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Athletes' exposure to air pollution during World Athletics Relays: A pilot study

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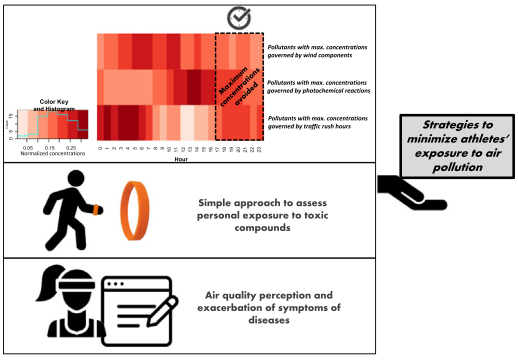
HIGHLIGHTS

- A multiparametric approach was tested to assess air quality during an athletics event.
- The approach was effective to provide guidance regarding training/competition schedules.
- Wearable wristbands proved useful to monitor personal exposure to PAHs.
- Air quality perception and health symptoms were assessed through questionnaires.
- Research needed on air pollutant exposures impacting athletic performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Potential adverse consequences of exposure to air pollutants during exercise include decreased lung function, and exacerbation of asthma and exercise-induced bronchoconstriction. These effects are especially relevant for athletes and during international competitions, as they may impact athletic performance. Thus, assessing and mitigating exposure to air pollutants during exercising should be encouraged in sports venues. A comprehensive air quality assessment was carried out during the World Relays Yokohama 2019, in the stadium and the warm-up track. The pilot included on-line and off-line instrumentation for gaseous and particulate pollutants and meteorological parameters, and the comparison with local reference data. Air quality perception and exacerbation of symptoms of already-diagnosed diseases (mainly respiratory and cardiovascular) were assessed by athletes by means of questionnaires during training sessions. Median NO_2 concentrations inside the stadium (25.6–31.9 $\mu g m^{-3}$) were in the range of the Yokohama urban background, evidencing the impact of urban sources (e.g., traffic) on athletes' exposure during training and competition. The assessment of hourly air pollutant trends was identified as a valuable tool to provide guidance to reduce atheletes' exposure, by identifying the periods of

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the day with lowest ambient concentrations. This strategy could be adopted to define training and competition schedules, and would have special added value for athletes with respiratory conditions. Personal exposure to polycyclic aromatic hydrocarbons was quantified through wearable silicone wristbands, and showed highly variability across volunteers. The wristbands are a simple approach to assess personal exposure to potentially toxic organic compounds. Further research would be necessary with regard to specific air pollutants that may trigger or exacerbate respiratory conditions typical of the athlete community. The availability of high time-resolved exposure data in the stadiums opens up the possibility to calculate doses of specific pollutants for individual athletes in future athletics events, to understand the impact of environmental factors on athletic performance.

1. Introduction

Evidence supports adverse effects from short-term and long-term inhalation of air pollution to the respiratory and the cardiovascular systems (Brook et al., 2002; Pietropaoli et al., 2004; Gauderman et al., 2007; de Prado Bert et al., 2018). Health impacts have been assessed for general and high-risk populations, and even for general populations performing physical activities such as walking or cycling while commuting (de Nazelle et al., 2012; Hofman et al., 2018; Luengo-Oroz and Reis, 2019; Qiu et al., 2019; Quiros et al., 2013; Rivas et al., 2014). However, research is scarce on the effects of ambient air pollution on exercising athletes and their athletic performance, who may have greater than average susceptibility and exposure to air pollutants because of the physiological changes that occur during prolonged exercise (Quin et al., 2019).

Specifically, there are 3 reasons why athletes are at higher risk from air pollution (McCafferty, 1981): (1) increased ventilation during exercise; (2) a greater fraction of air is inhaled through the mouth during exercise, effectively bypassing the normal nasal filtration mechanisms; and (3) the increased airflow velocity carries pollutants deeper into the respiratory tract. Furthermore, pulmonary diffusion capacity increases with exercise (Turcotte et al., 1997; Stokes et al., 1981; Fisher and Cerny, 1982; Flaherty et al., 2013), increasing gaseous pollutant intake. Nasal mucociliary clearance, impaired in long-distance runners, may also contribute to the higher susceptibility of endurance athletes given that pollutants which are normally cleared from the respiratory system, are instead absorbed (Atkinson, 1987).

Even though research is scarce, studies on the relationship between air quality, athletic performance, and respiratory symptoms encourage pursuing further investigations. Lichter et al. (2015) assessed the effects of particulate air pollution on soccer players in German stadiums, revealing that performance was reduced under poor air quality conditions. Bos et al. (2011) and Quin et al. (2019) observed that the health benefits of active commuting could be negatively influenced by exercising in polluted environments, while Rundell and Caviston (2008) reported that the acute inhalation of PM_1 at concentrations in the range of many urban environments could impair exercise performance. Carlisle and Sharp (2001) and Cakmak et al. (2011) concluded that O_3 was particularly damaging to athletes, with subjects achieving a lower aerobic fitness score on high ozone days. Finally, long-term exposure to outdoor air pollution may trigger intermittent endogenous airway acidification episodes indicative of pollution-related lung inflammation (Ferdinands et al., 2008). These results have particularly relevant implications for top-level athletes participating in international competitions: the performance of athletes training in highly polluted environments may be impaired compared to athletes training in cleaner environments and, similarly, athletes used to training in cleaner environments may be adversely affected when competing in highly polluted locations. Thus, assessing exposure to air pollution in athletics venues becomes a necessity when aiming at understanding environmental drivers of both athletic performance, and athletes' health.

In this framework, the aim of this study was to characterize air pollutant concentrations in the Yokohama stadium (in the competition and the training area) during the Yokohama 2019 World Relays Competition, using a multidisciplinary approach. The main goal was to monitor ambient and human exposure to air pollutants, as a pilot study aiming to understand which air quality parameters provide the most useful insights into athlete exposure. This set of parameters may then be used in future athletics events to explore the association between air quality, athletic performance and exacerbation of respiratory and atopic disease. Ultimately, this pilot study aimed at providing guidance to athletics associations and stadium managers on strategies to minimize athletes' exposure to ambient air pollutants.

2. Methodology

2.1. Sampling area

Air quality monitoring was carried out at the International Stadium Yokohama, located in the city of Yokohama, Kanagawa Prefecture, Japan (World Athletics news and press releases, 2019). The location of the stadium and the sampling locations are shown in Fig. 1: inside the main stadium, and in the warm-up track (adjacent to the main stadium). It is important to note that the online particle instrumentation deployed in the main stadium was located immediately below the field of play. This location was chosen as a compromise between meeting conditions for undisturbed measurement and obstructing athletes' path as little as possible. It should be also noted that the warm-up track is an open space facility compared to the main stadium, because it has no surrounding wall or spectators' stands.

2.2. Instrumentation

Air quality parameters were monitored by means of a combination of different instruments and monitoring strategies, aiming also to align with the requirements of epidemiological assessments, before and during the World Relays Championship (9th to 12th May 2019: 9th–12th training period, 11th–12th competition).

Diffusion tubes for NO_2 (Gradko international) were deployed along the fence surrounding the stadium (12 tubes), in a perimeter around the warm-up track (9 tubes), and in the vicinity of the sports venue (4 tubes; Fig. 1). The passive samplers provided a detailed mapping of gaseous pollutant concentrations in the area. They were installed on 7th of May and removed on 12th of May. Similarly, diffusion tubes for ozone were also deployed but the results obtained (not shown) were considered invalid probably due to the short exposure time. The exposure time did not impact the robustness of the NO_2 results.

Two sets of portable online particle instrumentation were deployed inside the stadium and in the warm-up area. These units monitored the fine-scale temporal variation of regulatory ($PM_{2.5}$) and novel parameters (ultrafine particles, UFP; black carbon, BC), with known links to adverse health effects. UFP number concentration (N) and mean diameter were monitored with DiSCmini monitors (Testo), with 1-min time resolution, detecting particles up to 700 nm (accuracy: $\pm$ 500 # cm^{-3}) (Fierz, 2011). The instrument's concentration range is from about 1000 to over 1,000,000 # cm^{-3}. BC measurements were carried out with MicroAeth AE51, with 5-min time resolution, providing data on Equivalent Black Carbon (BC, in μgm^{-3}) derived from absorption values.

Fig. 1. Location of the stadium and the general topographic characteristics of Yokohama city. The main stadium and warm-up track monitoring sites are indicated on the bottom map.

The effect of filter loading on BC measurements was kept to a minimum by replacing the filter strips every 24 h and setting a flowrate of 100 ml min^{-1}. Finally, a light-scattering laser photometer (DustTrak, Model 8533, TSI) was used to monitor $PM_{2.5}$ (particulate matter with aerodynamic diameter less 2.5 μm) mass concentrations, with 1-min time resolution. The DustTrak monitor also provides PM_{10} and PM_1 concentrations, but based on previous works (Rivas et al., 2017) only the $PM_{2.5}$ concentrations were considered valid during this pilot study. DiSCmini, MicroAeth and DustTrak instruments were calibrated against reference, or near-reference instrumentation, at an urban monitoring site in Barcelona (Spain). Details are presented in Supplementary information (Figs. S1, S2 and S3).

Four $PM_{2.5}$ gravimetric samples were collected on 37 mm diameter quartz microfiber filters using a Personal Environmental Monitor (PEM) and a Leland SKC pump with a flow rate of 10 l/min, and chemically analyzed using ICP-AES and ICP-MS for major and trace elements, respectively, after acid digestion. This methodology focuses on the determination of heavy metals, useful to identify potential air pollution sources.

Complementarily, five silicone wristbands were worn by volunteers from 8th of May at 12:00 h to 12th of May at 22:00, in order to quantify exposure to polycyclic aromatic hydrocarbons (PAH) and personal care products. The volunteers frequented the same areas as the athletes during the entire sampling campaign. For the analysis of the silicone wristbands, the methodologies of Anderson et al. (2017), Dixon et al. (2018), and O'Connell et al. (2014) were used. The exposed bracelets were rinsed with de-ionized water and isopropyl alcohol (Merck) to remove particles. Then, they were stored in 25 ml amber tubes and filed with ethyl acetate (Merck) and gently shaken for extraction during 24 h. Before extraction, 25 μl of 5 ng/μl deuterated PAHs were added (anthracene, benz[*a*]anthracene, benzo[*b*]fluoranthene and benzo[*ghi*]perylene). The extraction was repeated twice. Extracts (concentrated by Rotovap to 0.5 ml) were visibly colored, they were cleaned-up by passing over a C18-column (500 mg; Bakerbond) and eluted in 4 ml hexane:dichloromethane mixture (1:2 v/v; Merck). The extract was concentrated under a gentle nitrogen gas stream to 1 ml and injected into a gas-chromatograph coupled to a mass spectrometer for analysis of organic compounds under full-scan mode.

Wind speed and direction were monitored both in the stadium and in the warm-up track by means of a LCJ capteurs anemometer.

Finally, sensor nodes (Kunak AIR) were also deployed at each of the monitoring sites. These monitors incorporated electrochemical sensors

for phase gas pollutants NO_2, O_3, NO and CO, a laser-scattering sensor for particulate matter PM_1, $PM_{2.5}$, PM_{10}, and temperature (T), relative humidity (RH) and pressure (P) sensors. Data was provided with a 5-min time resolution. Sensors were calibrated by co-location at a reference air quality monitoring station in Barcelona during 1 month prior to shipment to Yokohama, and by deploying them side by side during one day inside the Yokohama stadium, prior to the training period (May 8th, 2019). The results from the co-location exercises are shown in Figs. S4 to S6 in Supporting information.

Regulatory-grade $PM_{2.5}$, NO_2 and O_3 concentrations were obtained for the study period from the three air quality monitoring stations closest to the stadium (Fig. S7; http://soramame.taiki.go.jp), in order to identify urban-scale pollution events and discriminate them from those originating in the sports venue.

2.3. Statistical air quality data analysis

Data management, descriptive statistics and plots were performed with the R statistical software (v 3.5.1., R Core Team, 2018) and the packages ggplot2 (https://www.tidyverse.org/), fields (Nychka et al., 2017) and cluster (Maechler et al., 2019).

2.4. Questionnaire design and data collection process

A specifically designed questionnaire was self-administered by athletes, using tablets. The goal of the questionnaire was two-fold: 1) to assess the degree of concern of athletes regarding air pollution, and 2) to evaluate the suitability of the questionnaire design for epidemiological assessments (missing, redundant information, etc.) in future competitions. The questionnaire collected information on basic characteristics, including place of residence and training, medical background information, performance information and exacerbation of the previously reported diseases, and a section on air quality perception. The list of diseases in the medical section was not exhaustive and requested information only about pulmonary, allergic or cardiovascular chronic disease, specifically asthma, allergy/atopic reactions, frequent acute lower respiratory infections, high blood pressure and others.

Athletes were invited to participate in the survey by World Athletics volunteers, during their training sessions in the warm-up area. All athletes signed a consent form before answering the questionnaire. The study was approved by the Barcelona Parc de Salut Mar Ethics Committee.

2.5. Study limitations

As previously mentioned, the monitoring location in the main stadium was set below the field of play. Although it is an open area with natural ventilation, this location may not have been totally representative of athletes' exposure, and this should be considered a limitation of this work.

On the other hand, the calibrations of the different on-line instrumentation used within this study were performed under meteorological conditions and aerosol mixes characteristic of the Barcelona urban background, which could have differed from those during the sport event in Yokohama. Thus, the results presented should be considered as informative and not be used for regulatory compliance checking purposes. Nonetheless, the values obtained can show relative differences in concentrations between locations, days and periods of the day, which is how our data are treated within the study.

3. Results and discussion

3.1. Meteorological scenario

During the monitoring campaign, temperatures ranged between 15 and 30 °C, while RH ranged between 20 and 85%. The dominant wind directions were south and southeast (sea breeze development), where the port is located, an area with an intense industrial and commercial activity; Figs. 1 and S8. The hourly evolution of wind speeds in the stadium and warm-up track (Fig. 2) showed a very marked cycle, with lower wind speeds between 0:00–6:00 and maximum values from 13:00 to 18:00. As will be shown below, wind speed was a major driver of particle concentrations and athlete's exposure levels during the study period. On average, wind speeds were higher at the warm-up track than inside the stadium, due to the enclosure around the stadium and the fact that the warm-up track was a more open space.

3.2. Pollutant concentrations and comparability between instruments

Table 1 summarizes the median concentration and interquartile range (IQR), for the full monitoring period, for PM_{10}, $PM_{2.5}$, PM_1, N, BC, NO_2, CO and O_3, in the stadium and the warm-up track. Differences in $PM_{2.5}$ and NO_2 concentrations were observed with the different techniques used (sensing nodes, DustTrak and diffusion tubes), which resulted from the different measurement principles. It is essential to highlight that the instrumentation used in this work was not regulatory-grade, and therefore the results should be considered as informative and not be used for regulatory compliance checking purposes.

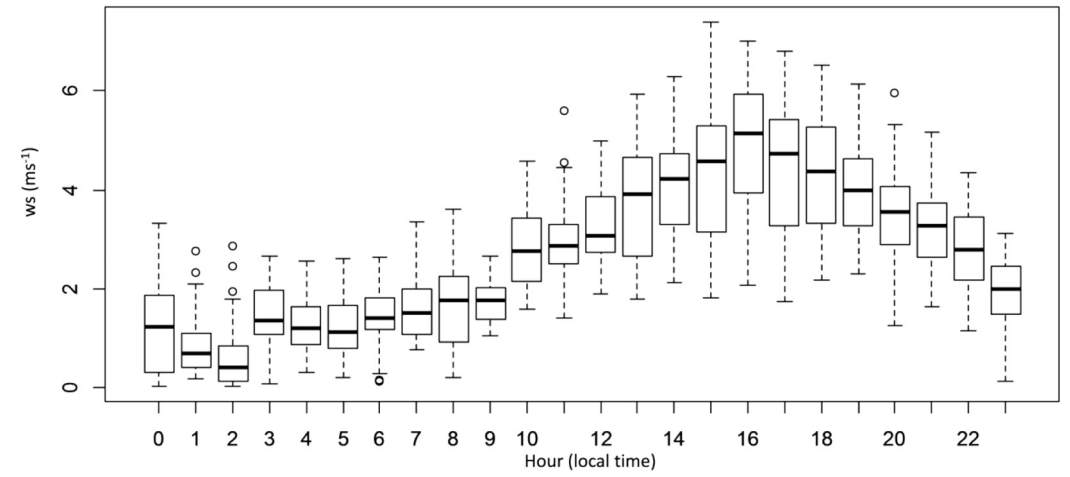
The median concentrations of gaseous pollutants monitored in the stadium and the warm-up track (25.6–31.9 $\mu g/m^3$ NO_2, 80.5–84.1 $\mu g/m^3$ O_3, 424 $\mu g/m^3$ CO; Table 1) were comparable to those monitored at the nearby reference air quality stations (22.6–30.1 $\mu g/m^3$ NO_2, 91.2–99.1 $\mu g/m^3$ O_3; Table 1), and mostly representative of urban background concentrations. NO_2 concentrations were similar when comparing the results from the diffusion tubes and the sensing nodes, especially in the stadium. Black carbon and N concentrations were representative of urban background concentrations reported in European cities (e.g., Barcelona, London, Basel; Reche et al., 2011), with 737–862 $ngBC/m^3$ and 9–11*$10^3/cm^3$ for particle number concentration, with mean diameters of approximately 45–60 nm which are typically representative of vehicular traffic emissions (Brines et al., 2015, and references therein). Finally, particle mass concentrations reported by the DustTrak monitor (17.8 $\mu g/m^3$; only available in the stadium due to technical issues in the warm-up track) were slightly higher than median urban background levels (12.0–16.5 μgm^{-3} at the nearby reference stations). The PM_x levels reported by the sensing nodes were significantly lower (6.9–8.4 $\mu g/m^3$ for $PM_{2.5}$). In general, the performance of particle sensors is known to be lower than that of gaseous pollutant sensors (WMO, 2018).

Differences in terms of absolute concentrations were not statistically significant between the main stadium and the warm-up track, even though the main tracers of traffic emissions (BC, N, NO_2) were slightly higher in the warm-up track. As mentioned, the warm-up track does not have a surrounding wall as the stadium does, and therefore it was considered to receive more direct impacts of background emissions (mostly driven by traffic).

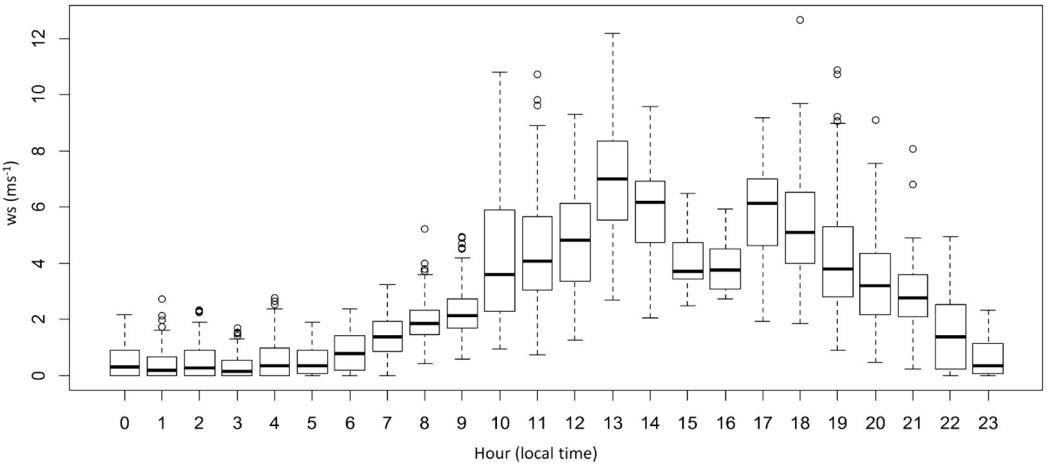
3.3. Spatial distribution of NO_2 concentrations

An assessment of the spatial distribution of NO_2 concentrations around the competition area was carried out by means of diffusion tubes (Fig. 3). Concentrations were not corrected against a reference method, but an inter-comparison was carried out for quality assurance at an urban air quality reference station in Barcelona. According to the inter-comparison (Table S2), NO_2 concentrations reported by diffusion samplers were slightly higher (3 μgm^{-3} higher) than the reference, and this difference was consistent across samples collected under different periods and meteorological conditions.

NO_2 concentrations were relatively higher in the warm-up track, and mostly homogeneous around each of the venues (the stadium and the warm-up track). Concentrations ranged between 25.2 and 28.7 μm^{-3} along the perimeter of the stadium, and between 30.4 and



(a)



(b)

Fig. 2. Box plot of hourly wind speed values in the stadium (a) and the warm-up track (b). The black line within the box plots shows the median concentrations, while the box bottom and top represent the 25th and 75th percentile, respectively. The whiskers represent the lower and the upper bounds.

39.4 μm^{-3} around the warm-up track. In addition, three samples were collected along a road close to the sports facilities, which reported similar mean concentrations (34.5 μgm^{-3}) to the warm-up track. The results obtained demonstrated that: (a) the location of the online instruments in the stadium and the warm-up track (indicated by large circles in Fig. 1) may be considered representative of concentrations in

Table 1
Summary of concentrations (median and inter-quartile range, IQR) of the different air quality parameters monitored during the sampling campaign, in the stadium and the warm-up track and in the nearby reference air quality monitoring stations (09/05/2019–12/05/2019).

	Monitor	Stadium	Warm-up track	Monitor	Kohoku	Kanagawa	Asahi
		Median (IQR)	Median (IQR)		Median (IQR)	Median (IQR)	Median (IQR)
PM_{10} (μgm^{-3})	KunakAir	15.6 (11.8–22.6)	14.1 (9.9–19.9)				
$PM_{2.5}$ (μgm^{-3})	DustTrak	17.8 (15.3–22.4)	–	Reference	15.1 (11.1–21.2)	16.5 (10.8–22.0)	12.0 (9.0–15.1)
$PM_{2.5}$ (μgm^{-3})	KunakAir	8.4 (6.5–11.5)	6.9 (5.2–8.9)				
PM_1 (μgm^{-3})	KunakAir	4.6 (3.8–5.9)	3.6 (2.7–4.5)				
N ($\#cm^{-3}$)	DISCmini	8968 (6285–11,365)	11,124 (7786–14,523)				
BC (ngm^{-3})	MicroAeth	737 (400–1178)	862 (578–1260)				
NO_2 (μgm^{-3})	Diffusion tubes	26.9 (26.4–27.4)	31.9 (31.5–33.3)				
NO_2 (μgm^{-3})	KunakAir	25.6 (12.1–35.6)	26.8 (10.2–44.4)	Reference[a]	28.2 (18.3–47.0)	30.1 (18.8–51.3)	22.6 (15.1–37.6)
O_3 (μgm^{-3})	KunakAir	84.1 (57.5–109.2)	80.5 (55.9–113.2)	Reference[b]	94.1 (64.2–123.0)	91 (63.5–120.5)	99.1 (65.5–134.5)
CO (μgm^{-3})	KunakAir	424 (373–491)	–				

[a] Mean NO_2 concentrations for comparison with diffusion tubes (07/05/2019–12/05/2019) were 23.1 $\mu g/m^3$ (Asahi), 30.6 $\mu g/m^3$ (Kohoku) and 31.3 $\mu g/m^3$ (Kanagawa).
[b] Mean O_3 concentrations for comparison with diffusion tubes (07/05/2019–12/05/2019) were 104.7 $\mu g/m^3$ (Asahi), 98.8 $\mu g/m^3$ (Kohoku) and 100.9 $\mu g/m^3$ (Kanagawa).

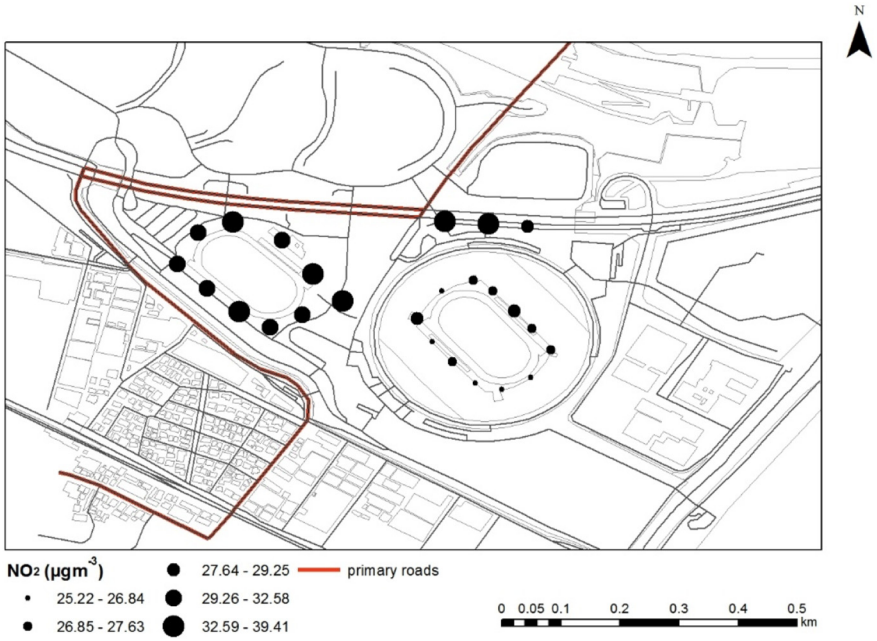


Fig. 3. Spatial distribution of NO_2 (μgm^{-3}) concentrations as reported by diffusion tubes.

each of the study areas, given the low spatial variability observed for NO_2; and (b) better isolation of the warm-up track (e.g., with a surrounding wall) would reduce the influence of urban emissions on athletes' exposures while training.

3.4. Time variation

Fig. 4a shows the daily variation of $PM_{2.5}$ concentrations (monitored with DustTrak and corrected against reference methods) at the main

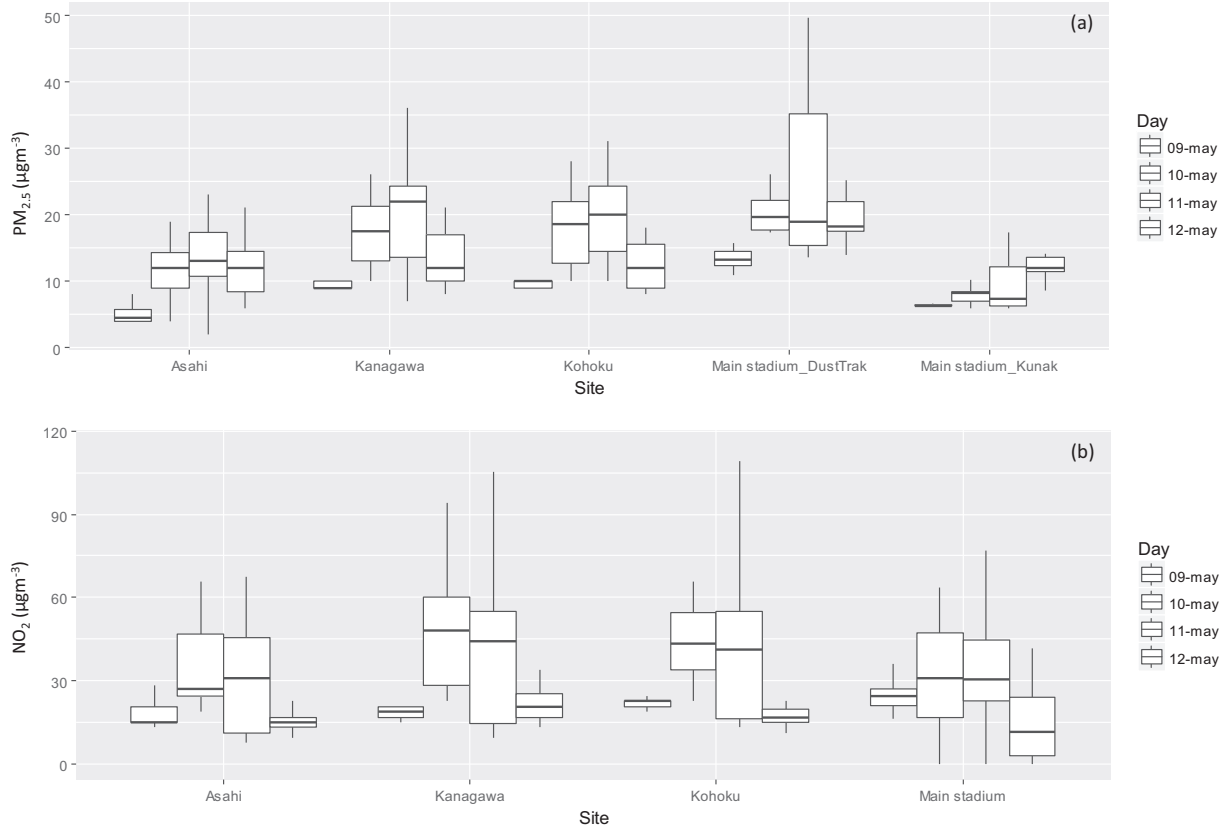


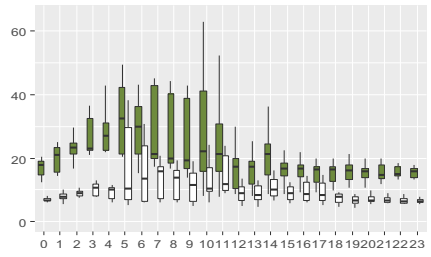
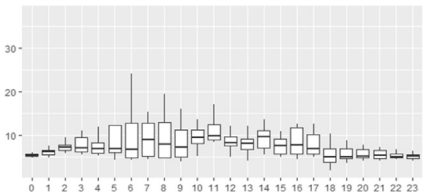
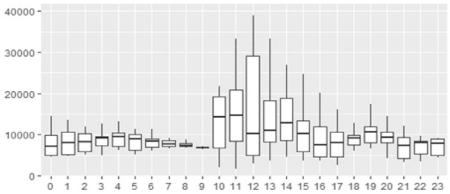
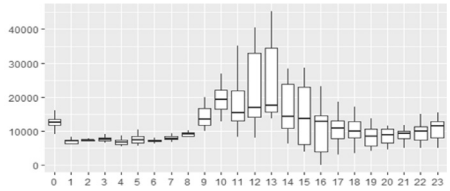
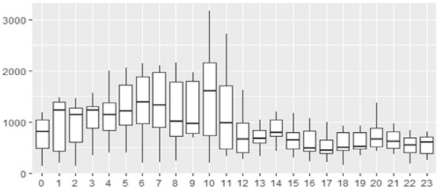
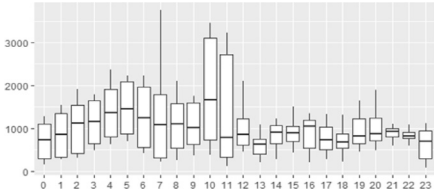
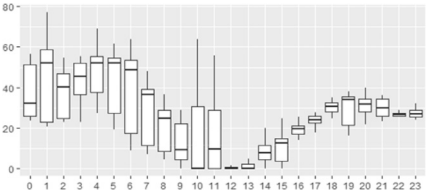
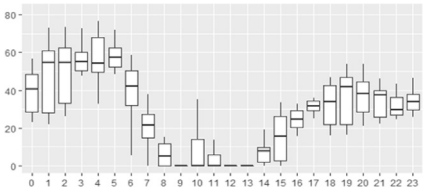
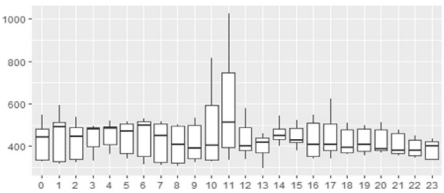
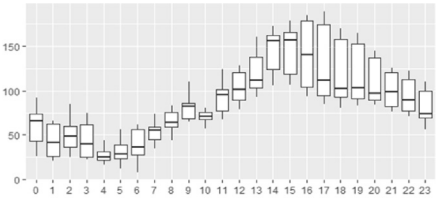
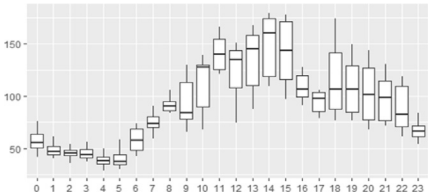
Fig. 4. Box plot of daily $PM_{2.5}$ (a) and NO_2 (b) concentrations (μgm^{-3}). NO_2 concentrations reported for the main stadium refer to Kunak AIR sensor nodes measurements. The black line within the box plot shows the median concentrations, while the box bottom and top represent the 25th and 75th percentile, respectively. The whiskers represent the lower and the upper bounds.

stadium during training (9-12th May) and competition days (11-12th May). Concentrations increased from the first to the second day, attaining maximum hourly concentrations during the third and fourth days. In order to asses if daily differences were due to local activities or the result of changes at urban scale, concentrations were compared to those recorded at local reference stations. Trends were very similar at all monitoring sites, with most of the variations in $PM_{2.5}$ taking place simultaneously at urban scale, thus probably driven by meteorology. However, concentrations underwent a much more marked decrease at the stations than in the stadium during the last monitoring day (Sunday 12th May), which could suggest the influence of local sources in the sports venue on that date. NO_2 showed similar results (Fig. 4b), although in this case concentrations decreased from the third to the fourth day, similarly to reference concentrations from the local network, probably due to a decrease in traffic emissions along the city on Sunday. Thus, the influence of local sources (e.g., vehicular traffic driving to the Yokohama stadium) was not detected clearly for NO_2 (as opposed to for $PM_{2.5}$).

Hourly trends were calculated based on the data reported by the online instrumentation (air quality monitors and sensor units) for $PM_{2.5}$, N, BC, NO_2, O_3 and CO (Table 2), for the stadium and the warm-up track. PM_{10} and PM_1 concentrations recorded with the sensor units are not reported due to the discrepancies observed for $PM_{2.5}$ (Table 2) and based on the lower performance of particle when compared to gaseous pollutant sensors (WMO, 2018). Distinct daily cycles were obtained for each parameter, with two main patterns:

1. Parameters driven mostly by wind speed: particle concentrations ($PM_{2.5}$) and BC followed an hourly trend which was inverse to that of wind speed (Fig. 2). For example, $PM_{2.5}$ concentrations at both monitoring locations increased at around 1:00, reaching maximum values at around 5:00–6:00, after which (from 7:00 onward)

Table 2
Box plot of hourly concentrations of the real-time air quality parameters measured in the stadium and the warm-up track.

Pollutant	Instrumentation	Units	Time variation: main stadium	Time variation: warm-up track
$PM_{2.5}$	DustTrak/Kunak AIR sensor node	μgm^{-3}		
N	DISCmini	$\#cm^{-3}$		
BC	MicroAeth	ngm^{-3}		
NO_2	Kunak AIR sensor node	μgm^{-3}		
CO	Kunak AIR sensor node	μgm^{-3}		
O_3	Kunak AIR sensor node	μgm^{-3}		

concentrations gradually decreased until 12:00 and remained relatively stable and low for the rest of the day (Table 2). In addition, BC concentrations showed a rapid and sporadic increase at 10 h, probably due to local traffic in the sports facilities related to the competition (e.g. arrival of buses, maintenance activities). The relevance of wind speed as main driver was confirmed by means of a multilinear regression model: for $PM_{2.5}$ (DustTrak) and BC, the link with wind speed was statistically significant at p-value < 0.001, with multiple R-squared values ranging between 0.41 and 0.48 (in the stadium and warm-up track). The relationships with temperature and relative humidity were not statistically relevant.

2. Parameters driven by wind speed and local emissions: NO_2, CO, O_3 and N showed trends which were driven by a combination of factors. NO_2 hourly concentrations showed peaks in the morning (with low wind speed) and at 17-20 h (with traffic rush hour). The early increase of wind velocity in the morning seemed to minimize the impact of traffic rush hours on NO_2 concentrations. A smaller peak was also observed at around 10:00–11:00 h, coinciding with the maximum values reported for CO concentrations, which could be related with emission sources proceeding from the port area or to local activities in the stadium (as in the case of BC). On the other hand, the diurnal cycle of O_3 is determined by a balance of local photochemical production (production of O_3 from NOx and VOCs mediated by solar radiation) and destruction by titration with NO, as tipically occurs in urban areas. Maximum concentrations were recorded at 11:00–16:00 h, while the minimum values occurred in the early morning, before solar radiation started increasing. Finally, N concentrations at the stadium and warm-up track followed a specific pattern with a midday increase (between 10 and 15 h) coinciding with relatively high wind speeds, which drove low $PM_{2.5}$ concentrations and thus favored new particle formation as has been reported for urban environments with relatively high insolation (Kulmala et al., 2012; Reche et al., 2011). These midday increases in N concentrations can be mainly attributed to nucleation processes, as they did not match BC increases. The multi-linear model showed a statistical link with wind speed (p-value < 0.01), which was weaker than in the case of $PM_{2.5}$ and BC, with a multiple R-squared of 0.18. The model could not be applied to NO_2, CO and O_3 from the sensors given that temperature and humidity are included as input in the sensors' calibration algorithm.

To further analyze the hourly variation of the air quality parameters, with different origins and physicochemical properties, a k-Means clustering was applied to the dataset, using an optimal 3 cluster solution. The k-Means algorithm separates the data into k clusters where k is an integer given by the user. The analysis was carried out on the scaled hourly averaged daily profiles. Fig. 5 summarizes the main information of the time variation of each cluster. Cluster 1 comprises $PM_{2.5}$, BC, and CO concentrations, while cluster 2 represents O_3 and N concentrations, and cluster 3 only includes NO_2 concentrations. Cluster 1 is thus mainly mediated by wind components, while cluster 2 is governed by photochemical reactions, and cluster 3 by traffic rush hours. The joint representation of the time pattern of the three clusters allows us to determine the period of the day in which exposure to the maximum concentrations of each parameter would be avoided, which in this case would be after 17:00 h. Thus, based on the data available and for the study period, >17 h would be the optimal time of the day for athletes to carry out training and competition activities, in view of minimizing their exposure to air pollutants. Exposure to NO_2 would not be strictly minimal during this period, however, but reducing ozone exposures would be more advisable based on the literature (Carlisle and Sharp, 2001). This method could be used as a strategic tool to develop recommendations for outdoor sports activities with the aim of minimizing exposure to airborne pollutants. For this purpose, a complete database combining particulate and gaseous air pollutants (primary and secondary) would be necessary.

3.5. Chemical exposures

Airborne particles ($PM_{2.5}$) were collected over 24 h periods inside the stadium at the monitoring site where the online instrumentation was deployed. Due to the dimensions of the filter substrate (37 mm in diameter) only the inorganic content of the particles was determined (Table 3). Road traffic-related compounds (Fe, Mn, Sn and Sn) were found in concentrations comparable to typical urban environments (Pérez et al., 2012; Charron et al., 2019). Fuel-oil combustion from ships is characterized by high contribution of V and Ni, which were found to be in concentrations similar to those reported in coastal cities in southern Europe (Viana et al., 2014; Amato et al., 2015). Finally, high concentrations of P, Ti, As, and Sr, tipically related with industrial emissions, were consistent with the predominant wind direction during the sampling period, blowing from the south-southeast sector, where industrial activities are located.

Furthermore, personal exposure to PAHs was also assessed by means of wearable silicone wristbands (Anderson et al., 2017). Wearable devices are increasingly being used to characterize personal exposure to indoor and outdoor atmospheric pollutants due to their

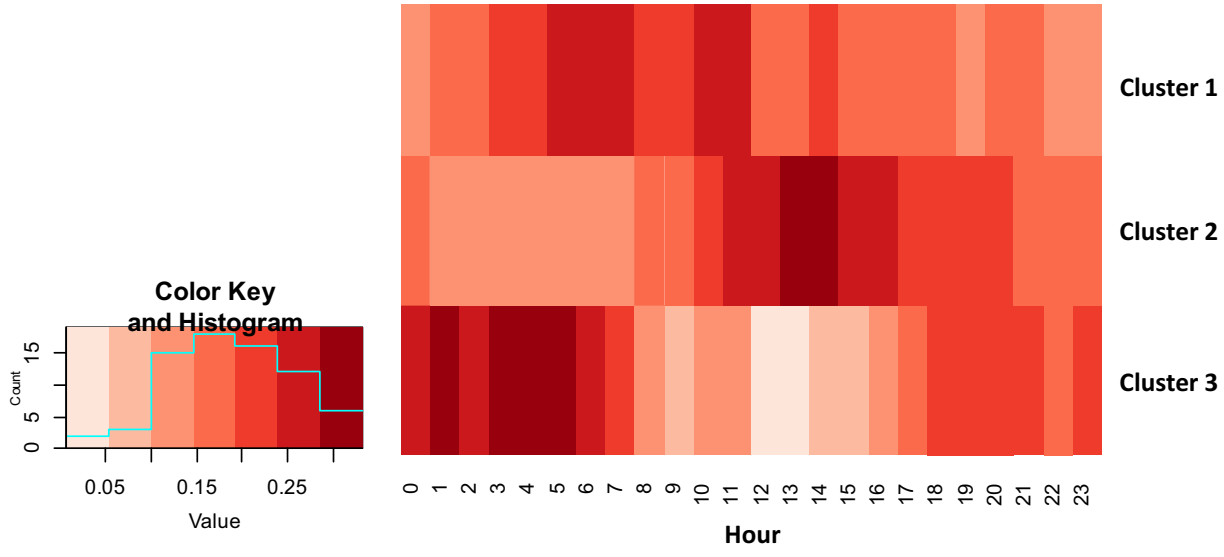


Fig. 5. Heatmap of the results of the k-Means clustering applied to the hourly variation of the available air quality parameters.

Table 3
Mean concentrations of inorganic chemical compounds detected from 09/05/2019 to 12/05/2019 in $PM_{2.5}$ samples.

Start date		09/05/2019 9:00	10/05/2019 9:00	11/05/2019 9:00	12/05/2019 9:00
End date		10/05/2019 9:00	11/05/2019 9:00	12/05/2019 9:00	12/05/2019 21:00
CO_3^{2-}	μg/m³	0.16	0.12	0.20	0.27
SiO_2	μg/m³	1.13	1.00	1.16	2.53
Al_2O_3	μg/m³	0.38	0.33	0.39	0.84
Ca	μg/m³	0.11	0.08	0.13	0.18
Fe	μg/m³	0.13	0.18	0.13	0.22
K	μg/m³	<0.001	<0.001	<0.001	<0.001
Mg	μg/m³	0.03	0.02	0.04	0.08
Na	μg/m³	0.14	0.17	0.11	0.21
SO_4^{2-}	μg/m³	1.15	2.63	2.55	2.18
Li	ng/m³	<0.1	<0.1	<0.1	<0.1
P	ng/m³	22.0	22.3	12.5	28.3
Ti	ng/m³	8.0	7.2	7.5	17.2
V	ng/m³	1.6	6.2	4.6	2.9
Cr	ng/m³	0.6	1.4	0.9	11.2
Mn	ng/m³	4.6	7.8	5.4	4.6
Ni	ng/m³	1.4	3.7	2.8	9.5
Cu	ng/m³	0.4	2.8	<0.001	<0.001
Zn	ng/m³	<0.001	12.5	6.7	<0.001
As	ng/m³	0.7	0.6	0.6	1.0
Se	ng/m³	0.2	<0.1	<0.1	<0.1
Rb	ng/m³	0.2	0.4	<0.1	0.4
Sr	ng/m³	2.4	2.0	2.1	2.9
Cd	ng/m³	<0.1	0.3	<0.1	<0.1
Sn	ng/m³	2.0	1.6	0.9	0.5
Sb	ng/m³	1.2	1.4	0.6	0.6
Ba	ng/m³	<0.001	<0.001	<0.001	<0.001
La	ng/m³	0.9	0.2	0.5	0.4
Ce	ng/m³	0.9	<0.1	0.7	0.3
Pb	ng/m³	2.9	5.7	4.0	5.3

versatility and portability (Larkin and Hystad, 2017; Lin et al., 2018). Wristbands were worn by 5 volunteers who were exposed to comparable environments as the athletes, who did not wear them to avoid compromising their athletic performance. Volunteers were not ask to keep a log of their activities given that this work aimed to make a preliminary assessment of the potential of wristbands as personal monitors.

PAH concentrations above the detection limit were found for tracers of combustion activities (e.g., vehicular traffic, cooking emissions at restaurants, etc.) acenaphthene, acenaphthylene, fluorene, and phenanthrene, with concentrations >8 times higher than the blanks (Table 4). A high variability was observed across wristbands, with the highest concentrations being recorded with wristband SIL_M_1290, roughly one order of magnitude higher than the rest of the wristbands. The lowest levels were observed for wristband SIL_L_481, thus evidencing that volunteers (and thus, potentially athletes) received markedly different exposures in terms of PAHs.

Aside from PAHs, the presence of other organic compounds was detected, specifically organic tracers of personal care products (e.g., perfumes and UV-B filters; Table 5). It is very likely that these compounds were adsorbed onto the wristbands after application of sunscreens, lotions and/or perfumes onto the skin. Once again, the variability across samples was high: while Lilial and Padimate UVB were observed in bracelet SIL_M_1290, other compounds showed the highest levels in SIL_M_1264.

Finally, plasticizers such as di-2-ethylhexyl phthalate (DEHP) were also detected in substantial concentrations in worn wristbands and in the blanks, probably originating from impurities in the wristband's silicone material.

In sum, PAHs and tracers of personal care products were detectable in the silicone wristbands, therefore confirming them as an adequate tool to monitor personal exposure to these compounds, during this study.

Table 4
PAH concentrations detected in silicone wristbands (ng/wristband).

ng/wristband	Acenaphthene	Acenaphthylene	Fluorene	Phenanthrene
BK1_1299	11	4	3	5
BK2_1279	13	4	6	14
SIL_M_1264	85	175	147	210
SIL_M_1290	956	734	1613	2968
SIL_L_444	211	147	78	266
SIL_L_466	135	86	141	206
SIL_L_481	83	56	57	146

3.6. Questionnaire/survey to athletes: an assessment of air quality perception

A total of 68 athletes (8.6% of the 790 registered athletes) responded to the survey, evidencing an interest of participants on air quality and health issues but also highlighting limitations such as the need to have questionnaires available in more than the three languages used (English, French and Spanish). The specific results obtained are reported in Supporting Information and Table S2. The design of the questionnaire was also evaluated, concluding on the need to measure health and athletic performance data (as opposed to perception) in future athletic competitions to correlate with air pollution exposure data. The Yokohama competition was not an adequate setting to evaluate performance as a function of air quality given that relay performance refers to the whole team, while exposure and/or health impacts are monitored at individual level.

4. Recommendations and concluding remarks

This pilot study aimed to characterize air pollutant concentrations in the Yokohama stadium during an international athletics event (Yokohama World Relays 2019) in view of understanding the environmental factors with potential to influence athletic performance. Whereas exposure to air pollution is an item of concern for the general population, athletes are especially vulnerable as their air intake is higher and they train and compete outdoors for large portions of the day. The main lessons learnt during this pilot study were:

- The implementation of a multiparametric approach monitoring particulate and gaseous air pollutants, and meteorological variables, allowed us to describe air quality during the international athletics event. Monitoring only a subset of parameters (e.g., only regulatory parameters) would have strongly hindered the interpretations and the applicability of this assessment.
- Correlating the hourly variability of the different pollutants was seen as a useful tool to identify the most optimal periods for training/competition, from the point of view of minimizing exposure to air pollutants. This tool may be used to provide guidance for setting training and competition schedules, and would have special added value for athletes with respiratory conditions (e.g., asthma).
- In view of minimizing exposures, further research would be necessary to identify which specific air pollutants may trigger or exacerbate respiratory conditions typical of the athlete community (e.g., asthma or exercise-induced-bronchospasm).
- Personal samplers such as silicone wristbands were useful to tailor exposure assessment to individual athletes for specific chemical exposures (in this case, PAHs and personal care products), and evidenced high variability across participants.
- The availability of high time-resolved exposure data in the stadiums opens up the possibility to calculate doses of specific pollutants (Larkin and Hystad, 2017; Ramos et al., 2016) for individual athletes, which would be a highly valuable information for athletes and trainers. Inhaled doses could be calculated for the time spent by athletes in the training and competition venues, but would however be unavailable for the time spent outside these areas.

Table 5
Organic molecular tracers of personal-care products detected in the silicone wristbands.

ng/wristband	Lilial (perfum)	Hedione (perfum)	Galaxolide (perfum)	Tonalide (perfum)	Parsol-MCX_1 (UVB)	Parsol-MCX_2 (UVB)	Padimate (UVB)
BK1_1299	6	19	18	13	53	78	1
BK2_1279	5	16	19	14	93	130	1
SIL_M_1264	7004	8931	7613	4714	9240	4027	55
SIL_M_1290	316310	84189	130609	33723	5131	2285	498186
SIL_L_444	2233	13968	3627	8116	6095	4917	19239
SIL_L_466	38733	25179	26295	11463	35180	11547	849
SIL_L_481	156789	24187	79087	34071	11784	10097	92

- In future studies, the combination of air quality and health data (not collected in this study) may enable us to determine the prevalence of pollution-related diseases (respiratory, atopic and cardiovascular) in athletes.
- Also in future studies, combining real-time air quality data and reports of exacerbations of diseases, will enable the association between the prevalence of respiratory and atopic diseases and exacerbations of symptoms, and competitions results and specific pollutant levels.

Specifically for the air quality assessment during the Yokohama World Relays 2019, it may be concluded that:

- Median particle and gaseous pollutant concentrations in the stadium were mostly comparable to the Yokohama urban background, with sporadic peaks associated with local activities in the sports areas.
- $PM_{2.5}$ and BC concentrations were driven by wind velocities, which exerted a major dilution effect from 9 to 10 h onwards. NO_2 concentrations showed a bimodal daily cycle resulting from the influence of traffic emissions and wind speed. Maximal CO concentrations were recorded when wind blew from the port area, probably related with industrial activities in this sector of the city. O_3 hourly variation was determined by a combination of photochemistry and consumption by NO. Finally, N showed maximum concentrations around midday, which were mainly attributed to the formation of secondary UFP by nucleation processes.
- Tracers of traffic, industry and fuel oil emissions were detected in $PM_{2.5}$ in the stadium and warm-up track. Personal exposure to PAHs, measurable on silicone wristbands, were highly variable across volunteers.
- During the study period, training and competing at >17 h would have minimised exposure to most of the air pollutants monitored.
- One-third of athletes felt that air pollution had some adverse effect on their health and training, mainly feeling breathlessness and/or irritation of the nose, eyes or throat.

Declaration of competing interest

The authors declare no conflict of interest in this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137161.

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