Air quality, respiratory health and performance in athletes: a summary of the IOC consensus subgroup narrative review on 'Acute Respiratory Illness in Athletes'

Valerie Bougault*

LAMHESS, Université Côte d'Azur, Nice, France; School of Kinesiology, The University of British Columbia, Vancouver, British Columbia, Canada (http: //orcid.org/0000-0002-2258-6562)

Christopher Carlsten

Division of Respiratory Medicine, Department of Medicine, University of British Columbia, Vancouver, British Columbia, Canada

Paolo Emilio Adami

Health and Science Department, World Athletics, Monaco (http: //orcid.org/0000-0001-5975-5342)

Nicola Sewry

Sport, Exercise Medicine and Lifestyle Institute, University of Pretoria Faculty of Health Sciences, Pretoria, South Africa; International Olympic Committee Research Centre, Pretoria, South Africa

Wolfgang Schobersberger

Institute for Sports Medicine, Alpine Medicine and Health Tourism, University Hospital - Tirol Kliniken, Innsbruck, Austria; Sport, Exercise Medicine and Lifestyle Institute, UMIT TIROL-Private University for Health Sciences and Health Technology, Hall in Tirol, Austria (http: //orcid.org/0000-0002-5657-0307)

Torbjørn Soligard

Medical and Scientific Department, International Olympic Committee, Lausanne, Vaud, Switzerland (http: //orcid.org/0000-0001-8863-4574)

Lars Engebretsen

Medical and Scientific Department, International Olympic Committee, Lausanne, Vaud, Switzerland

Richard Budgett

Medical and Scientific Department, International Olympic Committee, Lausanne, Vaud, Switzerland (http: //orcid.org/0000-0002-7474-8842)

Martin Schwellnus

Sport, Exercise Medicine and Lifestyle Institute, University of Pretoria Faculty of Health Sciences, Pretoria, South Africa; International Olympic Committee Research Centre, Pretoria, South Africa

Ken Fitch

School of Human Science, Sports, Exercise and Health, The University of Western Australia, Perth, Western Australia, Australia (http: //orcid.org/0000-0003-1303-0535)

*Correspondence to Dr Valerie Bougault; valerie.bougault@univ-cotedazur.fr

Abstract

With the WHO stating that nearly 99% of the global population is exposed to air pollution levels that increase the risk of chronic diseases, the question of exercising in polluted environments is relevant to the health of athletes. Major sporting events held under conditions of poor air quality (AQ) have highlighted the lack of answers to concerns raised by organisers and athletes about the associated health risks. This evidence-based narrative review compiles current knowledge and identifies gaps regarding the relationship between AQ and sport. It is a summary of a more comprehensive report prepared for the International Olympic Committee (IOC) Medical and Scientific Commission. This article discusses the various sources of air pollutants encountered during exercise, summarises current AQ guidelines and provides insights into AQ conditions during the Paris 2024 Olympic and Paralympic Games (OPG) as well as in Los Angeles over the past four summers, in preparation for the 2028 OPG. It also summarises the effects of air pollution on the respiratory health and performance of athletes, while proposing mitigation strategies, with a particular emphasis on AQ education.

WHAT IS ALREADY KNOWN ON THIS TOPIC

- Various tools and technologies are currently available to measure air pollution and inform the public about air quality (AQ).
- Air pollution promotes chronic disease development, increases mortality and reduces the benefits of physical activity.
- Mitigation strategies are available to reduce exposure to air pollutants.
- Regular physical activity has health benefits for almost all diseases and can help counter the effects of air pollution.

WHAT THIS STUDY ADDS

- The inhaled dose of air pollutants during exercise in different sports and environments remains to be established, especially for elite athletes which makes establishing firm recommendations to protect the health of athletes challenging.
- AQ education for athletes is needed but is often not accompanied by behaviour aimed at reducing exposure to air pollution.
- Political and sports authorities have a major role in protecting the health of athletes and currently, available AQ guidelines by a few International Sports Federations should be considered by all.
- Future research should focus on characterising the effects of different air pollutants in a dose-dependent manner in athletes.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

- Research: this study promotes studies on the inhaled dose of air pollutants in athletes and their health effects.
- Practice: this study highlights the need for better education about air quality and protective measures for athletes.
- Policy: our study encourages the adoption of international guidelines on air quality in sport and greater cooperation between authorities to measure and reduce air pollution in sport to protect athletes.

Introduction

Air quality (AQ) can be defined as the degree to which the ambient air is free of pollutants.[1] Air pollution affects the health of the population, increasing mortality[2–4] and causing or aggravating diseases, notably cardiovascular and respiratory disease. This includes but is not limited to respiratory diseases depending on the concentration of air pollutants and individual susceptibility.[5 6] Although there is a growing body of research on the effects of physical activity as a function of pollutant concentration on various health parameters, the cumulative dose of air pollution exposure at which the effects on health become detrimental remains unknown. Endurance athletes, who are exposed to pollutants during prolonged high-intensity exercise, are of particular concern. Up to now, we do not know the exact mechanisms of air pollution in the development of respiratory problems during sports nor do we know what other health risks athletes may face in the future. At times of exposure to air pollution, measures taken to reduce exposure depend on the type of event, the climatic conditions and the nature of the pollutants. This leaves several questions unanswered: Should a sports event be cancelled when air pollution reaches an alert level? What is this alert threshold? If not, what are the acute and longer-term risks to athlete health? Which athletes are at risk? What are the potential risks? The world is changing rapidly and with future sporting events predicted to take place increasingly in polluted environments, it is necessary to review our current knowledge of the effects of pollutants on the health and performance of all athletes. This narrative review presents a summary of a more comprehensive report on AQ on athlete health, that is freely available on the International Olympic Committee (IOC) website.[7]

The aim of the narrative review is to identify current knowledge and gaps regarding the effects of air pollution on respiratory health and performance in exercising people. The first part of the review describes the main sources of air pollutants during physical activity, the methods for measuring AQ and the global AQ index (AQI). The second part reviews the effects of different pollutants on respiratory parameters and athletic performance and considers management issues.

Methods

Constitution of the group

The authorship group was selected based on expertise in AQ, sports medicine, sports sciences, environmental health and respiratory diseases. In September 2019, on behalf of the IOC Medical and Scientific Commission, a core group for the IOC consensus statement on 'Acute respiratory illness in athletes' was convened, chaired by MS. A subgroup (number 3 of 7 subgroups) of this core panel, consisting of 7 members (VB, PEA, NS, KF, CC, MS, WS), focused on non-infectious acute respiratory illness caused by environmental factors in athletes. Three experts from the IOC Medical and Scientific Commission (LE, TS and RB) who were the originators of the request for the report on AQ in sport and who were involved in the discussions from the beginning, contributed to the formation of the group. The complete report on air pollution and sport is available on the IOC website and the present review is a summary. Each part has been reviewed in the context of the authors' collaborations with experts outside the IOC and/or their research work. We benefitted from the experience of some authors with the AQ during the Olympic and Paralympic Games (OPG) (KF) or during sport events (PEA, NS and VB) and the involvement of some authors with elite athletes, as sport scientist, medical doctor and member of International Federations or IOC. Consensus was obtained through several rounds of author revisions.

Equity, diversity and inclusion

This report has been developed with the aim of being inclusive and providing useful information to all. The IOC consensus subgroup 3 included experts from different countries (Australia, Austria, Canada, France, Italia, South Africa, Sweden, Switzerland) and continents (Africa, America, Europe, Oceania). The author group also includes a former Olympian (RB). Two women are involved in the group, including the leader.

Methodology

The starting point for this narrative review is a previous systematic review we conducted which highlighted the lack of data on the impact of environmental factors on non-infectious respiratory diseases in the context of physical activity among athletes.[8] This review provided a critical framework, emphasising the need for more targeted research and informing the structure of our guidelines. Existing position statements and narrative or systematic reviews, available for most of the topics covered—except for the role of education and the sections on AQ in Paris and Los Angeles—were consulted to ensure alignment with current knowledge and best practices. Additionally, more recent articles were identified through searches in PubMed, Scopus and Web of Science. The guidelines were developed through an interdisciplinary collaboration involving experts who synthesised the available evidence and tailored it to the specific focus of our study. Although we did not use a formal framework such as the Delphi methodology, as the expert group was already assembled, the process was rigorous and scientifically grounded. Given that existing reviews were available for each topic, we instead consolidated the work into an updated review which allowed us to produce a comprehensive report in the form of a synthesis.

Sources of air pollutants when exercising

Traffic-related air pollution

Exercising near major roads or in heavy traffic exposes the athlete to traffic-related air pollution (TRAP). Large stadiums are among the sport facilities that appear to be affected by traffic emissions.[9] In these stadiums, nitrogen dioxide (NO_2) concentration follows the characteristic traffic pattern with peaks during the morning and evening rush hours from car exhausts and inverse to the ozone (O_3) pattern due to titration (dissolution by interaction). The study of particulate matter (PM) concentrations showed markedly different trends, highlighting the hyper-local nature of these pollutants. Large sporting events can also have a significant impact on local AQ and the health of the local population, by increasing at least PM, NO_2 and O_3, from various sources.[10–12]

Wildfires, megafires and biomass combustion

Wildfires dramatically increase concentrations of air pollutants in the atmosphere. The 'black summer' (2019–2020) lasted for 5 months in eastern and southern Australia, leading to recommendations from the Australian Institute of Sport in 2023 on exercising in bushfire smoke for high performance athletes.[13]

In 2023, the impact of major wildfires on AQ in Canada, again raised questions about the dangers of exercising in such conditions,[14] as wood smoke and wildfire exposure can severely increase respiratory morbidity.[15 16] Major sporting events occurring during wildfire smoke episodes are generally postponed to protect the health of athletes.[17] The model of firefighters exposed to wildfire smoke is extreme, as they are subjected to very high concentrations of air pollutants while being physically active. A decrease in lung function has been observed up to 3 months after the onset of the first wildfire in these individuals.[18 19] Over the longer term, the risk of lung cancer mortality in wildfire firefighters is increased by 8–43%, according to notably the length of exposure.[20]

Artificial turf

Recreational and artificial turf fields are generally made of the recycled tyre, comprising polycyclic aromatic hydrocarbons, vulcanisates, additives, plasticisers, antioxidants and heavy metals.[21–23] Individuals playing on tyre crumbs are exposed to their constituents by inhalation of dust, skin contact with the material, surface water runoff or ingestion of the tyre crumb. Further studies are urgently needed on the potential hazardous effects on the health of playing or practising the sport on such artificial fields. Other considerations for grass include arsenic-contaminated irrigation water or the use of pesticides.[24–28] Artificial turfs also contain perfluoroalkylated and polyfluoroalkylated substances (PFAS).[29]

PFAS, phthalates and other substances

Many chemicals, such as phthalates or PFAS, are found in the air, although this is generally not the primary route of exposure. Instead, they are more commonly found in the athlete's environment, such as in clothing, drinking water, sports cans or bottles, cosmetics and other items. PFAS, in particular, have been detected in public swimming pools,[30] and can be released into the environment after ski waxing.[31–35] A systematic review found an increased incidence of cancer and Parkinson's disease among green space workers occupationally exposed to pesticides.[36] However, to date, there are no studies on the effects of pesticides or phthalates on athletes' health in the short or long term. In skiing activities, ski or snowboard waxing poses a significant risk of exposure to PFAS and other contaminants[31–35] but research in other sports remains limited. A recent review on professional ski wax technicians showed that waxes can lead to some of the highest airborne PFAS concentrations of any occupation, which may cause lung injuries, decreased lung diffusion capacity, severe dyspnoea, cough and rhinitis.[35] Additionally, PFAS exposure can impact immunity, suppress neutrophilic function and increase susceptibility to infections.[37] A recent study in an Inuit community also linked elevated blood PFAS levels to an increased risk of asthma and decrease lung function, though without affecting respiratory symptoms.[38]

Indoor pollutants

Indoor air pollution can come from both indoor and outdoor sources. The importance of the outdoor source depends on the penetration coefficient, the ventilation rate and the decay rate, despite some filtering. Recent studies, still insufficient, focused on pollution in gyms, fitness centres and sports halls.[39] PM, volatile organic compounds (VOCs), carbon dioxide (CO_2), bacteria and fungi may be found in high quantities, depending on the number of participants, and the efficiency of the gym's ventilation system.[39 40] High concentrations of VOCs may originate from cleaning products and alcohol-based hand disinfectants,[41] fragranced products,[42] gym equipment and building materials. The type of activity also influences the concentration of some pollutants in indoor air, for example, yoga classes being less exposed to pollutants than self-defence classes.[39 41] The resuspension of particles is a cause of high PM and very few studies report carbon monoxide (CO) or NO/NO_2, that have been found to be elevated in some sport halls. No increase in O_3 has been observed, due to indoor components, but there are insufficient data to confirm this. Open windows during concomitant hot summers and peak of O_3 may allow the spread of the gas into the room but in poorly ventilated rooms, the closed windows may increase CO_2.

High pollen and meteorological conditions

With climate change, pollen will be present in the atmosphere at higher concentrations for longer periods of time and a synergistic effect of pollutants, pollen and meteorological conditions has been observed in people with asthma.[43 44] The effect of such a combination during exercise has not yet been reported.

Methods to measure AQ

There are three main types of tools that in various combinations provide information on AQ: (1) Monitoring and measurements; (2) AQ modelling using both statistical and atmospheric dispersion/chemical transport models and (3) Assessment of AQ using a combination of measurements and models. The selection of the methodology depends on the purpose of the measurements. For example, the selection of instruments used for regulatory purposes must be in line with the legislative requirements. In the case of compliant monitoring networks, these require the use of reference instrumentation or instruments for which equivalence with the reference methods has been demonstrated. Monitoring devices integrate different sensors based on the type of pollutants they measure (see complete IOC report for details[7]).

Current general population guidelines on AQ

The US Environmental Protection Agency (US EPA) AQI has been widely adopted as a tool to report AQ status to the public in a simple way.[45] Briefly, the concentrations of six air pollutants (CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, sulphur dioxide (SO_2)) are converted into a number (index) and the higher number whatever the pollutant defines the AQI. According to this index, six categories were defined from good AQ (green colour) to hazardous AQ (brown colour) (figures 1 and 2). This index has since been revised, resulting in different indices that take into account local AQ characteristics, multipollutant exposure and impact on health on a country-wide scale.[45–47] Recent studies have also proposed disease-specific[48] or wildfire-specific adjustments of this new quality health index (AQHI).[49] In addition, the WHO sets out worldwide recommendations for keeping its population in good health and targets to be achieved in the event of non-compliance (table 1).[50] In all the guidelines, the short-term health effects are estimated by the effect of the pollutant concentration on the excess risk of hospital admissions, outpatient visits and/or morbidity and do not consider the public who do not seek hospital or medical attention when they have symptoms nor the individual's susceptibility to the pollutant or the inhaled dose. Therefore, these guidelines cannot be extrapolated to advise when a sports competition or training might be harmful to participants.

AQ index	AQ category	Health implication	Cautionary statement on outdoor physical activity*
0-50	Good	AQ is considered satisfactory, and air pollution poses little or no risk	It's a great day to be active outside.
51-100	Moderate	**Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.**	**Unusually sensitive people:** **O_3 and PM**: Consider making outdoor activities shorter and less intense. Watch for symptoms such as coughing or shortness of breath. These are signs to take it easier. **NO_2**: Consider limiting prolonged exertion especially near busy road. **CO:** It's a great day to be active outside. **SO_2**: It's a great day to be active outside.
101-150	Unhealthy for sensitive groups	Members of sensitive groups may experience health effects. The public is not likely to be affected.	**Sensitive groups:** **O_3:** Make outdoor activities shorter and less intense. Take more breaks. Watch for symptoms such as coughing or shortness of breath. Plan outdoor activities in the morning when ozone is lower. **People with asthma:** Follow your asthma action plan and keep quick-relief medicine handy. **PM**: Make outdoor activities shorter and less intense. It's OK to be active outdoors but take more breaks. Watch for symptoms such as coughing or shortness of breath. **People with asthma:** Follow your asthma action plan and keep quick relief medicine handy. **People with heart disease:** Symptoms such as palpitations, shortness of breath, or unusual fatigue may indicate a serious problem. If you have any of these, contact your health care provider **NO_2:** Limit prolonged exertion outdoors, especially near busy roads. **People with asthma:** Follow your asthma action plan and keep quick relief medicine handy. **CO:** Limit heavy exertion outdoors and avoid sources of CO, such as heavy traffic **SO_2:** Consider limiting outdoor exertion. **People with asthma**: Follow your asthma action plan and keep quick relief medicine handy.
151-200	Unhealthy	Everyone may begin to experience health effects; Members of sensitive groups may experience more serious health effects.	**Sensitive groups:** **O_3**: Make outdoor activities shorter and less intense. Take more breaks. Watch for symptoms such as coughing or shortness of breath. Plan outdoor activities in the morning when ozone is lower. **People with asthma:** Follow your asthma action plan and keep quick-relief medicine handy. **PM**: Make outdoor activities shorter and less intense. It's OK to be active outdoors but take more breaks. Watch for symptoms such as coughing or shortness of breath. **People with asthma**: Follow your asthma action plan and keep quick relief medicine handy.
			People with heart disease: Symptoms such as palpitations, shortness of breath, or unusual fatigue may indicate a serious problem. If you have any of these, contact your health care provider. **CO**: Limit moderate outdoor exertion and avoid sources of CO, such as heavy traffic. **NO_2**: Avoid prolonged outdoor exertion near roadways. **People with asthma:** Follow your asthma action plan and keep quick relief medicine handy. **SO_2:** Limit outdoor exertion. **People with asthma**: Follow your asthma action plan and keep quick relief medicine handy.
			Everyone else: **O_3**: Reduce long or intense outdoor activity. Take more breaks, do less intense activities. Schedule outdoor activities in the morning when O_3 is lower. **PM:** Keep outdoor activities shorter and less intense. Go inside if you have symptoms. **NO_2:** Limit prolonged outdoor exertion especially near busy roads
201-300	Very Unhealthy	Health warnings of emergency conditions. The entire population is more likely to be affected.	**Sensitive groups:** **O_3**: Avoid all physical activity outdoors. Move activities indoors** or reschedule to when air quality will be better. **People with asthma:** Follow your asthma action plan and keep quick-relief medicine handy. **PM:** Avoid all physical activity outdoors. Reschedule to a time when air quality is better or move activities indoors**. **People with asthma**: Follow your asthma action plan and keep quick relief medicine handy. **People with heart disease**: Symptoms such as palpitations, shortness of breath, or unusual fatigue may indicate a serious problem. If you have any of these, contact your health care provider. **CO**: Avoid outdoor exertion and sources of CO, such as heavy traffic **NO_2**: Avoid all outdoor exertion. **People with asthma:** Follow your asthma action plan and keep quick relief medicine handy. **SO_2:** Avoid outdoor exertion. **People with asthma**: Follow your asthma action plan and keep quick relief medicine handy. **Everyoyne else** **O_3**: Avoid long or intense outdoor exertion. Schedule outdoor activities in the morning when O_3 is lower. Consider moving activities indoors. **PM:** Limit outdoor physical activity. Go indoors if you have symptoms. **NO_2**: Avoid prolonged outdoor exertion especially near busy roads.
			SO_2: Reduce outdoor exertion.
300+	Hazardous	Health alert; Everyone may experience more serious health effects.	**Sensitive groups:** **O_3: People with asthma:** Follow your asthma action plan and keep quick-relief medicine handy. **PM:** Stay indoors** and keep activity levels light. Follow tips for keeping particle levels low indoors. **People with asthma**: Follow your asthma action plan and keep quick relief medicine handy. **People with heart disease**: Symptoms such as palpitations, shortness of breath, or unusual fatigue may indicate a serious problem. If you have any of these, contact your health care provider. **CO**: Avoid outdoor exertion and sources of CO, such as heavy traffic **NO_2**: Remain indoors Avoid all outdoor exertion. **People with asthma:** Follow your asthma action plan and keep quick relief medicine handy. **SO_2:** Remain indoors. **People with asthma**: Follow your asthma action plan and keep quick relief medicine handy.
			Everyone: **O_3**: Avoid all physical activity outdoors. **PM:** Avoid all physical activity outdoors. **CO:** Limit heavy outdoor exertion. **NO_2**: Avoid all outdoor exertion. **SO_2**: Avoid outdoor exertion.

Figure 1

Example of the modified version of Air Quality index with colour codes for the population (US EPA Health Classification of Air Quality Index).[132] Unusually sensitive groups are people with heightened sensitivity to pollutants: This can include individuals with allergies or those who are sensitive to specific components of air pollution. Sensitive groups for O_3 are people with lung disease, such as asthma; children, including teenagers, people who are active outdoors and older adults; for PM: people with heart or lung disease; older adults; and children, including teenagers. In addition, some minority groups, people with lower incomes and outdoor workers may experience higher exposure that can worsen underlying health conditions; for CO: people with heart disease; NO_2: people with lung disease, such as asthma, children, including teenagers and older adults; for SO_2: people with asthma, children and older adults.[132] **be careful of indoor heat and CO_2. Source of the figure: US EPA: US Environmental Protection Agency.[132] AQ, air quality; CO, carbon monoxide; NO_2 nitrogen dioxide; O_3 ozone; PM, particulate matter; SO_2 sulphur dioxide.

Air pollutant		AQ category					
Air pollutant	Averaging time	Good	Moderate	Unhealthy for sensitive groups	Unhealthy	Very Unhealthy	Hazardous
AQ index		0-50	51-100	101-150	151-200	201-300	300+
$PM_{2.5}$, µg/m^{-3}	24-hour mean	≤9	9.1-35.4	35.5-55.4	55.5-125.4	125.5-225.5	≥225.5
PM_{10}, µg/m^{-3}	24-hour mean	≤ 54	55-154	155-254	255-354	355-424	≥425
O_3, ppb	1-hour mean	--	-	125-164	164-204	205-404	≥405
	8-hour mean	≤ 54	55-70	71-85	86-105	106-200	≥201
NO_2, ppb	1-hour mean	≤ 53	54-100	101-360	361-649	650-1249	≥1250
SO_2, ppb	1-hour mean	≤ 35	36-75	76-185	186-304	305-604	≥605
CO, ppm	8-hour mean	≤ 4.4	4.5-9.4	9.5-12.4	12.5-15.4	45.5-30.4	≥30.5

Figure 2

Breakpoints for the Air Quality index (US EPA Health Classification of Air Quality Index)[132] Source of the figure: US EPA: US Environmental Protection Agency.[132] AQ, air quality; CO, carbon monoxide; NO_2 nitrogen dioxide; O_3 ozone; PM, particulate matter (diameters<2.5 µm and<10 µm); SO_2, sulphur dioxide.

Inhaled dose of pollutants when exercising

During exercise, people increase their inhaled dose of pollutants which is the product of the pollutant concentration, ventilation effort and exposure time. While this equation is useful for quantifying the inhaled dose of each pollutant, certain specifics need to be considered and the difficulty of accounting for the interdependence and co-occurrence of different pollutants raises questions. For example, in a comprehensive review of O_3 and exercise, Adams[51] reported that the primary predictor of the lung function change during exercise, was the O_3 concentration, accounting for 50–75% of the variance, whereas $\dot{V}_E$ needs defining for only 10–20% of the variance. The correlation coefficients for the regression of forced expiratory volume in one second (FEV_1) on effective O_3 dose were also higher when O_3 concentration was raised to the power of 1.8 (r=0.92), compared with when the simple product of concentration, $\dot{V}_E$ and exposure time was used (r=0.82). It should be noted that $\dot{V}_E$ is sometimes missing or not measured in studies, making it difficult to compare the effects of different inhaled doses.

Air pollution, the recent and the future Summer OPG

Paris 2024

The AQ data for the summer months in the Paris region area from 2020 to 2023 were analysed to inform attendees of the 2024 OPG about typical air quality conditions during this season.[52] The main conclusions were, that during sunny, hot and clear weather conditions, there was a high probability of elevated O_3 levels. The maximum hourly O_3 concentration during the four previous summers had been 221 µg.m^{-3} (~0.113 ppm) in a rural station.[52] While this level is not of concern according to the US EPA AQI, it exceeds the information threshold for sensitive individuals in France (180 µg.m^{-3}) and corresponds to a poor AQ level.[7] When analysing the literature on healthy athletes exercising at such O_3 level, only isolated cases reported significant respiratory symptoms or had a reduction of lung function[52] The highest values generally occurred between 13:00 and 20:00 local time, peaking around 16:00 local time during maximum solar radiation. In contrast, concentrations of NO_2 and PM were usually lower during this season due to reduced emissions from road traffic and residential heating, combined meteorological conditions favouring pollutant dispersion. We conducted an a posteriori analysis of AQ data during the 2024 OPG (July 26 to 8 September 2024), using open data from Airparif.[53] Overall, observed AQ during the summer of 2024 was consistent with prior summers and forecasts. On one particularly hot day (30 July 2024,~34°C), the O_3 information threshold (180 µg.m^{-3}) was exceeded between 13:00 and 18:00 local time, with a maximum hourly concentration of 199.8 µg.m^{-3} recorded at one station. However, this remained below the French alert threshold (240 µg.m^{-3}). Towards the end of the summer holiday period in late August, a peak in NO_2 and PM concentrations was observed, coinciding with increased traffic congestion in the Paris region, as previously described.[52]

Table 1

WHO air quality guidelines and interim targets.[50] The values expressed are limit values for human health

Pollutant	Averaging time	Air quality guideline level	Interim target			
			4	3	2	1
$PM_{2.5}$, µg.m^{-3}	Annual	5	10	15	25	35
	24-hour	15	25	37.5	50	75
PM_{10}, µg.m^{-3}	Annual	15	20	30	50	70
	24-hour	45	50	75	100	150
O_3, µg.m^{-3}	Peak season	60	–	–	70	100
	8 hours	100	–	–	120	160
NO_2, µg.m^{-3}	Annual	10	–	20	30	40
	24-hour	25	–	–	50	120
	1 hour	200	–	–	–	–
SO_2, µg.m^{-3}	24-hour	40	–	–	50	125
	10 min	500	–	–	–	–
CO, mg.m^{-3}	24-hour	4	–	–	–	7
	8 hours	10	–	–	–	–
	1 hour	35	–	–	–	–
	15 min	100	–	–	–	–

- **Air quality guideline level: it is assumed adverse health effects do not occur or are minimal below this concentration level.**
- **The interim targets represent air pollution concentrations with a specific increase of health risks.**
- **The WHO tables are copyrighted CC BY-NC-SA 3.0 IGO.**
- **CO, carbon monoxide; NO_2, nitrogen dioxide; O_3, ozone; PM, particulate matter (diameters <2.5 µm and <10 µm); SO_2, sulphur dioxide.**

Los Angeles 2028

The 2028 Summer OPG will be held in Los Angeles from 14 July 2028 to 30 July 2028 and 15 August 2028 to 27 August 2028, respectively. O_3 has been decreasing in Los Angeles since the 1984 Olympic Games, thanks to regulations that reduce its precursors such as nitrogen oxides and VOCs.[54] However, it has been recently confirmed that the heat wave and lack of ventilation on consecutive days, as observed in recent years, could largely offset the benefits of regulation.[54 55] In a period of climate change, it is difficult to predict the AQ in Los Angeles in 2028. However, all the updated concentrations and AQ data are freely available on the website of the US EPA.[56] Concentration plots of US EPA for O_3 and $PM_{2.5}$ from 2019 to 2023 are shown in figure 3. They confirm the region is at risk of high O_3 concentrations during July and August, especially in the case of heatwaves. From 2019 to 2023, the number of O_3 exceedance days (>0.07 ppm, eg, ~140 µg/m^{-3}) is stable and varies from 17 to 30 days in July and 19 to 22 days during August.

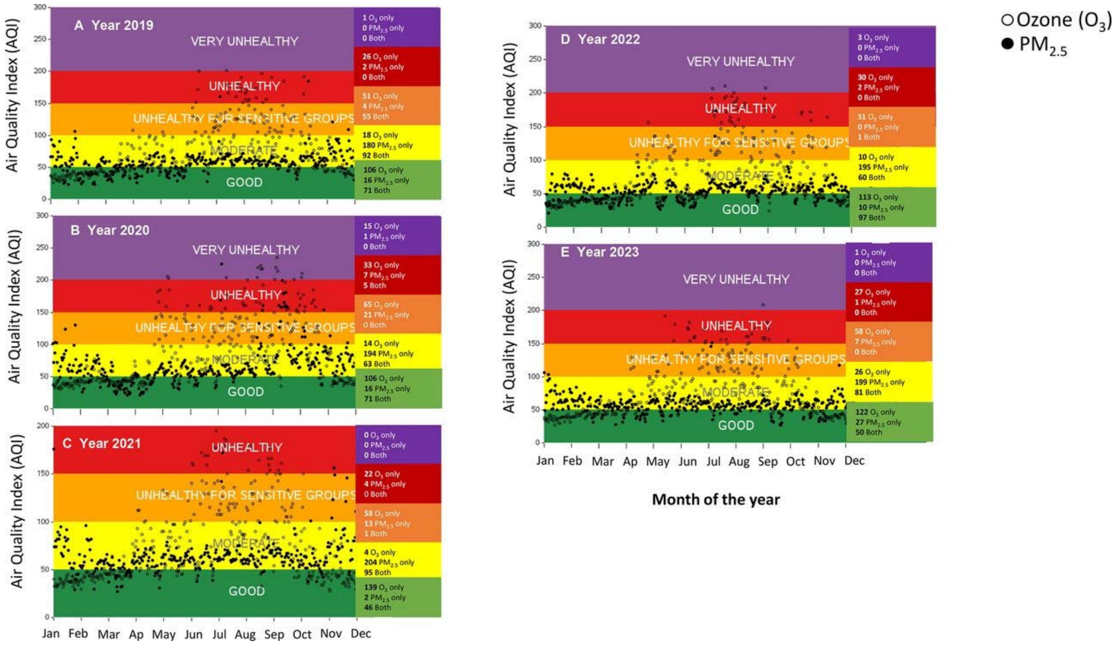

Figure 3

Daily ozone and $PM_{2.5}$ air quality index (AQI) values from 2019 to 2023 in Los Angeles County, California, USA according to the month of the year. Black circles: $PM_{2.5}$; Empty circles: Ozone (O_3). For each air quality index breakpoint, the number of O_3 only, $PM_{2.5}$ only or both pollutant concentration values in the zone during the year is shown on the right. Sources of the figure: US Environmental Protection Agency. Air Quality System Data Mart (internet database).[50] PM, particulate matter.

Effects of air pollution on athletes' respiratory health and sports performance

Short-term exercise in polluted air and respiratory health

Only a few studies have reported on the effects of exposure to air pollution during high-intensity exercise on respiratory health and sports performance and these have been summarised in various reviews.[57–60] For PM, most of the studies used the model of diesel exhaust to represent TRAP. Hung *et al*[59] recently synthesised randomised controlled trials in this domain and found that while short-term O_3 exposure in moderate-to-vigorous exercise causes transient reductions in lung function and increased symptoms, there is little evidence in the broader air pollution literature to suggest definitive harm on this time scale. Reductions in lung function observed are primarily in forced vital capacity (FVC), FEV_1 and forced expiratory flow from the midpoint of FVC ($FEF_{25–75}$).[59] The main reported respiratory symptoms include pain on deep inspiration, cough, dyspnoea and wheezing.[59] However, these authors identified major gaps in the literature, so the message should be a call for further research rather than simple reassurance. A commonality among these reviews is the lack of a reliable biomarker by which to practically follow pollution-related harm in an exercising population. There is no clear evidence that athletes with exercise-induced bronchoconstriction are at greater risk of being affected by contaminants,[8 51] despite being suggested in children.[61 62]

Long-term exercise in polluted air and respiratory health

The effects of long-term exposure to air pollution are well understood in the general population and have been the subject of numerous reviews.[63–65] What is poorly understood is the degree to which athletes are more at risk due to increased ventilatory rates during exertion which increases pollution intake. Although limited, the proportion of a given day that is associated with increased exertion is significant and can amount to several hours per day for some athletes, particularly during periods of high training load. While dose-response relationships are non-linear, the known multifold increase in airway exposure to particles and gases on increased exertion can reasonably be expected to have an adverse cumulative impact over years of athleticism. On the other hand, some authors have suggested that chronic exposure to pollutants in recreational athletes could lead to adaptations and, accordingly, to some attenuation of the airway response and some markers of oxidative stress and inflammation.[66] This interpretation should be taken with caution, as a decline in small airway function, a marker of early lung injury, has been observed in healthy young adults chronically exposed to the highest O_3 concentrations.[67 68]

Effects of air pollution on sports performance

Potential mechanisms of impact on athletic performance

Air pollution can affect exercise performance in healthy athletes, primarily due to its impacts on the respiratory system.[69] However, its influence may extend to cardiovascular[70] and muscular systems as well,[71] though these effects are less well understood and warrant further investigation. Exposure to various pollutants leads to oxidative stress and inflammation in the airways, leading to an increase in pulmonary resistance, a significant decrease in lung function and respiratory symptoms. The gas exchange may thus be impaired, reducing oxygen availability to the muscles during physical activity. This can lead athletes to experience fatigue earlier, a heightened perception of effort and a reduction in endurance or at least maximal performance capacities.[51 69] Moreover, exposure to some pollutants during exercise could increase cardiovascular stress, raising heart rate and systemic or pulmonary blood pressure which would reduce exercise efficiency.[70 72] In addition to its effects on physical performance, air pollution could also impair cognitive function in healthy athletes, leading to a decrease in technical or strategic skills in sports. Exposure to air pollutants has been shown to negatively affect brain function, leading to difficulties with attention, memory, reaction time, executive function task performance and decision-making,[73 74] all of which can be critical during team or technical sports performance. Finally, air pollution, through oxidative stress and inflammation, may significantly affect metabolic processes, including glucose metabolism, mitochondrial function and lipid regulation, while also disrupting insulin signalling.[75] These changes could potentially reduce the efficiency of both aerobic and anaerobic energy systems. Additionally, impacts on iron metabolism and other organs could be hypothesised, though comprehensive studies are lacking. The effects of air pollutants on the adaptation processes to training also remain largely unexplored, highlighting the need for further research in this area.

Individual susceptibility

In addition to the vulnerability attributed to higher pollutant concentration, there is susceptibility imposed by individual characteristics,[76] including a genetic susceptibility,[77 78] and that has not yet been clearly characterised in this context, as only a few studies have been carried out in elite athletes. Exposure to high levels of O_3 in elite cyclists and runners in exposure chambers led to the cessation of high-intensity exercise in 30–40% of them, depending on the concentration of the pollutant.[79–82] Variants in genes of oxidative stress metabolism are common and these common variants can acutely decrease airflow by nearly 25% when pollution is combined with allergen exposure, at least in laboratory settings.[83] While these simulations do precisely mimic competitive settings, they are proof of the principle of oxidative stress as a critical mechanism for impact on relevant physiology; one can easily imagine that even a minor version of such an effect in an elite athlete could have serious implications on performance. Interestingly, the most studied of these variants, GSTM1, did not influence the response to O_3, in particular, in a controlled human exposure study.[84] This suggests that for O_3, other susceptibility factors may be at play, but a multicentre study was unable to identify them in spite of an attempt to carefully do so.[85]

Experimental and epidemiological observations

Some mild effects of air pollution on the sports performance of athletes have been demonstrated even at low concentrations, mainly through epidemiological studies, despite low evidence. Randomised control studies in exposure chambers with isolated pollutants (mainly O_3) have shown the difficulty of observing such effects on maximal performance, despite the presence of respiratory symptoms and decline in lung function, except at very high concentrations. The effects appear to be individual. Athletes, who are sensitive to air pollution, complain of symptoms that are severe enough to prevent them from exercising even at moderate levels of air pollution and even during submaximal exercise.[79 80 82] During endurance exercise in O_3, for which there are more studies,[59] randomised controlled trials suggest that the higher the concentration, the greater the number of athletes unable to complete the effort or experiencing performance declines.[51]

Sport-specific impacts: endurance, team sports and E-sports

Retrospective analyses of air pollutants and performance in marathons, athletics and triathlons have shown correlations between finish times or rankings and concentrations of some air pollutants.[86 87] An increase of about 20 $\mu g.m^{-3}$ of O_3 decreases finishing time by 0.4–1%[88–90] and an increase of 10 $\mu g.m^{-3}$ of PM_{10} or $PM_{2.5}$, decreases performance by 1.2–1.4%.[89 91] Some studies have shown that increases in $PM_{2.5}$ and PM_{10} lead to longer marathon and 5 km running times, especially in women.[86 91] These performance changes may not be readily apparent on an individual basis or within short-term studies[92 93] but are sufficient to alter the order of finish and the podium to the detriment of the most susceptible. When the air is highly polluted, the effects become more pronounced. For example, during the 2014 Beijing Marathon, which had highly polluted air, the average marathon runner took about 12 min longer to complete the race than on a day with moderately polluted air.[94] In Italian amateur track and field athletes competing outdoors (running, jumping, throwing but not marathon), Granella[95] found that each 10 $\mu g/m^3$ increase in $PM_{2.5}$ resulted in a loss of one-third of a percentile in national rankings, even at concentrations well below the WHO threshold of 25

$\mu g/m^3$. The effects increased with the average duration of the event[95] and for the best athletes.[95] This contradicts two other studies reporting that professional or highly-trained endurance athletes are less susceptible to pollutant effects, possibly because their exposure is shorter than other athletes.[86 89] Granella *et al*[95] observed a more pronounced effect in high-level athletes, which may be attributed to their deliberate strategy of adjusting race pace strategically, regardless of AQ, focusing on winning rather than achieving specific times. This approach is particularly common during major events, where conserving energy can be critical. Conversely, less experienced athletes often adopt an all-out strategy throughout the race, prioritising maximum speed over tactical pacing. On the other side, it remains unclear whether elite athletes are protected from air pollution's effects on performance due to superior exercise-induced protection against air pollution[96] or whether they achieve elite status because of reduced sensitivity to pollutants, potentially due to genetic predisposition. Further investigation is needed to clarify these mechanisms. Team sports are not immune to these effects. Reductions in the total distance covered per match, high-intensity and sprint effort and change of direction speed have been reported in professional and adolescent soccer players.[97–100] Cognitive and executive functions as well as technical football skills are also negatively affected by increasing PM, NO_2 and/or O_3.[99 101] The number of errors and effectiveness in team sports has been shown to increase with a poor AQ index,[102 103] especially for visiting teams, who are thus at a disadvantage compared with the home team.[101] The term 'visitor teams' refers to teams that travel to participate in a game or match at the home venue of the opposing team. In electronic sports (e-sports), the League of Legends study found that higher $PM_{2.5}$ levels in the indoor stadium altered less the performance of the stronger team (rank above the 75th percentile) in a match and hindered that of the weaker team (rank below the 25th percentile), regardless of the absolute strength of a team.[104] This affects decision-making and tactics, especially in the weaker teams, favouring the better players.

The effects of pollution on performance can sometimes be overshadowed by the more substantial impact of heat.[105] However, these effects do exist and, although they may be relatively small in scale, they can affect outcomes in sporting events where victory is often determined by fractions of a second. In addition, athletes who train for several weeks in more polluted air have blunted training adaptations, increased fatigue and reduced performance compared with their peers who train in a less polluted environment.[106 107]

Guidelines: management of AQ to protect respiratory health and sports performance in athletes

Individual management plans and literature-based advice have been published previously.[8 13 59 108] It is estimated that more than 99% of the world's population is exposed to annual $PM_{2.5}$ concentrations above 5 $\mu g/m^3$ and more than 70% of the days per year have mean daily concentrations above 15 $\mu g/m^3$.[109] In these conditions, exposure to air pollutants during exercise should be avoided or reduced as much as possible. Conversely, stopping all physical activity in the event of air pollution is not a sustainable solution. Given the major health benefits of physical activity and the detrimental effects of sedentary lifestyles,[110] it is crucial to encourage everyone to take part in physical activity, especially as it can protect against the chronic effects of pollution.[111] However, physical activity in polluted environments should be adapted for everyone, especially those who are sensitive to AQ. The best preventive measure is to reduce the inhaled dose of pollutants and there are two ways to do this; (1) reduce the instantaneous inhaled concentration of pollutants (the most effective method supported by real-time and anticipated air pollution measurements); (2) reduce the ventilation and/or the duration of exercise (table 2). While acclimatisation is likely to occur after a few days, the long-term health effects of exposure are undesirable. Therefore, in the absence of further data, acclimatisation may be a voluntary short-term option for competitive athletes only, with pre-existing exposure at the competition site being preferable to artificial exposure in an exposure chamber.[8 112]

The role of regulatory agency and sport organisation policies

Combined public and sports policies play an important role in reducing air pollution and ensuring good AQ for physical activity. Effective measures used at various international sporting events hosted by China, including the Summer and Winter Olympic Games, included production shutdowns and restrictions on heavily polluting industrial activities, restrictions on motor vehicles and traffic control and strict control of construction dust to reduce transient pollutant emissions.[113 114] If these measures are effective for $PM_{2.5}$, PM_{10}, NO_2, CO and SO_2, O_3 is resistant;[113] this is consistent with observations made during the COVID-19 confinement which showed a decrease in air pollutants except for O_3 which varies little or increases.[115–125] Nevertheless, these measures are the privilege of the major world sporting events, nearly exclusively the OPG, and are seldom applied to other events. International sports organisations, such as the World Athletics, have also started to address the issue and are planning ways to improve the quality of air at sporting events.[9] The aim would be to identify site-specific pollution patterns and their sources by real-time monitoring and data collection over several sporting events, weeks or months and assist stadium operators in providing recommendations to the athlete community to minimise exposure to air pollutants.

Table 2

Strategies to reduce inhaled dose of air pollution during physical activity

Strategy	Example of action
Reduce and avoiding polluting the atmosphere	• **Choosing active mode transports** • **Choosing places close to home or work for sport or physical activity**
Follow air quality forecasts	• **Regularly check AQ forecasts to plan physical activities and sports**

Choose location of practise	• **If available in your city, check applications to choose the least polluted route when using active mobility**
	• **Stay as far away from busy roads as possible (every 10 metres counts)**
	• **Stay as far away from any local source of pollution**
	• **In case of episode of air pollution, you may choose an indoor sport facility well-ventilated and with HEPA filters. Be careful:**
	    ◦ **Some indoors facilities may be more polluted than outdoor**
	    ◦ **Open windows may favour penetration of O_3**

Choose the hours of practise	• **Each pollutant has generally a daily variation pattern. Choose less polluted hours.**
Adjust the load of physical activity (volume, type and intensity) in case of pollution	Sensitive athletes • **Replace activities that increase ventilation by low-ventilation activities, that is, relaxing activities, easy muscle conditioning, stretching.** • **Be aware that outdoor physical activities such as gardening or soccer game, but also child's games may increase ventilation.** Less sensitive athletes • **Decrease intensity (heart rate, power, speed, rate of perceived exertion)** • **Replace endurance training by a same intensity interval training but with rests periods** • **Replace high intensity interval training with moderate intensity interval training** • **Reduce duration of training, bouts of exercise…**
Facemasks (for PM only not for gases)	Some commercially available face masks are designed to reduce PM inhalation during physical activity.[133] Their tolerability during high-intensity exercise or heat needs to be investigated in athletes. Instructions should be carefully respected (filters change, sealing)

- **AQ, air quality; HEPA, high-efficiency particulate air; O_3, ozone; PM, particulate matter.**

The role of information and education

The general public is often unaware of the WHO or environmental protection agencies advice on how to exercise according to their health status, even though they are aware that air pollution can affect health.[126–128] In the US, a large survey on adults showed a third to 54% of the population being aware of the AQ alerts and only 19% of adolescents.[126–128] The change in behaviour or activities associated with a poor AQ index has been reported in only 10–15% of the US adult population studied.[126 127] Behavioural changes include reducing time spent outdoors (9%), reducing strenuous activities (3%), exercising indoors rather than outdoors (3%) and changing the timing or characteristics of physical activity (2%).[126] Psychosocial facilitators were identified as having knowledge of where to find AQ indices, beliefs that one's symptoms were due to air pollution or perception of poor AQ and advice received by healthcare professionals.[127 129] The severity of air pollution is also a facilitator, such as during wildfires, the adherence and change in behaviours is close to 100%.[130] On the contrary, barriers to adherence included a lack of understanding of the AQ indices and a lack of time.[129] In addition, which can make it difficult to assess the effectiveness of these communications, the health advice associated with AQ alerts is rarely specific and exhaustive.

Future research direction

Future research should focus on several key areas to address the existing gaps in our understanding of air pollution's effects on athletic performance and athletes' health. A key step is the detailed characterisation of the 'athletic exposome' according to the sport, which encompasses all the environmental exposures that athletes face during training and competition, including air pollutants (eg, PM, O_3 and NO_2), temperature, humidity and allergens. Such data are crucial for understanding the interactions between these exposures and their cumulative effects on exercise performance. Current studies have shown that air pollution, particularly fine PM and O_3, can notably impair lung function, provoke respiratory symptoms which can reduce negatively athletic performance in some endurance sport athletes. Further research should also continue to explore the specific mechanisms by which different air pollutants impact the respiratory system, including the increased pollutant-induced risk of acute respiratory infections[131] and how these pollutants might affect other physiological systems, including the cardiovascular, metabolic and cognitive systems. Longitudinal studies could elucidate the chronic effects of exposure on training adaptations, recovery and long-term performance. Such data are crucial for understanding how chronic exposure to air pollution may alter athletes' ability to adapt to training, recover effectively and maintain long-term performance and health. Addressing interindividual variability, such as genetic predisposition and the influence of pre-existing conditions, the role of sex or training status, would provide insights into athletes' susceptibility and resilience. In addition, the development and validation of practical mitigation strategies, ranging from behavioural adaptations (education) to technological interventions, is still necessary to complement existing recommendations. Finally, collaborative efforts involving researchers, policymakers and sports organisations could facilitate recommendations to reduce exposure during outdoor sports, especially in urban areas with high levels of pollution, while standardising methods for assessing both exposure and performance effects under different environmental conditions.

Conclusion

Athletes are unevenly exposed to a variety of air pollutants during their sporting activities, depending on where they live, train and compete. The means of measuring AQ have developed considerably in recent years but are still in their infancy and are poorly suited to sporting activities, especially those that require constant movement. Similarly, too few studies are currently available on the effects of acute exposure to air pollution during intense exercise, depending on the type and concentration of pollutants, confounding variables such as co-exposure, meteorological conditions, habitual exposure rates of athletes and exercise conditions (training load). It is not yet possible to give a clear answer to the demands of the sporting world as to the threshold at which an event should be cancelled or postponed. It is likely that air pollution affects various aspects of performance, which increase with concentration and intensity of effort, although there is no conclusive evidence. No data are available on the risk-benefit balance of year-round exposure to air pollutants during sports training (chronic exposure). To increase our understanding and optimise risk mitigation in the future, many studies are urgently needed to protect the health of athletes.

Ethics statements

Patient consent for publication

Not applicable.

Ethics approval

Not applicable.

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