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Exposure to Contaminants During Active Transport in Uruguay and the Effect on Health Parameters

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Abstract Air pollutants can have a substantial impact on health. Particulate matter (PM_{10} and $PM_{2.5}$) can penetrate the respiratory system and produce inflammation; chronic exposure can damage lung tissue. Several environmental and daily habits have been reported to increase the risk of disease and adverse health conditions. We carried out a study to assess the importance and effect of these factors on human health. The objective was to measure exposure to environmental pollutants ($PM_{2.5}$, PM_{10}, nitrogen dioxide, and noise) by studying cyclists in Montevideo, Uruguay. We measured environmental pollutants on two urban routes with high and low values of the environmental variables and biometrics of participating cyclists. No significant differences were found between routes. Our results suggest that active transport benefits seem to outweigh health risks in Montevideo for the sampled cycling routes. Our study provides knowledge about characteristics of the environment, which is an important input when planning where to place bikeways in Montevideo.

Keywords: environmental pollutants, bicycling, cycling, health, carbon monoxide, air quality

Introduction

Air pollutants can have a substantial impact on health, both in indoor and outdoor environments (Lopez, 2012). In a 2019 ranking of the global burden of disease, particulate air pollution ranked 8th in terms of years of healthy life lost due to disability, which globally contributes to 53.5 deaths per 100,000 population. Furthermore, particulate air pollution is estimated to contribute to a decrease of almost 9 months of life expectancy on average in Europe (Nieuwenhuijsen, 2016). An individual's reaction to these environmental exposures, however, can vary depending on sex, socioeconomic status, educational level, race, and other factors.

In cities, exposure to air pollutants and noise has been associated with adverse health effects (Health Effects Institute [HEI], 2022; Nieuwenhuijsen, 2016). Particulate matter (PM_{10} and $PM_{2.5}$) from soot and smoke can penetrate the respiratory system, producing inflammation. Chronic exposure to particulate air pollution can damage lung tissue. If the particles reach the bloodstream, they can also damage the tissues of other organs in the human body.

A systematic review of epidemiological studies showed that exposure to traffic-related air pollutants—such as elemental carbon, nitrogen dioxide (NO_2), and fine particulate matter—can cause cardiovascular diseases, brain diseases, and asthma (HEI, 2022). Exposure to PM_{10}, $PM_{2.5}$, and NO_2 has also been associated with human mortality (Orellano et al., 2020). Risks from environmental exposure to air pollutants, however, depend on the concentrations of the pollutants, the inhalation rate of exposed persons, and exposure time (Okokon et al., 2017; Targino et al., 2018).

In urban environments, the spatial distribution of air pollution is not homogeneous. Additionally, epidemiological studies indicate that patterns of spatial effects of air pollution within a city are important for public health, and health outcomes can be improved by reducing levels of air pollutants (Hankey et al., 2017; Schraufnagel et al., 2019). Transit micro-environments constitute important sites of exposure to atmospheric pollutants, mainly for people who use active means of transport and thus travel next to pollutant emitters such as cars, buses, and trucks (Farrell et al., 2015).

Even though short-term lung function has been reported to increase in response to physical activity (4.5 times more in people cycling versus driving a car), this beneficial effect is hampered when there are high levels of air pollution (Laeremans et al., 2018). Exposure time is another variable of interest. As the time of exposure to air pollutants increases, health risks increase, too. Still, for low or moderate levels of pollution ($PM_{2.5}$ background level of 50 µg/m^3), there is a time threshold (300 min of bicycle riding) above which risks can outweigh benefits (Targino et al., 2018).

Another potential pollutant, mainly in cities, is noise. Since 1972, the World Health Organization (WHO) has declared noise a pollutant (WHO, 2019; Wothge & Niemann, 2020). Noise is one of the most common urban environmental risk factors and road traffic is the primary source of community noise in urban areas (Okokon et al., 2017; Wothge & Niemann, 2020). Noise can cause hearing loss, sleeping disorders, annoyance, cardiovascular disease, stress (increasing serum cortisol levels have been demonstrated after exposure to noise levels >55 dB), and other health impairments (Gilani & Mir, 2021; Wallas et al., 2018; Wothge & Niemann, 2020).

Currently, WHO recommends that exposure to road traffic noise not exceed L_{den} = 53 dB or L_{night} = 45 dB outdoors (WHO, 2019), with L_{den} being a long-time exposure indicator considering sound pressure level at different times during the day and L_{night} being the equivalent A-weighted sound pressure level for 9 hr during the night, usually from 10 p.m. to 7 a.m. Moreover, active transport users are more exposed to traffic noise than other transport users in several European cities, which can increase health risks in these individuals (Okokon et al., 2017).

Montevideo, the capital city of Uruguay, has a population of more than 1 million inhabitants and shares with other cities of similar size several environmental risk factors such as noise and other pollutants. For surveillance of these factors, the city has an urban network of air monitoring stations (Montevideo Municipal Administration, n.d.). There is a difference, however, between the air quality at street level and measurements recorded at a greater height. Thus, existing records of regular monitoring of air pollutants might not be accurate reflections of air quality at the street level, and potential risk exposure of the general population and especially of people who use active means of transport might be underestimated.

Our study is part of a wider project aimed at contributing to active travel planning in Montevideo, including air quality management in decision-making processes (D'Angelo et al., 2023). The objective of our study was to measure exposure to environmental pollutants ($PM_{2.5}$, PM_{10}, NO_2, and noise) by assessing a group of cyclists in an urban ride of up to 30 min in Montevideo and the effect of this exposure on the cyclists' carbon monoxide (CO) exhaled at the end of the trip.

Methods

We selected two sampling routes, Central Route and Boulevard Route (hereafter referred to as Route 1 and Route 2, respectively). Route 1 had narrow streets, high buildings, and medium traffic flow. Route 2 had broad avenues, high and middle-height buildings, and heavy traffic flow. These routes were chosen based on the following criteria:

- Routes were frequently used by cyclists in Montevideo.
- Routes were located in high-mobility areas of the city.
- Routes surrounded air quality stations belonging to the Montevideo Air Quality Monitoring Network.
- Routes had areas with high and low values of the environmental variables to be evaluated as part of the recorded environmental exposure (e.g., vehicular flow, building height, street width, presence of cycling infrastructure).

We used a flyer to recruit broad participation of volunteer cyclists. Overall, >100 cyclists contacted our research team. Before participating, all participants involved in the study signed informed consent forms. Our study was conducted per the Declaration of Helsinki and approved by the Ethics Committee of the Faculty of Medicine at the University of the Republic (EXP No. 070153-000585-18, 01/11/2018).

Sample size calculations were reported in D'Angelo et al. (2023). We used the methodology developed by Van den Bossche et al. (2015) to estimate the minimum number of measurements to be done along each monitoring route to obtain representative atmospheric concentrations of the pollutants. It was determined that 30 measurements would be needed along each monitoring route.

Measurements from each participant were included once and an equal number of participants were measured in each route. Measurements were done periodically from February 2021 to December 2021, depending on participant availability and always at the same time (i.e., morning rush hour) on working days. The assembly of the necessary equipment to measure clinical and environmental variables included the installation of a basket (fixed to the bicycle) with devices to measure the concentration of contaminants, attachment of GPS equipment to the bicycle, placement of the noise dosimeter sensor on the cyclist's shoulder, and placement of the heart rate sensor on the cyclist using a chest strap design.

Before starting the cycling trip, all participants were asked to answer a questionnaire that included information on demographic variables, smoking habits, active lifestyle, height and weight, comorbidities, blood pressure, and CO-oximetry. After completion of the trip, a final CO-oximetry was performed.

Descriptive statistics of the main characteristics of the participants were done. Bivariate analysis with some selected variables in each sampling route was conducted, and parametric or nonparametric tests were used to compare continuous variables in each route depending on the normal distribution of data.

The percentage of time per trip and route during which PM_{10} and $PM_{2.5}$ concentrations were either >10 µg/m^3 or above concentrations recorded simultaneously at a monitoring station placed on the roof of a nearby building were measured according to recommendations by Orellano et al. (2020). The percentage of time per trip and route during which the noise levels were >70 dBA was also counted (WHO, 2019).

The potential inhaled dose for a specific air pollutant (D) was determined according to the following equation (Targino et al., 2018), with C being air pollutant concentrations and V being cyclist ventilation rates: D (µg/s) = C (µg/m^3) × V (m^3/s).

Lastly, multivariate models were done to assess the association between levels of CO in cyclists' expired air before and after the cycling trip. The models were adjusted for potential confounders. We conducted our analysis using R statistical software version 3.6.1.

Results

A total of 64 participants were recruited—32 for each route—and 60% of participants self-reported their sex as male (*n* = 38). For the participants, the mean age was 36.5 ± 10.2 years, the average body mass index (BMI) was 25 ± 3.71 kg/m^2, 20% of participants identified as current smokers or ex-smokers, and 37% of participants identified as current smokers or ex-smokers of cannabis.

In response to survey questions about their physical activity, 93% of participants answered that they frequently rode bicycles in the city. When asked if they did other regular physical activity, 62% of the participants answered yes. In response to questions about preexisting comorbidities, 11% of the participants reported they were asthmatic, and 3% reported high blood pressure. No participant reported having chronic obstructive pulmonary disease (COPD), heart failure, or another pathology. Characteristics of the participants by route of cycling are presented in Table 1.

A comparison of cyclists' ages between the two routes was made using a non-parametric Wilcoxon test and showed a nonsignificant difference (p = .087). The distribution of BMI in the sample was normal, and the difference in participant BMI measurements between both routes was not statistically significant (p = .504). Each participant had their blood pressure taken before starting the cycling trip. This measurement was taken twice. For the analysis, the average value of the two measurements was used. We did not detect any statistically significant differences in the blood pressure of participants in each route.

Exposure to environmental pollutants ($PM_{2.5}$, PM_{10}, NO_2, and noise) was explored in both routes. No statistically significant differences were found in $PM_{2.5}$ and PM_{10} concentrations between routes; however, the NO_2 concentration was higher in Route 1 and the noise level was higher in Route 2 (Table 2). Regarding potential inhaled doses per route, there were significant differences in PM_{10} and NO_2, with measurements for both being higher in Route 1 (Table 2).

Even though exposure to $PM_{2.5}$ and PM_{10} was not different between routes, in most of the cycling trips we detected exposure levels above the threshold at least 14% of the time for all the variables analyzed. The mean exceedance exposure time for $PM_{2.5}$ was higher for Route 2 and the difference was statistically significant (p = .0005). The percentage of time exposure to noise levels >70 dBA was also different and higher for Route 2 (p = .0003), which is also statistically significant (Table 3).

TABLE **1**

Demographics of Participants by Cycling Route (*N* = 64)

Demographic Variable	Route 1 Participants (*n* = 32)	Route 2 Participants (*n* = 32)	*p*-Value
Age (years)	33.8 ± 7.5	39.2 ± 11.9	.08
Sex (#)			
Female	13	13	1.00
Male	19	19	
BMI	24.7 ± 2.9	25.3 ± 4.4	.50
Smoking status (#/participant response)			
Tobacco	2/30	2/30	1.00
Cannabis	14/18	9/23	.29
Regular physical activity (#)			
Yes	23	18	.44
No	9	14	
Comorbidities (#)			
Respiratory	3	4	1.00
Cardiovascular	0	2	.47
Blood pressure			
Systolic	125 ± 12	123 ± 18	.18
Diastolic	83 ±7	81 ±13	.10

Note. BMI = body mass index.

A wide range of exceedance times was detected during some cycling trips on specific days; exceedance time in all variables was >60% (in Route 1 for days 8 and 17, and in Route 2 for days 5–8, 11, 12, 15, 17, and 34). For noise and PM_{10}, exceedance time was >60% of the cycling time in >80% of the days. On the other hand, some cycling trips showed no exceedance time, mainly for $PM_{2.5}$ (Supplemental Figure 1, www.neha.org/jeh-supplementals).

CO saturation measurements are the percentages of hemoglobin saturation with CO (%COHb) and the estimation of ppm of CO (CO-oximetry). These measurements were obtained from participants before and after completion of the cycling trips as a proxy of the short-term impact of air pollutants on the respiratory function of participants.

We estimated the differences in concentrations before and after the cycling trips. The mean CO-oximetry before the trip was 2.98 ± 2.8 ppm, with 3.06 ± 3.34 ppm in Route 2 and 2.91 ± 2.2 ppm in Route 1 (p = .831). After the trip, the CO-oximetry global mean was 2.32 ± 2.2 ppm, with 2.44 ± 2.79 ppm in Route 2 and 2.22 ± 1.43 ppm in Route 1 (p = .69). The mean of the differences was -0.652 ± 0.9 ppm and when differentiating between the routes, the differences had a mean of -0.625 ± 0.94 ppm for Route 2 and -0.688 ± 0.93 ppm for Route 1. In both routes, on average the measurements decreased after the cycling trip compared with the measurements before the trip. There were no differences, however, between routes (p = .975, Wilcoxon test).

Multivariate Statistical Analysis

To determine an association of various variables with the concentration of CO exhaled by the cyclist before and after completing the route, multivariate analyses were performed. Simple and multiple linear regression models were fitted for the difference between CO-oximetry (after versus before) and for the CO-oximetry measurement after. As explanatory variables, many scenarios were considered with different

TABLE 2

Parameters Measured During Cycling Trips on Each Route

Parameter	Route 1 *M* (*SD*)	Route 2 *M* (*SD*)	Mann–Whitney *p*-Value
Trip duration (min)	24.9 (4.3)	26.0 (7.4)	.767
Cyclist speed (km/h)	16.7 (2.6)	17.6 (2.8)	.168
Cyclist ventilation rate (L/min)	56.4 (17.5)	43.0 (13.4)	.003
PM_{10} concentration (µg/m³)	38.2 (10.5)	50.5 (33.6)	.475
$PM_{2.5}$ concentration (µg/m³)	15.1 (7.2)	26.5 (26.3)	.151
NO_2 concentration (µg/m³)	42.5 (10.1)	32.6 (8.1)	<.001
PM_{10} potential inhaled dose (µg)	45.0 (17.9)	41.7 (33.7)	.044
$PM_{2.5}$ potential inhaled dose (µg)	18.2 (11.5)	21.9 (26.2)	.169
NO_2 potential inhaled dose (µg)	47.4 (16.3)	28.2 (13.4)	<.001
Noise pollution dose (%)	14.0 (10.0)	51.4 (91.0)	<.001

Note. NO_2 = nitrogen dioxide; PM = particulate matter.
Source: D'Angelo et al., 2023.

TABLE 3

Percentage of Exceedance Time Over the Threshold for Measured Environmental Pollutants

Pollutant	Route	*M* and *SD* (%)	*p*-Value
Noise	1	70.8 ± 10.7	.0003
	2	81.2 ± 8.4	
$PM_{2.5}$	1	14.7 ± 17.8	.0005
	2	34.3 ± 33.2	
PM_{10}	1	81.7 ± 30.4	.8301
	2	83.3 ± 30.2	

Note. PM = particulate matter.

combinations of variables, including age; sex; smoking status; sedentary lifestyle; BMI; previous pathologies; the regular use of bicycles; and the proportion of time exposed to high levels of $PM_{2.5}$, PM_{10}, and noise. No significant associations were found in any setting with CO-oximetry measurements.

Discussion

This study is the first to report on the short-term impact of traffic-related atmospheric pollutants ($PM_{2.5}$, PM_{10}, CO, NO_2, and noise) at the street level among healthy cyclists in Uruguay.

Unfortunately, there is no estimation of the number of cyclists in the city of Montevideo; however, in 2016, the Origin-Destiny Survey was administered in Montevideo (https://montevideo.gub.uy/observatorio-de-movilidad). This survey explored the mobility patterns of a subset of people living in Montevideo. The resulting data showed that among adults using bicycles, the mean age was 47.9 years ± 18.1 (*SD*) and 54% of the sample self-reported their sex as female.

In our study, the mean age was 36.5 ± 10.2 years, and 40% of participants self-reported their sex as female. Demographic and epidemiological characteristics of cyclists on both routes were similar. Exposure to fine and middle-size particulate matter ($PM_{2.5}$ and PM_{10}, respectively) was not different between routes, but the NO_2 environmental concentration was higher in Route 1 and the noise level was higher in Route 2.

NO_2 is produced from vehicle emissions, petroleum refineries, and fuel combustion (WHO Regional Office for Europe, 2021). Exposure to NO_2 is converted to ozone (in the presence of sunlight) and promotes respiratory and cardiovascular morbidity as well as mortality; these adverse effects have been well documented in epidemiological and real-world evidence in Europe, Asia, and the U.S. (Burnett et al., 2018; Costa et al., 2017; Hvidtfeldt et al., 2019; Janssen et al., 2017; Linares et al., 2018; Liu et al., 2019; Zúñiga et al., 2016).

For our study, measurements of NO_2 concentrations were done in the morning during the rush hour when many people are traveling to schools and worksites. Due to the characteristics of Route 1, it is possible that a higher NO_2 concentration was facilitated by higher production in the busy time of the day (more traffic) and by the narrow corridors of streets surrounded by buildings (i.e., urban canyons). Potential inhaled doses were also higher in Route 1 for PM_{10} and NO_2.

Furthermore, Route 2 showed higher noise levels. This route has more traffic (perhaps because it has more schools and health centers along the route), and the route also has a high rate of use by trucks and buses, which are slower vehicles. These two factors could explain the high sound pressure levels. This finding coincides with the high percentage of time exceedances of noise >70 dBA along the route. Even though there is more traffic, NO_2 and $PM_{2.5}$ can better dissipate in an environment of broad streets, but the exceedance time remains high for $PM_{2.5}$ (Li et al., 2019).

Air quality cut-points for 24 hr suggested in the Air Quality Guidelines are 15 µg/m³ for $PM_{2.5}$ and 45 µg/m³ for PM_{10} (WHO, 2022). For Route 2, all mean values were above the recommendations. These findings suggest that the population might be exposed to higher health risks related to air pollutants along Route 2. The mean values for NO_2, however, were below the recommended limits of 200 µg/m³ for 1 hr for both routes.

When we considered the time of exceedance in the analysis, it was evident that PM levels are higher when measured at street level than at rooftop height. This finding is relevant because the information available for environmental pollutants is provided mainly from monitoring stations placed on building roofs. According to our data, these measures underestimate real exposure at the street level.

The effect of pollutants on respiratory health measured through CO-oximetry or %COHb was not evident. On average, CO-oximetry after the cycling trips was lower than before. A possible explanation is that an increase in ventilation during physical effort caused by cycling, in a short period, might wash pollutants from the respiratory airway, thus resulting in reduced exhaled CO after the cycling trip.

Cavaliere et al. (2009) demonstrated in healthy voluntary participants that exhaled CO decreased during acute hyperventilation (10%) but to a much lesser extent than exhaled CO_2 (25%). Similarly, Cope et al. (2004) found that ventilation patterns strongly influence the quantification of volatile analytes in exhaled breath, and observed a reduction of CO exhaled levels during hyperventilation.

The balance between the health benefits of physical activity (i.e., active transport in our study) and health risks due to exposure to pollutants (e.g., $PM_{2.5}$, PM_{10}, NO_2) has been studied by several authors. Tainio et al. (2016) defined a model that included air pollution exposures due to active travel and estimated the differences in the inhaled dose of fine particulate matter ($PM_{2.5}$), time of cycling, and risk for all-cause mortality. The break-even point beyond which additional physical activity might cause an increased risk for all-cause mortality was 300 min of cycling per day. Cycling trips in our experiment did not last >60 min, and they were defined according to the routes usually taken by active transport users.

Tainio et al. (2021) performed a mapping review of empirical and modeling evidence to identify possible links between exposure to air pollution and physical activity. Observational epidemiological studies identified in the review provided some evidence for a possible interaction between air pollution and physical activity for acute health outcomes in environments with high concentrations of pollutants (most studies were done in Europe or North America). They also reported that public health modeling studies have estimated that, in most situations, the benefits of physical activity outweigh the risks of air pollution—at least in the active transport environment. Evidence was scarce, however, for low- and middle-income countries.

In our study, we found low levels of NO_2 in routes that included busy streets within a city. Therefore, for cyclists in Montevideo, we find it reasonable to assume that the benefits of active transport likely outweigh the risks.

The impact of noise on human health depends on several factors, including the level of noise, the person who is exposed, and the exposure duration. In our study, noise has been one of the highest pollutants in the studied routes. We found that in 21 days, cyclists were exposed to >70 dBA more than 70% of the duration of the cycling trips.

Guidelines for European countries recommend reducing traffic noise levels to <53 dBA/day (WHO, 2019). Noise is an important stressor and contributes to increased risk of hypertension. Hypertension is one of the major risk factors for chronic disease in Uruguay (Hammer et al., 2014; Ministry of Public Health, 2018). As Gelb and Apparicio (2021) note, active transport users are exposed to a situation of clear injustice, as they are more exposed than other road users to environmental pollution—pollution that they do not contribute to producing themselves. They also found that cyclist exposure to noise is more dependent on the characteristics of the microscale environment (i.e., environments studied at the microscale, usually at characteristic distances not >300 m). This finding makes it possible to modify noise exposure by choosing appropriate streets to place active transport ways. In our study, this component should be balanced with traffic levels.

One strength of our study was that we measured air pollution at street level in a habitual active transport route and compared street-level measurements with roof-level air quality monitoring. This relationship had not been studied in Montevideo. Study routes were defined by experienced active transport users and thus represent routes that are the most used to access work for part of the population.

Regarding limitations, the accuracy of measures, mainly CO, could be skewed due to hyperventilation. Some of the measures were performed right after the COVID-19 mitigation control measures were suspended, and thus the traffic burden could be underrepresented during part of the data collection period. This fact constitutes a limitation of our study, although we did not conduct measurements during pandemic lockdown periods.

Nevertheless, sound pressure levels were also higher during days with less traffic flow. Furthermore, our study did not include other risks related to traffic routes such as accidents, which could represent extra health burdens for active transport users.

As we have shown, the usual air quality monitoring conducted in Montevideo is at roof level, and as such is not an accurate measure of air pollution at the street level. Future research to have a better representation of modeling data obtained in roof-level monitoring stations could be useful for health prevention purposes. Moreover, adding data of other determinants of street-level pollution to predict real exposure to cyclists of health-threatening air pollutants would benefit both cyclists and the broader public by informing mitigation strategies to lower atmospheric pollution.

Conclusion

Even though the street level of pollutants is above recommended thresholds, active transport benefits seem to outweigh health risks in Montevideo in our study on routes usually used by cyclists. Our study provided some knowledge about characteristics of the environment to be considered by city planners when selecting where to place bikeways in Montevideo.

According to the Intergovernmental Network on Air Pollution for Latin America and the Caribbean (2022), approximately 7 million people die every year around the world due to diseases and infections related to indoor and outdoor air pollution. In addition, Willberg et al. (2023) concluded that air pollution results in 400,000 premature deaths in Europe every year. In Uruguay, according to the Climate and Clean Air Coalition (2022), there are approximately 250 premature deaths every year related to outdoor exposure to $PM_{2.5}$. Consequently, air pollution research is a key aspect in guiding environmental public health practice.

In this study, we conducted a mobile monitoring of personal exposure to air pollutants. This technique allows for picturing air pollution in small temporal and spatial scales. Mobile monitoring of air pollution could be a powerful tool for detailed studies on environmental public health. In addition, our study results have been communicated to Montevideo government officials for their consideration when planning where to place cycling paths, especially as the cycling path network is expanding within the city.

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