in Table 4.

6.1.1 PM

Exposure to PM prior to exercise is associated with ST depression during exercise [133–135]. This includes exposure to $PM_{2.5}$ [133–135], and UFP [135], which originate from local traffic and long-range transport [133]. Exposure prior to exercise in the previous 1 h, 4 h [134], and 2 days [133, 135] is also associated with exercise-induced ST depression.

6.1.2 Carbon Monoxide

The majority of studies suggest that acute carbon monoxide exposure prior to exercise reduces TTA [136–142]. In those with coronary artery disease, reductions in TTA can occur at COHb levels of 2 % [132, 137]. As COHb

Table 4 Summary of studies assessing the effects of air pollution exposure on exercise induced angina and myocardial ischemia

Study	Population	Exposure	Exercise test	Measured outcome
Particulate matter				
Studies reporting significant effects				
Lanki et al. [133]	Coronary heart disease $N = 45$ (24 M, 21 F)	Ambient $PM_{2.5}$ levels measured preceding the visit	6 min sub-maximal exercise test	Exercise induced ST-segment depression (>0.1 mV) was associated with $PM_{2.5}$ from traffic Odds ratio at 2-day lag was 1.53 for long-range transport (95 % CI 1.19–1.97) and 1.11 for local traffic (95 % CI 1.02–1.20) per 1 μg/m^3, respectively
Lanki et al. [134]	Coronary heart disease $N = 41$ (22 M, 19 F)	Ambient UFP and $PM_{2.5}$, personal $PM_{2.5}$ levels measured preceding the visit	6 min sub-maximal exercise test	Personal and ambient $PM_{2.5}$ but not ambient UFP were associated with ST segment depression during sub maximal exercise Odds ratio for: The 1 h preceding 3.26 (95 % CI 1.07–9.99) 4 h average outdoor $PM_{2.5}$: 2.47 (95 % CI 1.05–5.85) per 10 μg/m^3 increase in $PM_{2.5}$
Pekkanen et al. [135]	Coronary heart disease $N = 45$ (21 M, 24 F)	Ambient $PM_{2.5}$, accumulation mode particles, and UFP levels measured preceding the visit	6 min sub-maximal exercise test	$PM_{2.5}$ and UFP 2 days prior to exercise were associated with increased risk of ST-segment depression during exercise Odds ratio: UFP (3.14; 95 % CI 1.56–6.32) per 10,000 particle increase $NC_{0.1–1}$ (3.29; 95 % CI 1.57–6.92) per 1,000 particle increase $PM_{2.5}$ (2.84; 95 % CI 1.42–5.66) per 10 μg/m^3 increase NO_2 and CO were also associated
Carbon monoxide				
Studies reporting significant effects				
Adams et al. [136]	Ischemic heart disease $N = 30$ (22 M, 8 F)	Carbon monoxide exposure to achieve 6 % COHb compared to 1.6 % in fresh air	Symptom limited supine exercise test	Subjects were more likely to experience angina earlier during exercise in carbon monoxide Time to onset of angina less in carbon monoxide vs. air (NS $p = 0.25$; 261 vs. 288 s)
Allred et al. [132, 137]	Coronary heart disease $N = 63$ M	117 or 253 ppm for 1 h to achieve 2 and 4 % COHb	Treadmill exercise test followed by carbon monoxide exposure followed by another treadmill exercise test	Significant 5.1 and 12.1 % reduction in time to reach a threshold of ischemic ST-segment for 117 and 253 ppm vs. air Significant 4.2 and 7.1 % decreases in time to the onset of angina for 117 and 253 ppm vs. air
Anderson et al. [138]	Coronary heart disease $N = 10$ M	50 ppm (2.9 % COHb) or 100 ppm (4.5 % COHb) for 4 h prior to exposure	Graded exercise test following exposure	Significant reduction in time to onset of angina following both carbon monoxide exposures

Table 4 continued

Study	Population	Exposure	Exercise test	Measured outcome
Aronow et al. [139]	Coronary heart disease $N = 10$ M	50 ppm for 2 h (2.7 % COHb)	Graded cycling exercise test prior to and following exposure	Significant reduction in time to onset of angina (37 s reduction) following carbon monoxide exposure
Kleinman et al. [141]	Coronary heart disease $N = 24$ M	100 ppm for 1 h to increase COHb from 1.5–2.9 %	Carbon monoxide exposure followed by a graded exercise test	5.9 % reduction in time to onset of angina during exercise on exposure days vs. air
Kleinman et al. [142]	Coronary heart disease $N = 17$	100 ppm for 2 h to achieve 3.9 % COHb, followed by exercise	Incremental exercise test	11.4 % reduction in the time to onset of angina on carbon monoxide exposure day vs. air
Studies reporting no significant effects				
Sheps et al. [205]	Ischemic heart disease $N = 30$ (25 M, 5 F)	1 h at 100 ppm to achieve 3.8 % COHb followed by exercise	Symptom limited supine exercise	No significant changes in time to onset of angina, maximal exercise time, or maximal ST decreases

COHb carboxyhemoglobin, *F* females, *M* males, *NS* non significant, $PM_{2.5}$ particulate matter with a mean diameter of 2.5 μm or less, *ppm* parts per million, *UFP* ultrafine particulate matter

increases, TTA decreases, and can be reduced up to 15 % during submaximal exercise [136, 138, 140–142]. This is particularly concerning as such low COHb levels (2.4 %) are easily attainable from standing on a busy street corner in a major city [143].

Given that myocardial ischemia is associated with air pollution exposure during and prior to exercise, it is important for exercise professionals involved in cardiac rehabilitation programs to consider how this may impact exercise sessions under their supervision.

6.2 Vascular Function

A disturbance in endothelial function is considered a key event in the development and clinical manifestation of atherosclerosis and is a key predictor in future cardiovascular events in those with cardiovascular disease. PM can affect the vasculature through perturbation of the autonomic nervous system, causing vasoconstriction and endothelial dysfunction [14]. There are currently a small number of studies assessing the effects of air pollution exposure on the vascular system, which exclusively focus on PM.

6.2.1 Particulate Matter in Laboratory and Field Studies

In healthy individuals, the effect of PM exposure on post-exercise brachial artery diameter is unclear [144, 145], but acute exposure to high levels of PM_1 (gasoline engine) during exercise impairs vascular function (measured by flow-mediated dilation) [144–146], and increases pulmonary artery pressure [146]. In contrast, acute exposure to high levels of $PM_{2.5}$ with exercise does not cause the micro-vascular dysfunction observed with rest [147], suggesting that exercise may be protecting against the adverse effects of PM_1. The differences in exposure, exercise duration and intensity, and measurements of endothelial function make it challenging to conclude how PM exposure during exercise affects endothelial function.

6.3 Heart Rate

6.3.1 PM

As PM perturbs the autonomic nervous system, it is plausible that exposure could increase heart rate. The effect of PM exposure during exercise on heart rate is unknown; however, pre-exercise exposure to high levels of $PM_{2.5}$ significantly increased exercise heart rate by 6 bpm [32].

6.3.2 Ozone

Acute exposure to ozone during exercise may not affect heart rate [100], and because of a decrease in maximum

exercise time, maximum heart rate may even be reduced [52]

6.3.3 Carbon Monoxide

COHb levels of 5 % can increase heart rate during exercise [148], with the magnitude of increase rising substantially when COHb reaches 15 % [149]. This increase could be due to the relative hypoxemia caused by the COHb displacing oxygen.

7 Cognitive Effects of Exercise and Air Pollution

Serum brain-derived neurotrophic factor (BDNF) typically increases following exercise, and is considered a key mechanism for improved cognition with exercise through improvements in learning and memory [150, 151]. This elevation in BDNF is significantly attenuated following exercise with exposure to UFP [150, 152], suggesting air pollution could counteract the beneficial effects of exercise on cognition. No data are available on cognition following exercise in ozone or carbon monoxide.

8 Systemic Effects of Exercise and Air Pollution

Systemic inflammation plays a key role in how air pollution affects the cardiovascular system [14]. There are currently no data regarding the systemic effects of carbon monoxide exposure during exercise.

In laboratory studies, acute exposure to high levels of $PM_{2.5}$ causes platelet activation with exercise but not during rest, implying that exercise may exacerbate the effects of $PM_{2.5}$ exposure [153]. Field studies suggest that parameters such as neutrophil and total leukocyte count, markers of systemic oxidative stress, and DNA damage all increase following acute exercise [120, 154–156]. These changes occur following exposure to PM in traffic [120, 156], by inhaling particle-rich air [154], and during exercise in cities with high concentrations of air pollution [155].

The role of chronic exposure to PM during exercise has been assessed following an exercise-training regime. Regular training in an urban environment with high levels of UFP increased leukocyte and neutrophil count, compared with training in a rural environment with lower levels of UFP [130].

In animals, 2 weeks of aerobic exercise training can attenuate ozone-induced oxidative stress [157]. However, compared with untrained rats, exercise training may increase the leukocyte inflammatory response due to ozone [158]. How this research translates to humans is unclear, and more research in this area is necessary prior to forming any conclusions.

9 Exercise Performance and Maximal Oxygen Consumption

Maximal oxygen consumption is a key indicator of aerobic exercise performance. Initial studies assessing the effects of air pollution exposure on exercise performance date back to the 1960s and involved exposure to car exhaust [159]. Since this research, the effects of air pollutants such as PM, ozone, and carbon monoxide have been investigated and these are discussed below in Sects. 9.1, 9.2, and 9.3, and summarized in Table 5.

9.1 PM

In children, higher levels of PM <10 μm in diameter (PM_{10}) are negatively associated with cardio-respiratory fitness and predicted maximal oxygen consumption (VO_{2max}) [160, 161], and there is also a correlation between PM_{10} levels and reduced marathon performance in women [162]. Experimental studies imply that acute exposure to high levels of PM during exercise may impair maximal accumulated work on a 6-min exercise test [146, 163]. However, if exposure occurs prior to exercise, the time taken to complete a 20-km cycling time trial is unaffected [32].

9.2 Ozone

For each 17-ppb increase in ozone there is an associated reduction in aerobic fitness score by 1.52 % [164]. Ambient ozone levels are associated with impaired marathon performance [165]; however, it is possible that the elevated temperature occurring in conjunction with ozone causes this response. Acute ozone exposure reduces maximal exercise time, workload, oxygen consumption, and performance on a maximal exercise test [52, 56, 166]. In addition, as ozone levels increase, the number of people unable to complete an exercise task also increases [92]. Performance impairments can occur at relevant environmental concentrations (120 ppb) [166], and at 200 ppb a 30 % reduction in maximal exercise time [56] and a 16 % reduction in mean oxygen consumption during the maximal test occur [56]. These performance decrements are likely due to increased respiratory discomfort [47]. In contrast to the above studies, two studies found that exposure ozone (100–300 ppb) does not affect exercise performance [97], or maximal work [57]. However, there is no clear reason for the discrepancy between studies.

Given the oxidizing effects of ozone, antioxidant supplementation could play a role in any ozone-induced decrements in exercise performance. While supplementation does not significantly improve exercise performance,

Table 5 Summary of the studies assessing the effects of air pollution exposure on exercise performance

Study	Population	Exposure	Exercise test	Measured outcome
Ambient mixtures				
Studies reporting significant effects				
Cakmak et al. [164]	$N = 5{,}011$ (2,495 M, 2,516 F)	Ambient $PM_{2.5}$ and ozone	Modified Canadian aerobic fitness test	IQR increase in ozone (17 ppb) was associated with a 1.52 % reduction in aerobic fitness score
Kargarfard et al. [155]	Healthy $N = 20$	Highly polluted area vs. low polluted area Ozone: 10.1 vs. 1.6 ppb Carbon monoxide: 35.4 vs. 2.4 ppm NO_2: 45.4 vs. 18.3 ppb PM_{10}: 248 vs. 20 μg/m^3	Cooper test	Significant reduction in distance travelled (2,810 vs. 2,880 m), and maximal oxygen consumption in high vs. low pollution Significant increase in blood lactate in high vs. low pollution
Particulate matter				
Studies reporting significant effects				
Cutrufello et al. [146]	Collegiate athletes $N = 16$ M	2 low PM_1 days (2,260 and 1,720 particles/cm^3) separated by 24 h followed by 2 high PM_1 days 7 days later (339,000 and 345,000 particles/cm^3)	20 min of sub-maximal exercise followed by a 6-min maximal exercise test	Work accumulated was significantly impaired (−2.87 %) in the high vs. low PM_1 days Non-blinded
Marr and Ely [162]	The top 3 M and F from seven competitive US marathon races	Pollution levels recorded during races	Marathon times recorded for top 3 male and female athletes	Correlation between PM_{10} levels and reduced marathon performance in women. For each 10 μg/m^3 increase in PM_{10} marathon performance decreased by 1.4 %
Rundell and Caviston [163]	Healthy $N = 15$ M	2 low PM_1 days (2,260 particles/cm^3) followed by 2 high PM_1 days (336,730 and 396,200 particles/cm^3 for trial 3 and 4)	6-min maximal exercise test	Work accumulated was significantly impaired on the second (final) high PM_1 day
Studies reporting no significant effects				
Giles et al. [32]	Cyclists $N = 8$ M	60-min exposure to diesel exhaust containing 300 μg/m^3 of $PM_{2.5}$ followed by exercise	20 km cycling time trial	Exercise performance was not significantly impaired
Ozone				
Studies reporting significant effects				
Foxcroft and Adams [52]	Aerobically trained $N = 8$ M	350 ppb for 1 h	50 min of steady state exercise ($V_E = 60$ L/min) followed by a maximal exercise test	Significant reduction in maximal oxygen consumption (3.62 vs. 3.85 L/min), maximum exercise time (211 vs. 253 s) in ozone vs. air

Table 5 continued

Study	Population	Exposure	Exercise test	Measured outcome
Gong et al. [56]	Elite athletes $N = 17$	120 or 200 ppb	60 min of exercise at 70 % max followed by a maximal exercise test	Significant 30 % reduction in maximal exercise time and an 8 % reduction in maximal workload following 200 ppb of ozone vs. air. No significant difference between air and 120 ppb of ozone
Linder et al. [166]	Healthy $N = 24$ (12 M, 12 F)	60 or 120 ppb	Maximal exercise test	120 ppb decreased exercise performance
Schelegle and Adams [92]	Endurance-trained athletes $N = 10$ M	120, 180, or 240 ppb	1-h competitive simulation on a bike. Endurance performance was measured as the number of participants unable to complete the simulation	Significant increase in the inability of subjects to complete the competitive simulations with increasing ozone concentration
Studies reporting no significant effects				
Gomes et al. [97]	$N = 10$ M	4 conditions 20 °C + air (control) 20 °C + 100 ppb 31 °C + air 31 °C + 100 ppb	8-km time-trial run	31 °C significantly reduced performance compared with control. No effect of ozone
Horvath et al. [206]	Healthy $N = 13$ (8 M, 5 F)	250, 500, or 750 ppb for 2 h prior to exercise	Maximal exercise test	No effect on exercise performance
Savin and Adams [57]	Healthy $N = 9$ M	150 or 300 ppb	Maximal exercise test	No effect on maximal work or oxygen uptake
Carbon monoxide				
Studies reporting significant effects				
Adams et al. [136]	Ischemic heart disease $N = 30$ (22 M, 8 F)	Carbon monoxide exposure to achieve 6 % COHb compared with 1.6 % in fresh air	Symptom limited supine exercise test	Mean exercise duration was significantly longer after air (626 vs. 585 s) vs. carbon monoxide exposure
Adir et al. [171]	Healthy $N = 15$ M	Exposure (3 min 45 s) that resulted in 5.12 % COHb, followed by exercise	Bruce protocol multistage fitness test	Significantly reduced exercise duration by 1.52 min vs. air
Aronow and Cassidy [172]	Healthy $N = 10$ (9 M, 1 F)	100 ppm for 1 h to achieve 3.95 % COHb	2 maximal exercise tests: 1 before and 1 after exposure	Significantly decreased from exercise time until exhaustion from 697.7 to 662.7 s
Aronow et al. [173]	COPD $N = 10$ M	100 ppm for 1 h to achieve 4.08 % COHb	2 maximal exercise tests: 1 before and 1 after exposure	Significant 33 % (147 vs. 221 s) decrease in time until marked dyspnea following carbon monoxide vs. air

Table 5 continued

Study	Population	Exposure	Exercise test	Measured outcome
Aronow et al. [72]	Anemic $N = 10$	50 ppm of carbon monoxide to increase COHb from 2.14 to 3.38 %	2 maximal exercise tests: 1 before and 1 after exposure	Significant 65 s (16 %) decrease in exercise time to fatigue following carbon monoxide exposure
Calverley et al. [174]	Chronic bronchitis and emphysema $N = 15$ (11 M, 4 F)	20–30 min of 0.02 % carbon monoxide exposure to achieve 12.3 % COHb	12-min walk test	A significant 42.7-m decrease in walking distance over a 12-min period with carbon monoxide vs. air
Drinkwater et al. [175]	Smokers and non-smokers $N = 20$ (10 per group)	50 ppm in 35 °C heat for 5 min. COHb increased from 0.9 to 2.5 % (non-smokers), from 2.1 to 4.6 % (smokers)	Modified Balke test: incremental treadmill test performed in 35 °C	Significant reduction in maximal exercise time (19.9 vs.20.9 min) in non-smokers but not in smokers
Flouris et al. [207]	Healthy $N = 16$ (8 M, 8 F)	1 h of second-hand smoke exposure that ended immediately, 1, and 3 h prior, 23 ppm of carbon monoxide	Maximal exercise test	Second-hand smoke was associated with a significant 12 % decrease in maximum power output, an 8.2 % reduction in maximal oxygen consumption, a 6 % increase in perceived exertion, and a 6.7 % decrease in time to exhaustion
Koike et al. [59]	Healthy $N = 10$ (9 M, 1 F)	1 % carbon monoxide exposure to achieve 11 and 20 % COHb	Incremental exercise test, followed by 2 constant workload tests (80 % lactate threshold and 40 % between lactate threshold and max)	Significant reduction in maximum work rate for 11 and 20 % COHb vs. air (263.8, 247.8 vs. 295.2 W) and exercise duration (644.6, 598.7 vs. 725.8 s)
Studies reporting no significant effects				
Keramidas et al. [176]	Healthy $N = 9$ M	2 h at 18.9 ppm	Constant power test at 85 % peak power until exhaustion	No significant effect on exercise performance
Turner et al. [177]	Fit and healthy $N = 9$ M	320 ppm to achieve 6.9 % COHb	Sub-maximal exercise test	No significant effect on exercise performance

COHb carboxyhemoglobin, *COPD* chronic obstructive pulmonary disease, *F* females, *M* males, *max* maximum, PM_1 particulate matter with a mean diameter of 1 μm or less, $PM_{2.5}$ particulate matter with a mean diameter of 2.5 μm or less, PM_{10} particulate matter with a mean diameter of 10 μm or less, V_E minute ventilation, *ppm* parts per million, *ppb* parts per billion

there is a significant positive correlation with antioxidant concentration in plasma and nasal lavage and improvement in running speed; implying that with a sufficient dose, antioxidant supplementation may be beneficial [167].

9.3 Carbon Monoxide

Carbon monoxide-induced hypoxemia reduces maximal oxygen consumption in proportion to the increase in COHb [59, 168], and this becomes significantly impaired at COHb levels above 4.3 % [169]. At the extremes of exposure (15–20 % COHb), maximal oxygen consumption can be reduced by 15–23 % [149, 170].

Most studies assessing the effects of carbon monoxide exposure on exercise performance suggest that performance is impaired [59, 72, 136, 171–175, 207]. However, a few studies do not [176, 177] and this difference is likely explained by the low levels of carbon monoxide administered, or the submaximal nature of exercise protocols [176, 177]. When exercise performance is affected, this can occur in healthy individuals, and in those with anemia, chronic obstructive pulmonary disease (COPD), and heart disease. In healthy individuals, COHb levels less than 4 % cause a significant reduction in maximal exercise time between 30 and 90 s, in tests lasting between 11 and 17.5 min [171, 172]. In those with COPD and anemia, carbon monoxide exposure causes a 33 % reduction in time until marked dyspnea [173] and a 16 % reduction in exercise time to fatigue [72]. Exercise performance (the time taken to complete a walking task) may be more impaired in non-smokers than smokers, [175], and is likely because of smokers adapting to high levels of COHb. Similar COHb levels to those measured in the above studies (4–5 %) can occur during exercise in an urban environment [143] therefore, oxygen consumption and exercise performance could be affected in urban environments on a regular basis. This suggests that the location of exercise events may play a key role in determining exercise performance

9.4 Field Studies

Compared with a cohort living in a less-polluted city, exercise performance in a 12-min run for those residing in a highly polluted city is significantly impaired [155]. In contrast, in a more robust study using a repeated-measures design, air pollution levels do not affect maximal oxygen consumption, but do reduce anaerobic threshold [178].

10 Balancing Risk and Benefit

Exercise plays a key role in improving some of the physiologic mechanisms and health outcomes that air pollution exposure may exacerbate. For example, regular exercise reduces blood pressure, systemic inflammation, and blood coagulation, and enhances autonomic tone and endothelial function, all of which may play a role in lowering the risk of heart disease and stroke [179, 180], but may be adversely affected by air pollution exposure [14]. Acutely, the exercise-induced hypotension seen for 6–12 h following exercise [181] may offset any increase in blood pressure associated with PM exposure.

Despite the potential adverse effects of exercising in air pollution, studies imply that the beneficial effects of exercise outweigh the adverse effects of air pollution [182–186], and that exercise reduces the likelihood of air pollution-related mortality [186, 187]. Animal studies support this notion and suggest that aerobic exercise training protects against air pollution and environmental tobacco smoke-induced lung inflammation [188, 189], the proinflammatory response to inhaled aluminum refinery dust [190], and ozone-induced oxidative stress [157]. Low physical fitness and obesity increase the effects of air pollution on blood pressure [191]. For a 10.5-$\mu g/m^3$ increase in $PM_{2.5}$, individuals with a resting heart >70 bpm experienced a significant increase in exercise diastolic and mean arterial pressure. However, this effect is not seen in those with a heart rate <70 bpm [192]. As regular exercisers have lower heart rates, this highlights the importance of physical fitness in the vascular response to air pollution.

11 Recommendations

One strategy to reduce the impact of air pollution exposure is to reduce the risk of cardiovascular disease [193]. The evidence for the cardio-protective effects of exercise is sound [180], and animal research supports the notion that regular exercise can attenuate air pollution-induced lung inflammation [188, 189] and oxidative stress [157]. Therefore, individuals should be encouraged to engage in regular physical activity, but consider some of the strategies discussed below to minimize the health effects of air pollution exposure.

Antioxidant supplementation can reduce the adverse health effects of air pollution [194–197] and protects exercisers against the acute effects of ozone on lung function [198] and lung injury [167]. Therefore, in an attempt to offset adverse health effects of air pollution, individuals could consider a diet rich in antioxidants.

Wearing a facemask during exercise lowers blood pressure and increases heart rate variability in healthy individuals [199]; in those with heart disease it reduces mean arterial pressure and ST depression, and increases heart rate variability [200]. While this area of research is promising, individuals should be aware that both the quality and fit of facemasks are important.

Pre-treatment with anti-asthmatics may protect against the adverse effects of air pollution during exercise, although the research is limited. Pre-treatment with salbutamol (a bronchodilator) [201, 202] in non-asthmatic individuals does not mitigate the adverse effects of ozone exposure during exercise on FEV_1 or FVC [201, 202], or on respiratory symptoms [201]. In contrast, pre-treatment with montelukast (a leukotriene antagonist) 6–8 h prior to exercise attenuates the effects of a high PM_1 environment on post-exercise flow-mediated dilation [145], and FEV_1 in those with exercise-induced bronchoconstriction (90 % protection) [203]. At this point, there is no clear evidence for using anti-asthmatic drugs in non-asthmatic individuals, but they are appropriate for asthmatic patients.

Until further research is conducted other recommendations include:

- Individuals should follow local air quality forecasts and plan workouts around them.
- In the summer, exercising in the morning should be encouraged to minimize afternoon ozone exposure.
- As much as possible individuals should exercise away from traffic.
- Exercisers should consider the environment prior to and during exercise, and how travel to an exercise location could alter exposure.
- When possible, skaters and hockey players should choose an ice arena with an electric ice resurfacer.
- Exercise and event organizers should consider the location and time of exercise and competition venues. University soccer fields and elementary school playgrounds where many sporting activities take place can record high levels of PM_1 [204].
- At-risk individuals, such as those with pre-existing cardiovascular or respiratory disease, should consult their physician prior to starting an exercise program.

12 Summary and conclusions

In air pollution the higher V_E and breathing frequency, and lower tidal volumes for the same amount of work may increase dead space ventilation, perceived exertion, and competition for blood flow between the exercising and respiratory muscles, all of which may impair exercise performance. Elevated ambient temperature can also increase perceived exertion and air pollution-induced lung inflammation, and impair exercise performance; therefore, exposure to high levels of air pollution in a warm climate may be the least suitable environment for exercise performance. Individuals should take into account the method of transport to an exercise location. In particular, competing athletes and those with heart disease could consider avoiding traffic prior to exercise to minimize the health risk and potential effects on exercise performance. Because high levels of ozone and carbon monoxide increase symptoms during exercise, this could also discourage an individual from exercising, thus reducing physical activity levels and health status. Therefore, to avoid exposure to air pollution, individuals should be encouraged to exercise away from traffic. The adverse effects of air pollution exposure during exercise highlight the importance of land-use planning in selecting exercise locations for training and competition within an urban environment. The elevated heart rate and myocardial ischemia seen with exposure to $PM_{2.5}$ or carbon monoxide prior to exercise are important to consider in exercise populations with compromised cardiovascular function, who may not be to able to accommodate the additional cardiovascular strain. Therefore, it is important to consider how air pollution will affect exercise testing and prescription by those involved in cardiac rehabilitation programs. Acute and chronic $PM_{2.5}$ and ozone exposure, prior to or during exercise, impairs lung function and may promote lung inflammation. While some data are inconsistent, individuals with pre-existing conditions and children are sensitive to air pollution exposure, and therefore could minimize exercise on days with high levels of air pollution.

The role of PM exposure on cognition is concerning and presents an interesting area for future research. Researchers could consider direct measures of cognitive performance following exposure to PM. Given the pathophysiologic basis of impaired vascular function with PM exposure, the effects during exercise warrant further investigation. While both PM and ozone cause oxidative stress and systemic inflammation, these effects vary based on the measured outcome, and this body of research is far from comprehensive. Therefore, more research determining which parameters of oxidative stress and inflammation are affected with air pollution exposure during exercise is needed. Many exercise studies do not have a control resting condition making it hard to disentangle the effects of exercise from air pollution; therefore, future research should take this into account. More information on the cardiovascular, respiratory, and systemic responses to air pollution exposure are needed, particularly for PM. How these responses change with temperature, exercise intensity, sex, and different cohorts such as the elderly, the young, and those with pre-existing diseases would be important. For laboratory-based studies the role of pollutant synergy/co-exposure during exercise is important to understand. Finally, the role of genetics in the health effects of combined exercise and air pollution exposure warrants further investigation.

Acknowledgments The authors have no declared conflicts of interest. No sources of funding were used to assist in the preparation of this review.

References

1. Blair SN. Physical inactivity: the biggest public health problem of the 21st century. Br J Sports Med. 2009;43(1):1–2.
2. Williams PT. Reduction in incident stroke risk with vigorous physical activity: evidence from 7.7-year follow-up of the national runners' health study. Stroke. 2009;40(5):1921–3. doi:10.1161/STROKEAHA.108.535427.
3. World Health Organisation. Global health risks. Mortality and burden of disease attributable to major risks; 2009.
4. United Nations. World urbanization prospectus the 2011 revision; 2012. http://esa.un.org/unup/pdf/WUP2011_Highlights.pdf (Accessed 1 April 2013).
5. World Health Organisation. Air quality guidelines global update Geneva; 2005. http://www.euro.who.int/_data/assets/pdf_file/0005/78638/E90038.pdf (Accessed 1 April 2013).
6. van Donkelaar A, Martin RV, Brauer M, et al. Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: development and application. Environ Health Perspect. 2010;118(6):847–55. doi:10.1289/ehp.0901623.
7. Zhang A, Qi Q, Jiang L, et al. Population exposure to pm2.5 in the urban area of Beijing. PLoS ONE. 2013;8(5):e63486. doi:10.1371/journal.pone.0063486.
8. Cohen AJ. Air pollution and lung cancer: what more do we need to know? Thorax. 2003;58(12):1010–2.
9. Lisabeth LD, Escobar JD, Dvonch JT, et al. Ambient air pollution and risk for ischemic stroke and transient ischemic attack. Ann Neurol. 2008;64:53–9.
10. McConnell R, Berhane K, Gilliland F, et al. Asthma in exercising children exposed to ozone: a cohort study. Lancet. 2002;359(9304):386–91.
11. Pope CA 3rd, Muhlestein JB, May HT, et al. Ischemic heart disease events triggered by short-term exposure to fine particulate air pollution. Circulation. 2006;114(23):2443–8.
12. Suwa T, Hogg JC, Quinlan KB, et al. Particulate air pollution induces progression of atherosclerosis. J Am Coll Cardiol. 2002;39(6):935–42.
13. Zemp E, Elsasser S, Schindler C, et al. Long-term ambient air pollution and respiratory symptoms in adults (SAPALDIA study): the SAPALDIA team. Am J Respir Crit Care Med. 1999;159(4 Pt 1):1257–66.
14. Brook RD, Rajagopalan S, Pope CA 3rd, et al. Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. Circulation. 2010;121(21):2331–78.
15. US EPA. Air quality criteria for ozone and related photochemical oxidants; 2005. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=149923 (Accessed 1 April 2013).
16. Gent JF, Triche EW, Holford TR, et al. Association of low-level ozone and fine particles with respiratory symptoms in children with asthma. JAMA. 2003;290(14):1859–67. doi:10.1001/jama.290.14.1859290/14/1859.
17. Park SK, O'Neill MS, Vokonas PS, et al. Effects of air pollution on heart rate variability: the VA normative aging study. Environ Health Perspect. 2005;113(3):304–9.
18. Davidge KS, Motterlini R, Mann BE, et al. Carbon monoxide in biology and microbiology: surprising roles for the "Detroit perfume". Adv Microb Physiol. 2009;56:85–167. doi:10.1016/S0065-2911(09)05603-3.
19. Omaye ST. Metabolic modulation of carbon monoxide toxicity. Toxicology. 2002;180(2):139–50.
20. Raub JA, Mathieu-Nolf M, Hampson NB, et al. Carbon monoxide poisoning: a public health perspective. Toxicology. 2000;145(1):1–14. pii:S0300-483X(99)00217-6.
21. US EPA. Air quality criteria for carbon monoxide. Washington DC, Development OoRa; 2000. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=18163 (Accessed 1 April 2013).
22. World Health Organisation. WHO air quality guidelines for Europe, 2nd edition; 2000. http://www.euro.who.int/en/what-we-do/health-topics/environment-and-health/air-quality/publications/pre2009/who-air-quality-guidelines-for-europe,-2nd-edition,-2000-cd-rom-version (Accessed 1 April 2013).
23. US EPA. Acute exposure guideline levels, carbon monoxide; 2008.
24. World Health Organization. Environmental health criteria 213: carbon monoxide. Geneva: World Health Organization; 1999. http://whqlibdoc.who.int/ehc/WHO_EHC_213.pdf (Accessed 1 April 2013).
25. Turrens JF, Freeman BA, Levitt JG, et al. The effect of hyperoxia on superoxide production by lung submitochondrial particles. Arch Biochem Biophys. 1982;217(2):401–10.
26. Alonso JR, Cardellach F, Lopez S, et al. Carbon monoxide specifically inhibits cytochrome c oxidase of human mitochondrial respiratory chain. Pharmacol Toxicol. 2003;93(3):142–6. pii:pto930306.
27. Kaur S, Nieuwenhuijsen MJ, Colvilea RN. Pedestrian exposure to air pollution along a major road in central London, UK. Atmos Environ. 2005;39:7307–20.
28. Kaur S, Nieuwenhuijsen MJ. Determinants of personal exposure to pm2.5, ultrafine particle counts, and co in a transport microenvironment. Environ Sci Technol. 2009;43(13):4737–43.
29. McNabola AB, Broderick BM, Gill LW. Relative exposure to fine particulate matter and VOCs between transport microenvironments in Dublin: personal exposure and uptake. Atmos Environ. 2008;42(26):6496–512.
30. van Wijnen JH, Verhoeff AP, Jans HW, et al. The exposure of cyclists, car drivers and pedestrians to traffic-related air pollutants. Int Arch Occup Environ Health. 1995;67(3):187–93.
31. Zuurbier M, Hoek G, Oldenwening M, et al. Commuters' exposure to particulate matter air pollution is affected by mode of transport, fuel type, and route. Environ Health Perspect. 2010;118(6):783–9. doi:10.1289/ehp.0901622.
32. Giles LV, Carlsten C, Koehle MS. The effect of pre-exercise diesel exhaust exposure on cycling performance and cardiorespiratory variables. Inhal Toxicol. 2012;24(12):783–9. doi:10.3109/08958378.2012.717649.
33. Peters A, von Klot S, Heier M, et al. Exposure to traffic and the onset of myocardial infarction. N Engl J Med. 2004;351(17):1721–30. doi:10.1056/NEJMoa040203.
34. Niinimaa V, Cole P, Mintz S, et al. The switching point from nasal to oronasal breathing. Respir Physiol. 1980;42(1):61–71.
35. Chalupa DC, Morrow PE, Oberdorster G, et al. Ultrafine particle deposition in subjects with asthma. Environ Health Perspect. 2004;112(8):879–82.
36. Daigle CC, Chalupa DC, Gibb FR, et al. Ultrafine particle deposition in humans during rest and exercise. Inhal Toxicol. 2003;15(6):539–52.
37. Oravisjarvi K, Pietikainen M, Ruuskanen J, et al. Effects of physical activity on the deposition of traffic-related particles into the human lungs in silico. Sci Total Environ. 2011;409(21):4511–8. doi:10.1016/j.scitotenv.2011.07.020.
38. Bennett WD, Messina MS, Smaldone GC. Effect of exercise on deposition and subsequent retention of inhaled particles. J Appl Physiol. 1985;59(4):1046–54.

39. Kinker JR, Haffor AS, Stephan M, et al. Kinetics of co uptake and diffusing capacity in transition from rest to steady-state exercise. J Appl Physiol. 1992;72(5):1764–72.
40. Tikuisis P, Kane DM, McLellan TM, et al. Rate of formation of carboxyhemoglobin in exercising humans exposed to carbon monoxide. J Appl Physiol. 1992;72(4):1311–9.
41. Ultman JS, Ben-Jebria A, Arnold SF. Uptake distribution of ozone in human lungs: intersubject variability in physiologic response. Res Rep Health Eff Inst. 2004(125):1–23 (discussion 5–30).
42. Muns G, Singer P, Wolf F, et al. Impaired nasal mucociliary clearance in long-distance runners. Int J Sports Med. 1995;16(4):209–13. doi:10.1055/s-2007-972993.
43. Salzano FA, Manola M, Tricarico D, et al. Mucociliary clearance after aerobic exertion in athletes. Acta Otorhinolaryngol Ital. 2000;20(3):171–6.
44. Adams WC. Effects of ozone exposure at ambient air pollution episode levels on exercise performance. Sports Med. 1987;4(6):395–424.
45. Adams WC. Comparison of chamber and face-mask 6.6-hour exposures to ozone on pulmonary function and symptoms responses. Inhal Toxicol. 2002;14(7):745–64. doi:10.1080/08958370290084610.
46. Adams WC. Comparison of chamber and face mask 6.6-hour exposure to 0.08 ppm ozone via square-wave and triangular profiles on pulmonary responses. Inhal Toxicol. 2003;15(3):265–81. doi:10.1080/08958370304505.
47. Adams WC, Schelegle ES. Ozone and high ventilation effects on pulmonary function and endurance performance. J Appl Physiol. 1983;55(3):805–12.
48. Alfaro MF, Walby WF, Adams WC, et al. Breath condensate levels of 8-isoprostane and leukotriene B4 after ozone inhalation are greater in sensitive versus nonsensitive subjects. Exp Lung Res. 2007;33(3–4):115–33. doi:10.1080/01902140701364367.
49. Brookes KA, Adams WC, Schelegle ES. 0.35 ppm O_3 exposure induces hyperresponsiveness on 24-h reexposure to 0.20 ppm O_3. J Appl Physiol. 1989;66(6):2756–62.
50. DeLucia AJ, Adams WC. Effects of O_3 inhalation during exercise on pulmonary function and blood biochemistry. J Appl Physiol. 1977;43(1):75–81.
51. Folinsbee LJ, Hazucha MJ. Time course of response to ozone exposure in healthy adult females. Inhal Toxicol. 2000;12(3):151–67. doi:10.1080/089583700196211.
52. Foxcroft WJ, Adams WC. Effects of ozone exposure on four consecutive days on work performance and VO_{2max}. J Appl Physiol. 1986;61(3):960–6.
53. Gibbons SI, Adams WC. Combined effects of ozone exposure and ambient heat on exercising females. J Appl Physiol. 1984;57(2):450–6.
54. Messineo TD, Adams WC. Ozone inhalation effects in females varying widely in lung size: comparison with males. J Appl Physiol. 1990;69(1):96–103.
55. Schonfeld BR, Adams WC, Schelegle ES. Duration of enhanced responsiveness upon re-exposure to ozone. Arch Environ Health. 1989;44(4):229–36. doi:10.1080/00039896.1989.9935888.
56. Gong H Jr, Bradley PW, Simmons MS, et al. Impaired exercise performance and pulmonary function in elite cyclists during low-level ozone exposure in a hot environment. Am Rev Resp Dis. 1986;134(4):726–33.
57. Savin WM, Adams WC. Effects of ozone inhalation on work performance and $VO_{2\ max}$. J Appl Physiol. 1979;46(2):309–14.
58. Schelegle ES, Alfaro MF, Putney L, et al. Effect of C-fiber-mediated, ozone-induced rapid shallow breathing on airway epithelial injury in rats. J Appl Physiol. 2001;91(4):1611–8.
59. Koike A, Wasserman K, Armon Y, et al. The work-rate-dependent effect of carbon monoxide on ventilatory control during exercise. Respir Physiol. 1991;85(2):169–83.
60. Pelham TW, Holt LE, Moss MA. Exposure to carbon monoxide and nitrogen dioxide in enclosed ice arenas. Occup Environ Med. 2002;59(4):224–33.
61. Holgate ST, Sandstrom T, Frew AJ, et al. Health effects of acute exposure to air pollution. Part I: healthy and asthmatic subjects exposed to diesel exhaust. Res Rep Health Eff Inst. 2003(112):1–30 (discussion 51–67).
62. Kelly FJ. Oxidative stress: its role in air pollution and adverse health effects. Occup Environ Med. 2003;60(8):612–6.
63. Rundell KW. High levels of airborne ultrafine and fine particulate matter in indoor ice arenas. Inhal Toxicol. 2003;15(3):237–50. doi:10.1080/08958370304502.
64. Rundell KW. Pulmonary function decay in women ice hockey players: Is there a relationship to ice rink air quality? Inhal Toxicol. 2004;16(3):117–23. doi:10.1080/08958370490270918.
65. Coleridge HM, Coleridge JC. Pulmonary reflexes: neural mechanisms of pulmonary defense. Annu Rev Physiol. 1994;56:69–91. doi:10.1146/annurev.ph.56.030194.000441.
66. Schelegle ES, Carl ML, Coleridge HM, et al. Contribution of vagal afferents to respiratory reflexes evoked by acute inhalation of ozone in dogs. J Appl Physiol. 1993;74(5):2338–44.
67. Islam T, Berhane K, McConnell R, et al. Glutathione-*S*-transferase (GST) P1, GSTM1, exercise, ozone and asthma incidence in school children. Thorax. 2009;64(3):197–202. doi:10.1136/thx.2008.099366.
68. Adams WC. Ozone dose–response effects of varied equivalent minute ventilation rates. J Expo Anal Environ Epidemiol. 2000;10(3):217–26.
69. Adams WC, Brookes KA, Schelegle ES. Effects of NO_2 alone and in combination with O_3 on young men and women. J Appl Physiol. 1987;62(4):1698–704.
70. Adams WC, Savin WM, Christo AE. Detection of ozone toxicity during continuous exercise via the effective dose concept. J Appl Physiol. 1981;51(2):415–22.
71. Aris R, Christian D, Sheppard D, et al. The effects of sequential exposure to acidic fog and ozone on pulmonary function in exercising subjects. Am Rev Respir Dis. 1991;143(1):85–91. doi:10.1164/ajrccm/143.1.85.
72. Aronow WS, Schlueter WJ, Williams MA, et al. Aggravation of exercise performance in patients with anemia by 3% carboxyhemoglobin. Environ Res. 1984;35(2):394–8.
73. Braun-Fahrlander C, Kunzli N, Domenighetti G, et al. Acute effects of ambient ozone on respiratory function of Swiss schoolchildren after a 10-minute heavy exercise. Pediatr Pulmonol. 1994;17(3):169–77.
74. Brunekreef B, Hoek G, Breugelmans O, et al. Respiratory effects of low-level photochemical air pollution in amateur cyclists. Am J Respir Crit Care Med. 1994;150(4):962–6.
75. Dillard CJ, Litov RE, Savin WM, et al. Effects of exercise, vitamin E, and ozone on pulmonary function and lipid peroxidation. J Appl Physiol. 1978;45(6):927–32.
76. Folinsbee LJ, Bedi JF, Horvath SM. Combined effects of ozone and nitrogen dioxide on respiratory function in man. Am Ind Hyg Assoc J. 1981;42(7):534–41. doi:10.1080/15298668191420206.
77. Folinsbee LJ, Bedi JF, Horvath SM. Pulmonary function changes after 1 h continuous heavy exercise in 0.21 ppm ozone. J Appl Physiol. 1984;57(4):984–8.
78. Folinsbee LJ, Bedi JF, Horvath SM. Pulmonary response to threshold levels of sulfur dioxide (1.0 ppm) and ozone (0.3 ppm). J Appl Physiol. 1985;58(6):1783–7.
79. Folinsbee LJ, Horstman DH, Kehrl HR, et al. Respiratory responses to repeated prolonged exposure to 0.12 ppm ozone. Am J Respir Crit Care Med. 1994;149(1):98–105. doi:10.1164/ajrccm.149.1.8111607.

80. Folinsbee LJ, Horvath SM, Raven PB, et al. Influence of exercise and heat stress on pulmonary function during ozone exposure. J Appl Physiol. 1977;43(3):409–13.
81. Folinsbee LJ, McDonnell WF, Horstman DH. Pulmonary function and symptom responses after 6.6-hour exposure to 0.12 ppm ozone with moderate exercise. JAPCA. 1988;38(1):28–35.
82. Gerrity TR, Bennett WD, Kehrl H, et al. Mucociliary clearance of inhaled particles measured at 2 h after ozone exposure in humans. J Appl Physiol. 1993;74(6):2984–9.
83. Grievink L, Jansen SM, van't Veer P, et al. Acute effects of ozone on pulmonary function of cyclists receiving antioxidant supplements. Occup Environ Med. 1998;55(1):13–7.
84. Horstman DH, Folinsbee LJ, Ives PJ, et al. Ozone concentration and pulmonary response relationships for 6.6-hour exposures with five hours of moderate exercise to 0.08, 0.10, and 0.12 ppm. Am Rev Respir Dis. 1990;142(5):1158–63. doi:10.1164/ajrccm/142.5.1158.
85. Hynes B, Silverman F, Cole P, et al. Effects of ozone exposure: a comparison between oral and nasal breathing. Arch Environ Health. 1988;43(5):357–60. doi:10.1080/00039896.1988.9934949.
86. Korrick SA, Neas LM, Dockery DW, et al. Effects of ozone and other pollutants on the pulmonary function of adult hikers. Environ Health Perspect. 1998;106(2):93–9.
87. Lauritzen SK, Adams WC. Ozone inhalation effects consequent to continuous exercise in females: comparison to males. J Appl Physiol. 1985;59(5):1601–6.
88. Linn WS, Shamoo DA, Anderson KR, et al. Effects of prolonged, repeated exposure to ozone, sulfuric acid, and their combination in healthy and asthmatic volunteers. Am J Respir Crit Care Med. 1994;150(2):431–40. doi:10.1164/ajrccm.150.2.8049826.
89. McDonnell WF, Kehrl HR, Abdul-Salaam S, et al. Respiratory response of humans exposed to low levels of ozone for 6.6 hours. Arch Environ Health. 1991;46(3):145–50. doi:10.1080/00039896.1991.9937441.
90. McKittrick T, Adams WC. Pulmonary function response to equivalent doses of ozone consequent to intermittent and continuous exercise. Arch Environ Health. 1995;50(2):153–8. doi:10.1080/00039896.1995.9940892.
91. Mihevic PM, Gliner JA, Horvath SM. Perception of effort and respiratory sensitivity during exposure to ozone. Ergonomics. 1981;24(5):365–74. doi:10.1080/00140138108924858.
92. Schelegle ES, Adams WC. Reduced exercise time in competitive simulations consequent to low level ozone exposure. Med Sci Sports Exerc. 1986;18(4):408–14.
93. Spektor DM, Lippmann M, Thurston GD, et al. Effects of ambient ozone on respiratory function in healthy adults exercising outdoors. Am Rev Respir Dis. 1988;138(4):821–8.
94. Holz O, Jorres RA, Timm P, et al. Ozone-induced airway inflammatory changes differ between individuals and are reproducible. Am J Respir Crit Care Med. 1999;159(3):776–84. doi:10.1164/ajrccm.159.3.9806098.
95. Adams WC, Schelegle ES, Shaffrath JD. Oral and oronasal breathing during continuous exercise produce similar responses to ozone inhalation. Arch Environ Health. 1989;44(5):311–6. doi:10.1080/00039896.1989.9935899.
96. Fernandes AL, Molfino NA, McClean PA, et al. The effect of pre-exposure to 0.12 ppm of ozone on exercise-induced asthma. Chest. 1994;106(4):1077–82.
97. Gomes EC, Stone V, Florida-James G. Investigating performance and lung function in a hot, humid and ozone-polluted environment. Eur J Appl Physiol. 2010;110(1):199–205. doi:10.1007/s00421-010-1485-8.
98. Koenig JQ, Covert DS, Smith MS, et al. The pulmonary effects of ozone and nitrogen dioxide alone and combined in healthy and asthmatic adolescent subjects. Toxicol Ind Health. 1988;4(4):521–32.
99. Krishna MT, Springall D, Meng QH, et al. Effects of ozone on epithelium and sensory nerves in the bronchial mucosa of healthy humans. Am J Respir Crit Care Med. 1997;156(3 Pt 1):943–50. doi:10.1164/ajrccm.156.3.9612088.
100. Superko HR, Adams WC, Daly PW. Effects of ozone inhalation during exercise in selected patients with heart disease. Am J Med. 1984;77(3):463–70. pii:0002-9343(84)90105-0.
101. Avol EL, Linn WS, Venet TG, et al. Comparative respiratory effects of ozone and ambient oxidant pollution exposure during heavy exercise. J Air Pollut Control Assoc. 1984;34(8):804–9.
102. Schneider A, Neas L, Herbst MC, et al. Endothelial dysfunction: associations with exposure to ambient fine particles in diabetic individuals. Environ Health Perspect. 2008;116(12):1666–74. doi:10.1289/ehp.11666.
103. European Environment Agency. Air pollution by ozone across Europe during summer 2012: European Environment Agency; 2012.
104. Brunekreef B, Stewart AW, Anderson HR, et al. Self-reported truck traffic on the street of residence and symptoms of asthma and allergic disease: a global relationship in ISAAC phase 3. Environ Health Perspect. 2009;117(11):1791–8. doi:10.1289/ehp.0800467.
105. Avol EL, Linn WS, Shamoo DA, et al. Short-term respiratory effects of photochemical oxidant exposure in exercising children. JAPCA. 1987;37(2):158–62.
106. Avol EL, Linn WS, Shamoo DA, et al. Respiratory effects of photochemical oxidant air pollution in exercising adolescents. Am Rev Respir Dis. 1985;132(3):619–22.
107. Avol EL, Linn WS, Shamoo DA, et al. Acute respiratory effects of Los Angeles smog in continuously exercising adults. J Air Pollut Control Assoc. 1983;33(11):1055–60.
108. Brauner EV, Mortensen J, Moller P, et al. Effects of ambient air particulate exposure on blood–gas barrier permeability and lung function. Inhal Toxicol. 2009;21(1):38–47. doi:10.1080/08958370802304735.
109. Girardot SP, Ryan PB, Smith SM, et al. Ozone and pm2.5 exposure and acute pulmonary health effects: a study of hikers in the Great Smoky Mountains National Park. Environ Health Perspect. 2006;114(7):1044–52.
110. Kulstrunk M, Bohni B. Comparison of lung function parameters in healthy non-smokers following exertion in urban environmental air and in air-conditioned inside air. Schweiz Med Wochenschr. 1992;122(11):375–81.
111. McCreanor J, Cullinan P, Nieuwenhuijsen MJ, et al. Respiratory effects of exposure to diesel traffic in persons with asthma. N Engl J Med. 2007;357(23):2348–58.
112. Strak M, Boogaard H, Meliefste K, et al. Respiratory health effects of ultrafine and fine particle exposure in cyclists. Occup Environ Med. 2010;67(2):118–24.
113. Timonen KL, Pekkanen J, Tiittanen P, et al. Effects of air pollution on changes in lung function induced by exercise in children with chronic respiratory symptoms. Occup Environ Med. 2002;59(2):129–34.
114. Rundell KW, Slee JB, Caviston R, et al. Decreased lung function after inhalation of ultrafine and fine particulate matter during exercise is related to decreased total nitrate in exhaled breath condensate. Inhal Toxicol. 2008;20(1):1–9. doi:10.1080/08958370701758593.
115. Balmes JR, Chen LL, Scannell C, et al. Ozone-induced decrements in FEV1 and FVC do not correlate with measures of inflammation. Am J Respir Crit Care Med. 1996;153(3):904–9. doi:10.1164/ajrccm.153.3.8630571.
116. Chen LL, Tager IB, Peden DB, et al. Effect of ozone exposure on airway responses to inhaled allergen in asthmatic subjects. Chest. 2004;125(6):2328–35.

117. Devlin RB, Horstman DP, Gerrity TR, et al. Inflammatory response in humans exposed to 2.0 ppm nitrogen dioxide. Inhal Toxicol. 1999;11(2):89–109. doi:10.1080/089583799197195.
118. Devlin RB, McDonnell WF, Mann R, et al. Exposure of humans to ambient levels of ozone for 6.6 hours causes cellular and biochemical changes in the lung. Am J Respir Cell Mol Biol. 1991;4(1):72–81. doi:10.1165/ajrcmb/4.1.72.
119. Ferdinands JM, Crawford CA, Greenwald R, et al. Breath acidification in adolescent runners exposed to atmospheric pollution: a prospective, repeated measures observational study. Environ Health. 2008;7:10. doi:10.1186/1476-069X-7-10.
120. Jacobs L, Nawrot TS, de Geus B, et al. Subclinical responses in healthy cyclists briefly exposed to traffic-related air pollution: an intervention study. Environ Health. 2010;9:64. doi:10.1186/1476-069X-9-64.
121. Long NC, Suh J, Morrow JD, et al. Ozone causes lipid peroxidation but little antioxidant depletion in exercising and nonexercising hamsters. J Appl Physiol. 2001;91(4):1694–700.
122. Scannell C, Chen L, Aris RM, et al. Greater ozone-induced inflammatory responses in subjects with asthma. Am J Respir Crit Care Med. 1996;154(1):24–9.
123. Weichenthal S, Kulka R, Dubeau A, et al. Traffic-related air pollution and acute changes in heart rate variability and respiratory function in urban cyclists. Environ Health Perspect. 2011;119(10):1373–8. doi:10.1289/ehp.1003321.
124. Zuurbier M, Hoek G, Oldenwening M, et al. Respiratory effects of commuters' exposure to air pollution in traffic. Epidemiology. 2011;22(2):219–27. doi:10.1097/EDE.0b013e3182093693.
125. Bhalla DK, Mannix RC, Lavan SM, et al. Tracheal and bronchoalveolar permeability changes in rats inhaling oxidant atmospheres during rest or exercise. J Toxicol Environ Health. 1987;22(4):417–37.
126. Mautz WJ. Exercising animal models in inhalation toxicology: interactions with ozone and formaldehyde. Environ Res. 2003;92(1):14–26. pii:S0013935102000245.
127. Mautz WJ, McClure TR, Reischl P, et al. Enhancement of ozone-induced lung injury by exercise. J Toxicol Environ Health. 1985;16(6):841–54.
128. Aris RM, Christian D, Hearne PQ, et al. Ozone-induced airway inflammation in human subjects as determined by airway lavage and biopsy. Am Rev Respir Dis. 1993;148(5):1363–72. doi:10.1164/ajrccm/148.5.1363.
129. Gomes EC, Stone V, Florida-James G. Impact of heat and pollution on oxidative stress and CC16 secretion after 8 km run. Eur J Appl Physiol. 2011;111(9):2089–97. doi:10.1007/s00421-011-1839-x.
130. Bos I, De Boever P, Vanparijs J, et al. Subclinical effects of aerobic training in urban environment. Med Sci Sports Exerc. 2013;45(3):439–47. doi:10.1249/MSS.0b013e31827767fc.
131. Srebot V, Gianicolo EA, Rainaldi G, et al. Ozone and cardiovascular injury. Cardiovasc Ultrasound. 2009;7:30. doi:10.1186/1476-7120-7-30.
132. Allred EN, Bleecker ER, Chaitman BR, et al. Effects of carbon monoxide on myocardial ischemia. Environ Health Perspect. 1991;91:89–132.
133. Lanki T, de Hartog JJ, Heinrich J, et al. Can we identify sources of fine particles responsible for exercise-induced ischemia on days with elevated air pollution? The ultra study. Environ Health Perspect. 2006;114(5):655–60.
134. Lanki T, Hoek G, Timonen KL, et al. Hourly variation in fine particle exposure is associated with transiently increased risk of ST segment depression. Occup Environ Med. 2008;65(11):782–6. doi:10.1136/oem.2007.037531.
135. Pekkanen J, Peters A, Hoek G, et al. Particulate air pollution and risk of ST-segment depression during repeated submaximal exercise tests among subjects with coronary heart disease: the exposure and risk assessment for fine and ultrafine particles in ambient air (ultra) study. Circulation. 2002;106(8):933–8.
136. Adams KF, Koch G, Chatterjee B, et al. Acute elevation of blood carboxyhemoglobin to 6% impairs exercise performance and aggravates symptoms in patients with ischemic heart disease. J Am Coll Cardiol. 1988;12(4):900–9.
137. Allred EN, Bleecker ER, Chaitman BR, et al. Short-term effects of carbon monoxide exposure on the exercise performance of subjects with coronary artery disease. N Engl J Med. 1989;321(21):1426–32. doi:10.1056/NEJM198911233212102.
138. Anderson EW, Andelman RJ, Strauch JM, et al. Effect of low-level carbon monoxide exposure on onset and duration of angina pectoris: a study in ten patients with ischemic heart disease. Ann Intern Med. 1973;79(1):46–50.
139. Aronow WS, Isbell MW. Carbon monoxide effect on exercise-induced angina pectoris. Ann Intern Med. 1973;79(3):392–5.
140. Hinderliter AL, Adams KF Jr, Price CJ, et al. Effects of low-level carbon monoxide exposure on resting and exercise-induced ventricular arrhythmias in patients with coronary artery disease and no baseline ectopy. Arch Environ Health. 1989;44(2):89–93. doi:10.1080/00039896.1989.9934381.
141. Kleinman MT, Davidson DM, Vandagriff RB, et al. Effects of short-term exposure to carbon monoxide in subjects with coronary artery disease. Arch Environ Health. 1989;44(6):361–9. doi:10.1080/00039896.1989.9935908.
142. Kleinman MT, Leaf DA, Kelly E, et al. Urban angina in the mountains: effects of carbon monoxide and mild hypoxemia on subjects with chronic stable angina. Arch Environ Health. 1998;53(6):388–97. doi:10.1080/00039899809605726.
143. Nicholson JP, Case DB. Carboxyhemoglobin in New York City runners. Physician Sports Med. 1983;11(3):135–8.
144. Rundell KW, Hoffman JR, Caviston R, et al. Inhalation of ultrafine and fine particulate matter disrupts systemic vascular function. Inhal Toxicol. 2007;19(2):133–40.
145. Rundell KW, Steigerwald MD, Fisk MZ. Montelukast prevents vascular endothelial dysfunction from internal combustion exhaust inhalation during exercise. Inhal Toxicol. 2010;. doi:10.3109/08958371003743254.
146. Cutrufello PT, Rundell KW, Smoliga JM, et al. Inhaled whole exhaust and its effect on exercise performance and vascular function. Inhal Toxicol. 2011;23(11):658–67. doi:10.3109/08958378.2011.604106.
147. Wauters A, Dreyfuss C, Hendrick P et al., editors. Acute exposure to diesel exhausts impairs endothelial vasomotor function and nitric oxide bioavailability. 31st annual scientific meeting of the Belgian Society of Cardiology. Acta Cardiologica, Brussels; 2012.
148. Kizakevich PN, McCartney ML, Hazucha MJ, et al. Noninvasive ambulatory assessment of cardiac function in healthy men exposed to carbon monoxide during upper and lower body exercise. Eur J Appl Physiol. 2000;83(1):7–16. doi:10.1007/s004210000256.
149. Pirnay F, Dujardin J, Deroanne R, et al. Muscular exercise during intoxication by carbon monoxide. J Appl Physiol. 1971;31(4):573–5.
150. Bos I, Jacobs L, Nawrot TS, et al. No exercise-induced increase in serum BDNF after cycling near a major traffic road. Neurosci Lett. 2011;500(2):129–32. doi:10.1016/j.neulet.2011.06.019.
151. Vaynman S, Ying Z, Gomez-Pinilla F. Hippocampal BDNF mediates the efficacy of exercise on synaptic plasticity and cognition. Eur J Neurosci. 2004;20(10):2580–90. doi:10.1111/j.1460-9568.2004.03720.x.
152. Bos I, De Boever P, Int Panis L, et al. Negative effects of ultrafine particle exposure during forced exercise on the expression of brain-derived neurotrophic factor in the hippocampus of rats. Neuroscience. 2012;223:131–9. doi:10.1016/j.neuroscience.2012.07.057.

153. Wauters A, Dreyfuss C, Hendrick P, et al., editors. Acute exposure to diesel exhausts induces immediate platelet activation. Munich: European Society of Cardiology; 2012.
154. Brauner EV, Forchhammer L, Moller P, et al. Exposure to ultrafine particles from ambient air and oxidative stress-induced DNA damage. Environ Health Perspect. 2007;115(8):1177–82.
155. Kargarfard M, Poursafa P, Rezanejad S, et al. Effects of exercise in polluted air on the aerobic power, serum lactate level and cell blood count of active individuals. Int J Prev Med. 2011;2(3): 145–50.
156. Vinzents PS, Moller P, Sorensen M, et al. Personal exposure to ultrafine particles and oxidative DNA damage. Environ Health Perspect. 2005;113(11):1485–90.
157. Martinez-Campos C, Lara-Padilla E, Bobadilla-Lugo RA, et al. Effects of exercise on oxidative stress in rats induced by ozone. Sci World J. 2012;2012:135921. doi:10.1100/2012/135921.
158. Jafari A, Faizi MA, Askarian F, et al. Effect of regular aerobic exercise with ozone exposure on peripheral leukocyte populations in Wistar male rats. J Res Med Sci. 2009;14(5):277–83.
159. Holland GJ, Benson D, Bush A, et al. Air pollution simulation and human performance. Am J Public Health Nations Health. 1968;58(9):1684–91.
160. Gao Y, Chan EYY, Zhu Y, Wong TW. Adverse effect of outdoor air pollution on cardiorespiratory fitness in Chinese children. Atmos Environ. 2013;64:10–7.
161. Yu IT, Wong TW, Liu HJ. Impact of air pollution on cardiopulmonary fitness in schoolchildren. J Occup Environ Med. 2004;46(9):946–52. pii:00043764-200409000-00008.
162. Marr LC, Ely MR. Effect of air pollution on marathon running performance. Med Sci Sports Exerc. 2010;42(3):585–91. doi:10.1249/MSS.0b013e3181b84a85.
163. Rundell KW, Caviston R. Ultrafine and fine particulate matter inhalation decreases exercise performance in healthy subjects. J Strength Condition Res. 2008;22(1):2–5.
164. Cakmak S, Dales R, Leech J, et al. The influence of air pollution on cardiovascular and pulmonary function and exercise capacity: Canadian Health Measures Survey (CHMS). Environ Res. 2011;111(8):1309–12. doi:10.1016/j.envres.2011.09.016.
165. El Helou N, Tafflet M, Berthelot G, et al. Impact of environmental parameters on marathon running performance. PLoS ONE. 2012;7(5):e37407. doi:10.1371/journal.pone.0037407.
166. Linder J, Herren D, Monn C, et al. Effect of ozone on physical performance capacity. Soz Praventivmed. 1987;32(4–5):251–2.
167. Gomes EC, Allgrove JE, Florida-James G, et al. Effect of vitamin supplementation on lung injury and running performance in a hot, humid, and ozone-polluted environment. Scand J Med Sci Sports. 2011;21(6):e452–60. doi:10.1111/j.1600-0838.2011.01366.x.
168. Koike A, Wasserman K. Effect of acute reduction in oxygen transport on parameters of aerobic function during exercise. Ann Acad Med Singapore. 1992;21(1):14–22.
169. Horvath SM, Raven PB, Dahms TE, et al. Maximal aerobic capacity at different levels of carboxyhemoglobin. J Appl Physiol. 1975;38(2):300–3.
170. Vogel JA, Gleser MA. Effect of carbon monoxide on oxygen transport during exercise. J Appl Physiol. 1972;32(2):234–9.
171. Adir Y, Merdler A, Ben Haim S, et al. Effects of exposure to low concentrations of carbon monoxide on exercise performance and myocardial perfusion in young healthy men. Occup Environ Med. 1999;56(8):535–8.
172. Aronow WS, Cassidy J. Effect of carbon monoxide on maximal treadmill exercise: a study in normal persons. Ann Int Med. 1975;83(4):496–9.
173. Aronow WS, Ferlinz J, Glauser F. Effect of carbon monoxide on exercise performance in chronic obstructive pulmonary disease. Am J Med. 1977;63(6):904–8.
174. Calverley PM, Leggett RJ, Flenley DC. Carbon monoxide and exercise tolerance in chronic bronchitis and emphysema. Br Med J Clin Res Ed. 1981;283(6296):878–80.
175. Drinkwater BL, Raven PB, Horvath SM, et al. Air pollution, exercise, and heat stress. Arch Environ Health. 1974;28(4): 177–81.
176. Keramidas ME, Kounalakis SN, Eiken O, et al. Carbon monoxide exposure during exercise performance: muscle and cerebral oxygenation. Acta Physiol (Oxf). 2012;204(4):544–54. doi:10.1111/j.1748-1716.2011.02363.x.
177. Turner JA, McNicol MW. The effect of nicotine and carbon monoxide on exercise performance in normal subjects. Respir Med. 1993;87(6):427–31.
178. Oliveira RS, Barros Neto TL, Braga AL, et al. Impact of acute exposure to air pollution on the cardiorespiratory performance of military firemen. Braz J Med Biol Res. 2006;39(12):1643–9. pii:S0100-879X2006001200016.
179. DeSouza CA, Shapiro LF, Clevenger CM, et al. Regular aerobic exercise prevents and restores age-related declines in endothelium-dependent vasodilation in healthy men. Circulation. 2000;102(12):1351–7.
180. Warburton DE, Nicol CW, Bredin SS. Health benefits of physical activity: the evidence. CMAJ. 2006;174(6):801–9.
181. Thompson PD, Crouse SF, Goodpaster B, et al. The acute versus the chronic response to exercise. Med Sci Sports Exerc. 2001;33(6 Suppl):S438–45 (discussion S52–3).
182. de Hartog J, Boogaard H, Nijland H, et al. Do the health benefits of cycling outweigh the risks? Environ Health Perspect. 2010;118(8):1109–16. doi:10.1289/ehp.0901747.
183. Grabow ML, Spak SN, Holloway T, et al. Air quality and exercise-related health benefits from reduced car travel in the midwestern United States. Environ Health Perspect. 2011;. doi:10.1289/ehp.1103440.
184. Hamer M, Chida Y. Active commuting and cardiovascular risk: a meta-analytic review. Prev Med. 2008;46(1):9–13. doi:10.1016/j.ypmed.2007.03.006.
185. Rojas-Rueda D, de Nazelle A, Tainio M, et al. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. BMJ. 2011;343:d4521.
186. Wong CM, Ou CQ, Thach TQ, et al. Does regular exercise protect against air pollution-associated mortality? Prev Med. 2007;44(5):386–92. doi:10.1016/j.ypmed.2006.12.012.
187. Dong GH, Zhang P, Sun B, et al. Long-term exposure to ambient air pollution and respiratory disease mortality in Shenyang, China: a 12-year population-based retrospective cohort study. Respiration. 2012;84(5):360–8. doi:10.1159/000332930.
188. Vieira RP, Toledo AC, Silva LB, et al. Anti-inflammatory effects of aerobic exercise in mice exposed to air pollution. Med Sci Sports Exerc. 2012;. doi:10.1249/MSS.0b013e31824b2877.
189. Yu YB, Liao YW, Su KH, et al. Prior exercise training alleviates the lung inflammation induced by subsequent exposure to environmental cigarette smoke. Acta Physiol (Oxf). 2012;205(4):532–40. doi:10.1111/j.1748-1716.2012.02433.x.
190. Normando VM, Mazzoli-Rocha F, Moreira DK, et al. Regular exercise training attenuates pulmonary inflammatory responses to inhaled alumina refinery dust in mice. Respir Physiol Neurobiol. 2013;186(1):53–60. doi:10.1016/j.resp.2012.12.010.
191. Delfino RJ, Tjoa T, Gillen DL, et al. Traffic-related air pollution and blood pressure in elderly subjects with coronary artery disease. Epidemiology. 2010;21(3):396–404. doi:10.1097/EDE.0b013e3181d5e19b.
192. Zanobetti A, Canner MJ, Stone PH, et al. Ambient pollution and blood pressure in cardiac rehabilitation patients. Circulation. 2004;110(15):2184–9. doi:10.1161/01.CIR.0000143831.33243.D8.

193. Giles LV, Barn P, Kunzli N, et al. From good intentions to proven interventions: effectiveness of actions to reduce the health impacts of air pollution. Environ Health Perspect. 2011;119(1):29–36. doi:10.1289/ehp.1002246.
194. Romieu I, Sienra-Monge JJ, Ramirez-Aguilar M, et al. Genetic polymorphism of GSTM1 and antioxidant supplementation influence lung function in relation to ozone exposure in asthmatic children in Mexico City. Thorax. 2004;59(1):8–10.
195. Romieu I, Sienra-Monge JJ, Ramirez-Aguilar M, et al. Antioxidant supplementation and lung functions among children with asthma exposed to high levels of air pollutants. Am J Respir Crit Care Med. 2002;166(5):703–9.
196. Samet JM, Hatch GE, Horstman D, et al. Effect of antioxidant supplementation on ozone-induced lung injury in human subjects. Am J Respir Crit Care Med. 2001;164(5):819–25.
197. Sienra-Monge JJ, Ramirez-Aguilar M, Moreno-Macias H, et al. Antioxidant supplementation and nasal inflammatory responses among young asthmatics exposed to high levels of ozone. Clin Exp Immunol. 2004;138(2):317–22. doi:10.1111/j.1365-2249.2004.02606.x.
198. Grievink L, Zijlstra AG, Ke X, et al. Double-blind intervention trial on modulation of ozone effects on pulmonary function by antioxidant supplements. Am J Epidemiol. 1999;149(4):306–14.
199. Langrish JP, Mills NL, Chan JK, et al. Beneficial cardiovascular effects of reducing exposure to particulate air pollution with a simple facemask. Part Fibre Toxicol. 2009;6:8. doi:10.1186/1743-8977-6-8.
200. Langrish JP, Li X, Wang S, et al. Reducing personal exposure to particulate air pollution improves cardiovascular health in patients with coronary heart disease. Environ Health Perspect. 2012;120(3):367–72.
201. Gong H Jr, Bedi JF, Horvath SM. Inhaled albuterol does not protect against ozone toxicity in nonasthmatic athletes. Arch Environ Health. 1988;43(1):46–53. doi:10.1080/00039896.1988.9934373.
202. McKenzie DC, Stirling DR, Fadl S, et al. The effects of salbutamol on pulmonary function in cyclists exposed to ozone: a pilot study. Can J Sport Sci. 1987;12(1):46–8.
203. Rundell KW, Spiering BA, Baumann JM et al. Bronchoconstriction provoked by exercise in a high-particulate-matter environment is attenuated by montelukast. Inhal Toxicol. 2005;17(2):99–105. doi:10.1080/08958370590899479.
204. Rundell KW, Caviston R, Hollenbach AM, et al. Vehicular air pollution, playgrounds, and youth athletic fields. Inhal Toxicol. 2006;18(8):541–7. doi:10.1080/08958370600685640.
205. Sheps DS, Adams KF, Jr., Bromberg PA et al. Lack of effect of low levels of carboxyhemoglobin on cardiovascular function in patients with ischemic heart disease. Arch Environ Health. 1987;42(2):108–16. doi:10.1080/00039896.1987.9935805.
206. Horvath SM, Gliner JA, Matsen-Twisdale JA. Pulmonary function and maximum exercise responses following acute ozone exposure. Aviat Space Environ Med. 1979;50(9):901–5.
207. Flouris AD, Metsios GS, Carrillo AE et al. Respiratory and immune response to maximal physical exertion following exposure to secondhand smoke in healthy adults. PLoS One. 2012;7(2):e31880. doi:10.1371/journal.pone.0031880