

Article

Personal Exposure to Air Pollution in Office Workers in Ireland: Measurement, Analysis and Implications

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Received: 8 October 2013; in revised form: 13 November 2013 / Accepted: 14 November 2013 /
Published: 2 December 2013

Abstract: An experimental assessment of personal exposure to PM₁₀ in 59 office workers was carried out in Dublin, Ireland. Two hundred and fifty five samples of 24 hour personal exposure were collected in real time over a 28 month period. The investigation included an assessment of the uptake of pollutants in the lungs during various daily activities using a Human Respiratory Tract Model. The results of the investigation showed that indoor air quality was the overriding determinant of average daily personal exposure as participants in the study spent over 92% of their time indoors. Exposure in the workplace and exposure at home were the most important microenvironments in total uptake of particulate matter. Exposure while commuting or shopping were found to play a minor role in comparison. The investigation highlighted the importance of considering pollutant uptake as well as personal exposure among receptors where variations in levels of physical activity and duration of exposure are present.

Keywords: air pollution; PM₁₀; personal exposure; activity patterns; uptake; indoor air quality

1. Introduction

Clean air is a basic requirement for the well-being of human health and development, yet the atmosphere is continually being polluted through human activities with a variety of gaseous and

particulate air pollutants. Over the past few decades the importance of air pollution and its association with harm to human health has been examined in numerous epidemiological studies [1]. The effects of air pollution on human health may include aggravating pre-existing conditions like asthma, heart and lung disease as well as causing bronchitis and lung cancer in adults, and respiratory diseases in children [2,3].

The personal exposure of an individual to air pollution is multifaceted and varies according to numerous factors. The impacts of meteorological factors and traffic conditions on personal exposure, for example, are well documented [4]. The impacts on personal exposure of activities such as commuting have been examined in numerous cities [5], as have the health impacts of these activities in terms of acute exposure to particulate matter [6,7] and in terms of the uptake of these pollutants in the lungs [8].

In previous studies, determinants of personal exposure such as smoking have been shown to have a large influence on personal exposure concentrations of an individual [9]. A study carried out in the Czech Republic [10] found high concentrations associated with personal sampling in restaurants and indoor microenvironments where stoves were present. The indoor activity of cooking is known to produce an appreciable mass of airborne particles in the vicinity of the cooker [11]. Previous research has also indicated possible adverse health effects such as cardiovascular disease associated with occupational particulate exposures [12,13]. As such, it is clear that the variety of activities carried out by individuals on a daily basis has an important influence on their personal exposure to air pollutants.

The uptake of pollutants in the lungs is also an important element in the assessment of the health impact of air pollution exposure and an area often neglected by studies of personal exposure to air pollutants. Investigations have shown that the differences in the physiological state (breathing rate, frequency, *etc.*) of population subgroups can result in differing impacts of air pollutant exposure among such groups. For example, investigations have shown that while exposure of individuals to air pollutants in private vehicles may be typically higher than for cyclists or pedestrians in commuter transport, when breathing parameters and duration of exposure are taken into account, transport modes such as cycling often exhibits a higher health impact from air pollution [8].

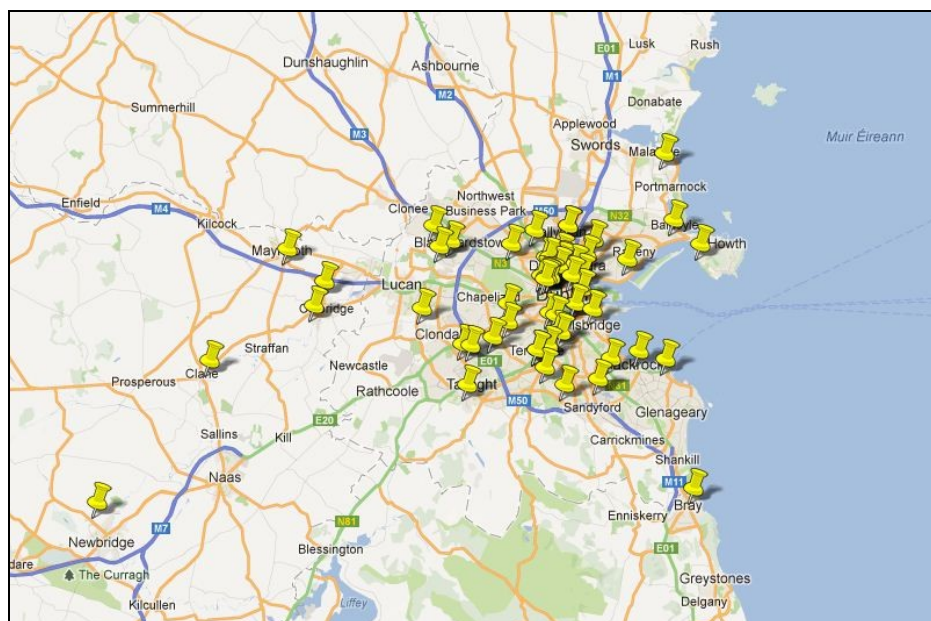
This paper presents an investigation into the personal exposure of office workers over 24 hour periods. Exposure while carrying out different activities in various microenvironments was examined and the associated uptake of pollutants was determined in each case. Exposure assessments were carried out for subjects spread over the Greater Dublin Area and its satellite towns in Ireland. The obtained results quantify the relative importance of exposure to air pollution in different microenvironments on overall health impact. Personal exposure and pollutant uptake were analysed and compared. The relative importance of activities such as smoking and cooking on personal exposure are highlighted, as is the overriding importance of indoor air quality on the exposure of office workers.

2. Methodology

A 24 hour personal exposure monitoring campaign was undertaken for a period of 28 months from February 2009 to June 2011. A total of 59 subjects were recruited on a voluntary basis completing 255 24-hour sampling periods. The recruitment of subjects was restricted to office workers living and working in the Greater Dublin area, in order to limit the extent of variation in personal exposure among the sample population. Samples were also collected during week days only. The study population was 57% male and 43% female. The majority (48%) of subjects were aged 26 to 35 years,

with 27% in the 18 to 25 years category and the remainder between 36 and 55. Approximately 12% of subjects declared themselves as smokers of some degree, or were in residence with a smoker. A good distribution of subject home locations was achieved across the city as illustrated in Figure 1.

Figure 1. Residential locations of subjects in Dublin, Ireland.



2.1. Sampling Equipment

Sampling of personal exposure, activity and location of subjects was carried out using a real time particulate matter (PM₁₀) sampling device (Met One Aerocet-531 particle profiler), GPS tracking equipment (Garmin GPSMAP[®] 60CSx), and a personal activity diary. Particulate Matter (PM) was chosen as the main pollutant to be monitored due to its health significance, its multisource nature (indoor and outdoor environments), and the ability to record its concentration using real-time monitors that are small and mobile whilst maintaining sufficient resolution and accuracy.

The Aerocet-531 is a real-time automatic particulate matter monitor capable of recording concentrations of PM₁₀ at two minute intervals. The instrument uses a laser diode with a right angle scatter method at 0.78 μm . The light travels at a right angle to the collection sensor and detector, and the instrument uses the information collected from the scattered particles to calculate a mass per unit volume. A mean particle diameter is recorded and is used to calculate a volume in cubic meters, which is then multiplied by the number of particles and a generic density that is representative of typical aerosols. The calculated mass is then divided by the volume of air sampled to obtain mass per unit volume ($\mu\text{g m}^{-3}$) [14].

The GPS device used as part of this research project was chosen because of its high sensitivity receiver which meant it could easily and quickly obtain GPS satellite signal in an urban landscape. It was also a small handheld device which made it convenient for subjects to carry on their person along with the Aerocet-531 instrument, bringing the total weight of the sampling equipment to approximately 1.1 kg.

The activities of the subjects were also monitored through use of an activity log. Each subject was instructed to record, in as much detail as possible, the time of day they partook in a certain activity or

were in a specific location. This information, together with the GPS data, were then used to divide up the particulate concentrations recorded by the Aerocet-531 and assign them to defined microenvironments or activity groups.

2.2. Calibration of Equipment

Measurements obtained from the optical light scattering technique (Aerocet-531) were compared, for quality control purposes, to the traditional particulate sampling method of gravimetric analysis. Details of the calibration procedure and resulting adjustment of measurements obtained from the Aerocet 531 are contained in the supplementary material section (Figure A1).

2.3. Data Analysis

The dataset for all 24 hour sampling periods collected by the subjects was compiled in the statistical software package SPSS (v16.0). Each sample in the dataset comprised the following variables:

- date
- time
- PM₁₀
- wind speed
- wind direction
- temperature
- precipitation
- sunshine hours
- pressure
- relative humidity

The concentrations of PM₁₀ were tabulated as overall 24 hour daily averages, followed by the concentration encountered in each of the main microenvironment/activity categories:

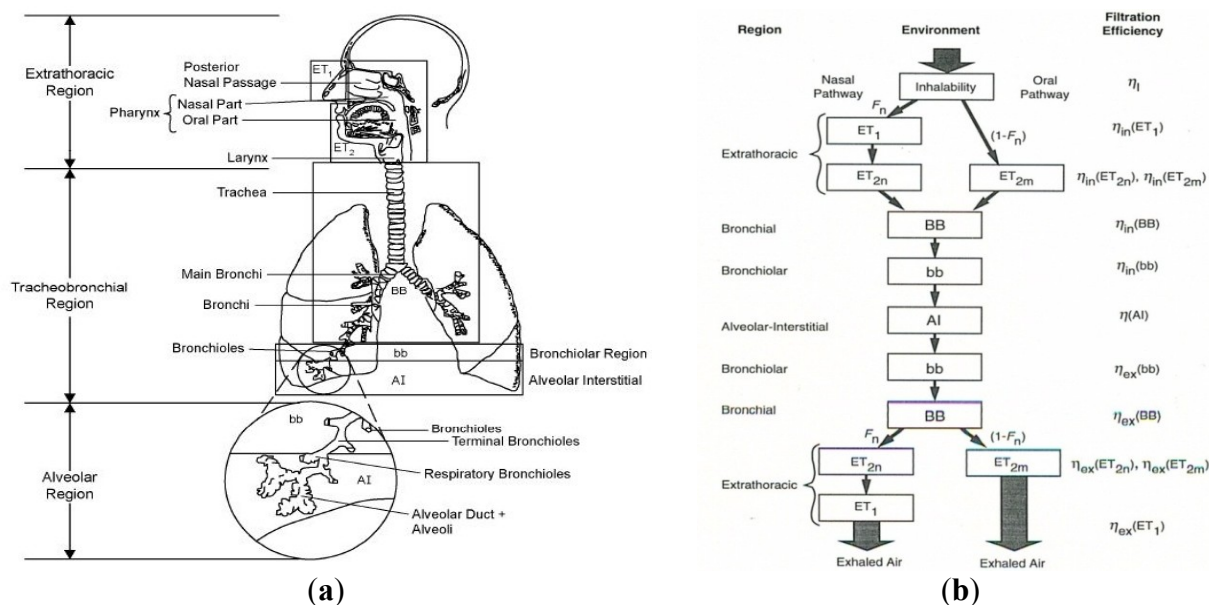
- at work
- at home
- sleeping
- shopping
- recreation/sport
- commuting (bus/car/walk/cycle/train)
- café/restaurant
- public house
- cooking
- other indoor
- other outdoor

The final two activity categories of “other indoor” and “other outdoor” described unique indoor and outdoor activities that occurred during sampling on a very seldom basis such as visiting a library or a post office. Too few of such activities existed to warrant a single category and thus these were amalgamated. The resulting matrix was subsequently analysed for descriptive statistics and mean comparison tests were carried out to investigate statistically significant (or otherwise) relationships within the data.

2.4. Uptake Modelling

The uptake of particulate matter during various activities was estimated in this study using an adaption of the International Commission on Radiological Protection (ICRP), Human Respiratory Tract (HRT) Model. The model, its adaption and application are described in full in McNabola *et al.* [8] and in ICRP [15]. In brief, the HRT model divides the anatomy of the respiratory tract system into 4 regions as shown in Figure 2. In the HRT model, the deposition of particles in each region is estimated by an equivalent particle filter representing each region of the lungs on inhalation and exhalation. The filtration efficiencies of these particle filters were determined using a combination of empirical experimentation and theoretical models of particle deposition.

Figure 2. (a) Human Respiratory Tract (HRT) model, (b) equivalent particle filters [15]. The model was used to convert personal exposure concentrations ($\mu\text{g}/\text{m}^3$) in each microenvironment to uptake (μg). This was carried out by assigning respiratory rates to the different levels of physical exertion along with information on the time spent in particular microenvironments for each sampling period. The model also took account of variations in uptake according to the subject's gender, age, height and weight.



2.5. Ventilation Parameters

The ventilation parameters employed in the HRT model were reference values for both male and female workers at different activity levels, as shown in Table 1. For the purposes of this study, advice on the attribution of activity levels for office workers has been taken both from literature and suggested reference values given in the HRT model. In a study of various occupations in the Netherlands [16], it was found that office based workers spent on average nearly three hours of their working day sitting. The evenings were also spent mainly sitting, almost three hours on average. Thus, in this study the exertion levels for the various activities and microenvironments were defined as shown in Table 2.

Table 1. Reference respiratory values for a general Caucasian population at different levels of activity [15].

		Resting		Sitting awake		Light exercise		Heavy exercise	
Gender (Male/Female):		M	F	M	F	M	F	M	F
Breathing Parameters *	V_T (L)	0.625	0.444	0.75	0.464	1.25	0.992	1.923	1.364
	B (m^3h^{-1})	0.45	0.32	0.54	0.39	1.5	1.25	3.0	2.7
	f_R (min^{-1})	12	12	12	14	20	21	26	33

* V_T = volume total, B = breathing rate; f_R = breathing frequency.

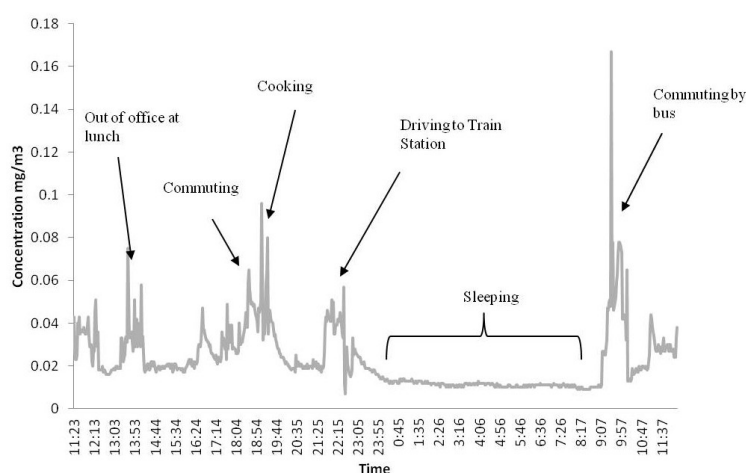
Table 2. Physical exertion levels used for various activities in the HRT model for subject uptake estimation.

Activities/microenvironments	Physical exertion levels				
	Resting	Sitting	Light exercise	Moderate exercise	Heavy exercise
At home		60%	40%		
Sleeping	100%				
Work		40%	60%		
Walking			100%		
Bus/car/tram/train		100%			
Cycling				100%	
Café/restaurant		100%			
Playing sport					100%
Shopping			100%		

3. Results

3.1. Personal Exposure

The mean 24 hour PM_{10} concentration for the study population was found to be $32 \mu g/m^3$ ($\sigma = 31 \mu g/m^3$). The highest mean 24 hour PM_{10} concentration for an individual subject in the dataset was recorded as $293 \mu g/m^3$; however 75% of the daily average data concentrations for subjects were under $36 \mu g/m^3$. Figure 3 illustrates a typical 24 hour PM_{10} personal exposure time series history collected during the sampling campaign.

Figure 3. Typical 24-hour time series profile annotated with the activities carried out.

As shown in Table 3, the highest mean PM_{10} concentration during a discrete activity was found to occur during the activity of cooking with a mean concentration of $146 \mu g/m^3$. Cooking events primarily occurred during the evening in the subjects home and typical concentrations varied according to the type of cooking, length of cooking and ventilation conditions in the dwelling. This was followed by the category of “other indoor” which had a mean concentration of $67 \mu g/m^3$. However, this category included many activities not repeated on a daily basis by the majority of subject i.e. activities seldom undertaken in comparison to the other clearly defined microenvironments such as at home or at work.

Table 3. The mean and standard deviation values for the primary activities and microenvironments of all the 24 hour PM₁₀ personal exposure samples collected.

Activity or microenvironment	N	Mean (µg/m ³)	Standard deviation (µg/m ³)
At work	244	39	35
At home	255	26	21
Sleeping	255	10	8
Cooking	134	146	193
In a pub	15	44	34
Walking	212	28	28
Driving	93	33	27
Train	35	27	15
Bus	100	43	31
Tram	10	14	8
Cycling	67	24	25
Shopping	61	43	44
Recreation or sport	29	59	47
Café or restaurant	60	53	84
Other indoor	72	67	67
Other outdoor	34	25	21

3.2. Time-activity Budgets

A large amount of activity data was gathered in conjunction with PM₁₀ exposure sampling. The activity diary and GPS enabled different activities, as well as microenvironments to be identified and matched to the data set values obtained from the Aerocet-531 instrument. The results of the population mean time-activity budgets are shown in Table 4.

Table 4. Time spent in different microenvironments (min d⁻¹).

Microenvironment	Population mean (min d ⁻¹)	Doer (%)	Doer mean(min d ⁻¹)
<i>Indoor</i>			
In a residence	848	100	848
Office	430	96	448
Cooking	49	53	92
Café/Restaurant	12	24	51
Public House	8	6	127
Shopping	7	24	31
Other indoor	23	28	79
Recreation/Sport	6	9	73
<i>Enclosed Transit</i>			
Bus	23	40	58
Car	18	36	48
Train	7	14	49
Tram	1	4	20
<i>Outdoors</i>			
Cycling	10	26	38
Walking	39	84	47
Recreation/Sport	2	3	87
Other outdoor	6	13	43

During the sampling campaign subjects spent 92% of their time indoors on average per day, with a further 3% spent in enclosed transit. While the percentage of time spent outdoors by the study population in comparison was just 5%. The total indoor time percentage can be broken down into four major microenvironments of at home in a residence, at work, in a café/public house/restaurant, or some “other indoor” location. The largest amount of time was spent by subjects in a residence which represented 59% of their time. Of this time spent at home, the average time spent sleeping was found to be 494 minutes, while the subjects were classified as “active” in the home for the other 305 minutes. Time spent cooking also comprised on average 49 minutes of the time the study population spent in a residence.

The next major location outside the home that the sampling population spent their time in was at work, which made up on average 30% of a person’s day. Smaller amounts of time were spent in other places such as a café, pub, restaurant, commuting or other indoor locations which made up 3% of the overall mean daily 24 hour time budget for the subject population.

3.3. Exposure among Smokers

In total, of the 34 sampling days carried out by the self-identified smokers involved in the study, only 12 of these days had a smoking event recorded in the activity diary. The population mean 24 hour PM_{10} concentration amongst the subjects who did report smoking events on sampling days was $42 \mu g/m^3$. This figure was over twice the 24 hour mean PM_{10} exposure ($20 \mu g/m^3$) of the self-identified smokers who did not report a smoking event. The impact of smoking could be seen in greater detail from the “at home” and “sleeping” concentrations of the sampling days when the subject smoked compared to days when they did not. On average, the “at home” concentration was $63 \mu g/m^3$ on days when they smoked compared with $23 \mu g/m^3$ on other days. The in-home PM_{10} concentrations at night when subjects were sleeping was $17 \mu g/m^3$ after smoking in the house, compared to just $8 \mu g/m^3$ when there was no smoking reported. Similar findings were reported by Nasir and Colbeck [17], where PM_{10} concentrations were found to double in residences where smoking took place.

3.4. Exposure While Cooking

In total 134 sampling days reported a cooking event, of these 83% reported just a single cooking event, 14% of sampling days had two separate cooking events, and just 3% recorded three cooking events in a single 24 hour period. This resulted in a total of 158 cooking events during the personal exposure sampling campaign. The types of cooking methods varied widely amongst subjects, with the primary types being boiling, frying, grilling, microwave, oven usage, and toasting. Many of the cooking events that were reported also involved a combination of different cooking methods, which therefore hindered the identification of each method’s exact contribution to particulates. Cooking events that were identified as a single method are shown Table 5.

Table 5. Summary statistics of the primary cooking methods when reported as the sole type of cooking taking place by a subject.

Type of cooking	N	Mean PM ₁₀ concentration (µg/m ³)	St dev (µg/m ³)	Average duration (min)
Boiling	17	105.6	144.9	59
Frying	11	312.6	178.5	167
Grilling	3	200.1	23.2	89
Microwave	10	95.3	63.1	22
Oven	7	68.8	30.1	52
Toasting	6	51.2	16.0	29

The mean duration in Table 5 is in reference to the length of time that a cooking source raised the PM₁₀ concentration above the original ambient “in home” concentration, and not the length of time spent cooking as reported by the subject. As can be seen from Table 5, the cooking method with the largest PM₁₀ concentration was frying which had a mean concentration of 312.6 µg/m³. Additionally, the variability of the PM₁₀ concentrations during frying was found to be the largest of the 6 techniques ($\sigma = 178.5$ µg/m³). Similar findings are summarised in Abdullahi *et al.* [11], where cooking of fatty foods and frying are reported to produce very high concentrations of particulate matter in a number of investigations.

3.5. Pollutant Uptake

The mean 24 hour PM₁₀ uptake amongst subjects was found to be 425 µg ($\sigma = 347$ µg). The uptake for the study population was found to vary considerably across the different microenvironments and activities. The mean uptake and associated descriptive statistics for each of the main activities of the study population are shown in Table 6. These results are discussed in Section 4.1.

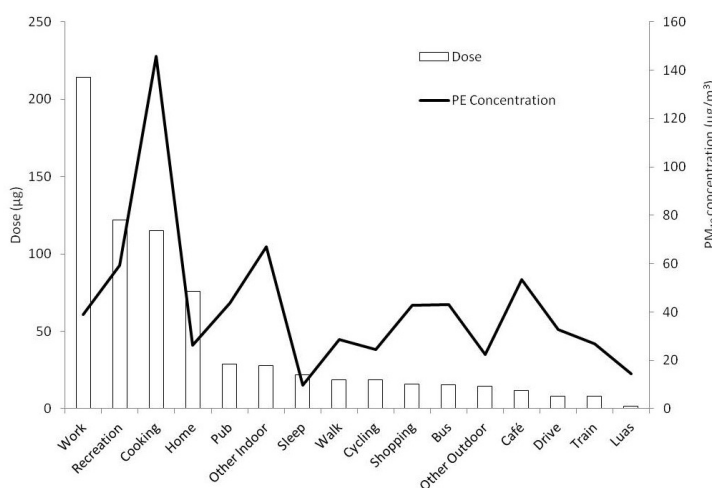
Table 6. Descriptive statistics for uptake of the study population for the main activities and microenvironments.

Activity/Microenvironment	Mean (µg)	St Dev (µg)
<i>Primary activities/locations</i>		
Working	214	229
Active in Home	76	70
Sleeping	22	18
<i>Other activities/locations</i>		
Café/Restaurant	12	17
Other Indoor	28	33
Cooking	115	296
Other Outdoor	15	27
Pub	29	23
Recreation/Sport	122	134
Shopping	16	24
<i>Transport modes</i>		
Bus	16	19
Car	8	11
Cycling	19	21
Train	8	7
Tram	2	1
Walking	19	16

3.6. Comparison of Personal Exposure and Uptake

It was considered important to highlight the reasons behind why, in certain microenvironments, subjects were found to have higher uptake than in others. Figure 4 highlights the differences in mean personal exposure concentrations and uptake experienced by subjects in differing microenvironments. These differences are discussed in Section 4.4.

Figure 4. A comparison of the mean daily uptake of the study population in various microenvironments with the corresponding personal PM₁₀ concentrations in each.



4. Discussion

4.1. Overview of Personal Exposure and Pollutant Uptake

Air quality in Dublin has improved significantly over the last 30 years and compared to the mean personal exposure of the study population, the average ambient outdoor PM₁₀ concentration during the sampling campaign was recorded as just 13 µg/m³ at a fixed site monitor in Dublin City. Personal exposure studies of PM₁₀ and PM_{2.5} in a number of other cities have found much higher concentrations [10,18] but such studies have been conducted in regions that are subject to greater ambient concentrations of PM. Improvements in air quality in this jurisdiction have been brought about by a number of measures including a ban on certain forms of coal combustion in major cities [19], a number of EU directives limiting ambient concentrations and improving emissions standards, licensing of point emissions sources, taxation on fuels and carbon, tobacco control measures *etc.* In addition, the geographic location of Ireland in North West Europe, with a prevailing wind travelling across the Atlantic Ocean results in little trans-boundary air pollution contributions to urban air quality in Dublin.

The largest uptake of PM₁₀ among subjects was found to be in the office working environment, which had a mean uptake of 214.2 µg. This was followed by recreation or sport (122.0 µg) and cooking (115.2 µg). The mean uptake while each subject was classified as active at home was 75.9 µg. The mean uptake that subjects absorbed while sleeping fell to 22.9 µg. The commuting modes of subjects were observed to have some of the lowest mean uptake of all microenvironments for the study population.

Exposure and uptake of pollutants in the workplace was a common factor in all samples and clearly a key area through which improvements in health impact could be achieved using control measures.

Sport and recreation activities were less common among the study population but were nonetheless surprisingly elevated in terms of both exposure and uptake. The majority of these activities were incidences of subjects attending a gym or playing indoor sports, and as such this is an area requiring further research into the reasons behind high exposure levels at a number of separate sports facilities in the city.

Cooking was also not universally undertaken across the sampling campaign with approximately 50% of sampling days including one or more cooking event. As the third highest source of pollutant uptake cooking activities were also a key determinant in overall exposure and uptake of PM₁₀. A number of cooking events resulted in very high concentrations of particles being measured. Variations in these concentrations were present depending on cooking type and duration as well as ventilation conditions. However it was impractical to accurately determine the ventilation parameters for each cooking event during this study and it was also difficult to separate the impact of differing types of cooking as these were often carried out in combination (e.g., boiling and frying, *etc.*). Increased awareness among the public of the benefits of adequate ventilation during cooking on their environmental health would be an obvious step in reducing this component of exposure.

It is the view of the authors that there is limited awareness among the public or among policy makers of the relative importance of differing sources of air pollution for a large group of the population such as office workers. There is significant awareness and policy attention on the transport sector, but relative to cooking or the workplace this was not found to be an important microenvironment in the current study. However, it should be noted that the numerous types of air pollution emitted from transport sources such as VOCs, NO_x, *etc.* may not be as prevalent in cooking emissions (*i.e.*, the results and findings of this study are limited to particulate matter).

It is also worth highlighting that just under 50% of subjects did not cook and presumably either dined outside the home or ordered takeaway food. For numerous reasons relating to healthy diet, eating out and takeaway food are often highlighted for their negative health impacts, however as found here through the act of not cooking, subjects were not exposed to the third highest source of pollutant uptake found in this study.

4.2. Indoor Air Quality

The majority of the time was spent indoors by subject and this was predominantly in the subject's residence. Time spent there was split almost two thirds in favour of the activity of sleeping, with one third of the time whereby the subject was active in the home. The activity of sleeping had a relatively low mean personal exposure concentration (10 µg/m³), and this was partially as a result of lack of activity in the residence. In contrast, the personal exposure concentrations when each individual was active at home were far greater. In addition to the home microenvironment, a large proportion of the study population's day was also spent at work. Other microenvironments such as commuting, shopping, recreation *etc.* were responsible for only small portions of the daily routine of the study population. The mean occupational exposure (39 µg/m³) for the office workers in this study was found to be higher than the overall 24 hour mean personal exposure. This microenvironment played a key role in the day to day personal exposure concentrations of individuals as 30% of every weekday was found to be spent in work on average by the study subjects.

These findings highlight the importance of indoor air quality on the overall impacts of air pollution on the health of a typical office worker. Office workers in this study lived predominantly outside of the city centre while they worked in offices located in the city centre. This was also reflected in the fact that in-home concentrations were typically lower than at work. The control of air pollution in the workplace in Ireland has seen some improvement in recent years with the introductions of ban on smoking for example. This was evident in the elevated in-home concentrations found in the houses of smokers including the activity of sleeping in contrast to their workplace exposure concentration.

The extension of indoor air pollution control policy to the monitoring of air quality in the workplace and the enforcement of air quality standards indoors would bring about significant improvements in population health. The mean outdoor PM₁₀ concentration recorded by the local authorities during the sampling period of 13 µg/m³ was less than half of the population's mean personal exposure and was at a level which was of no cause for concern. However this clearly underestimated the exposure of a significant proportion of the population and the control of air quality in such locations does not directly target equivalent reductions in personal exposure. As outlined in the most recent European Directive for air quality (CAFÉ 2008/50/EC) national exposure reductions targets must be achieved for PM_{2.5} of 0%–20% depending on 2010 levels. The results of this investigation clearly demonstrate in which areas the most significant gains in personal exposure reduction can be achieved.

4.3. Transport Microenvironments and Commuting

The highest PM₁₀ concentrations were found while travelling by bus (43 µg/m³), while travel by tram had the lowest personal exposure associated with it (14 µg/m³). However in the context of the overall daily average personal exposure these contributed only a small fraction. Significant research efforts have focused on personal exposure in the transport microenvironment, particularly during commuting. However, certainly in the case of Dublin, where air quality is generally good, exposure during transport activities was insignificant in comparison to the contribution of indoor air quality in the workplace and at home to overall daily exposure.

Michaels and Kleinman [7] highlighted the significance of brief excursions in microenvironments with high 1-hour peak concentrations of particulate matter on the health of human and animal receptors. In this investigation such high peaks were predominantly found in the home associated with cooking or smoking as opposed to in outdoor transport microenvironments. In addition, much of the air quality legislation in place today and the monitoring of compliance focus on the outdoor environment. Given that over 90% of time was spent indoors by typical office workers in this study, it is clear that indoor air quality is the key factor influencing exposure and health impact among this population sub-group. Such findings highlight further the need for policy development in the area of indoor air quality to improve human health.

However it is also important to highlight that this does not suggest that transport emissions in Dublin had little impact on the environment or the public. The key contribution of transport emissions in this study was their likely elevation of urban background concentrations in general and their infiltration into city centre office buildings where workers spent significant amounts of time breathing elevated levels of pollutants. Previous investigations have shown that 50%–80% of particulate air pollution in buildings originated from external sources [20]. As such it is too early to conclude that

outdoor air pollution plays a minor role in the total uptake of particulate pollution among this population. Further work is needed to characterise the source of indoor air pollution (*i.e.*, indoor or outdoor sources).

4.4. Comparison of Personal Exposure and Uptake

Some of the microenvironments which were highlighted in Section 3.1 as having the largest mean personal PM₁₀ concentrations associated with them, in fact contributed relatively little to the 24 hour uptake of subjects. This was particularly apparent in the case of the category “other indoor” along with cafés and restaurants. The impact of highest exposure category, cooking, was also shown to be lower when breathing rates and exposure duration were accounted for.

The activity category of “other indoor” was found to have a relatively high mean PM₁₀ concentration (67 µg/m³) during the measurement campaign. However, due to the relatively infrequent and short amount of time spent in some of these microenvironments, the actual population uptake over 24 h was low (27.8 µg). A similar situation was seen with cafés and restaurants.

The uptake for the subjects while at work and active at home were, as expected, both large contributors to the 24 hour total uptake of subjects. This was due to the majority of each 24 hour sampling day being spent in either location. However, the greater activity levels while at work (40% sitting and 60% light exercise) amplified the difference in uptake even though the personal concentration population average was just 13 µg/m³ greater than “active at home”. For example, the uptake while at work (214.2 µg) was over 280% greater than that in the home (75.9 µg) on average, compared with the 49% difference between the two exposure concentrations.

The importance of considering both exposure and uptake of pollutants is clearly demonstrated here, however it is worth noting that the HRT models predictions of uptake took account of particle size, particle physics, the exhalation of particles, variations in physiology of subjects (sex, weight, height, *etc.*), duration of exposure, *etc.* As such the result of this model provide a more realistic estimate of air quality health impacts than the ‘inhaled dose technique’ used in a number of other studies *e.g.* [5].

4.5. Transferability of Results

The transferability and limitations of the results of the current study are worth highlighting. Emphasis has been given to the importance of indoor air quality on the likely health impact of air pollution on office workers, particularly in the workplace. Clearly this may differ for those with differing workplace environments or those who are retired/unemployed *etc.* Exposure in predominantly outdoor or industrial settings is likely to differ from those found in the present study.

The transferability of the results of the present study to other locations is also worth noting. As mentioned, air quality in Dublin is generally quite good and perhaps the contribution of commuting may be more significant in cities with greater air quality problems. Branis and Kolomazikova [10] performed a similar long term exposure assessment exercise using real time monitoring of one subject in the Czech Republic. Concentrations of PM_{2.5} measured in various microenvironments during this study were typically higher than those found here for PM₁₀. However the relative importance of each microenvironment was similar. Furthermore the findings here in relation to PM₁₀ on the importance of

the transport microenvironment do not necessarily translate to exposure to other traffic related pollutants e.g., NO_x, PM_{2.5}, VOCs, *etc.*

The authors would like to thank the Environmental Protection Agency (STRIVE programme) for funding this research.

5. Conclusions

Arising from the results of this investigation the following conclusions can be drawn:

- The importance of indoor air quality on the overall impacts of air pollution on the health of a typical office worker has been highlighted by the results of this investigation. Exposure and uptake during activities such as working, cooking or at-home, significantly outweighed those found during outdoor activities such as commuting.
- The extension of indoor air pollution control policy to the monitoring of air quality in the workplace and the enforcement of air quality standards indoors would bring about significant improvements in population health.
- The importance of considering both exposure and uptake of pollutants when comparing the health impacts of air pollution across differing activities has been highlighted. Using exposure alone as a measure of air pollution health impacts would result in significant errors in the interpretation of relative health impacts.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix

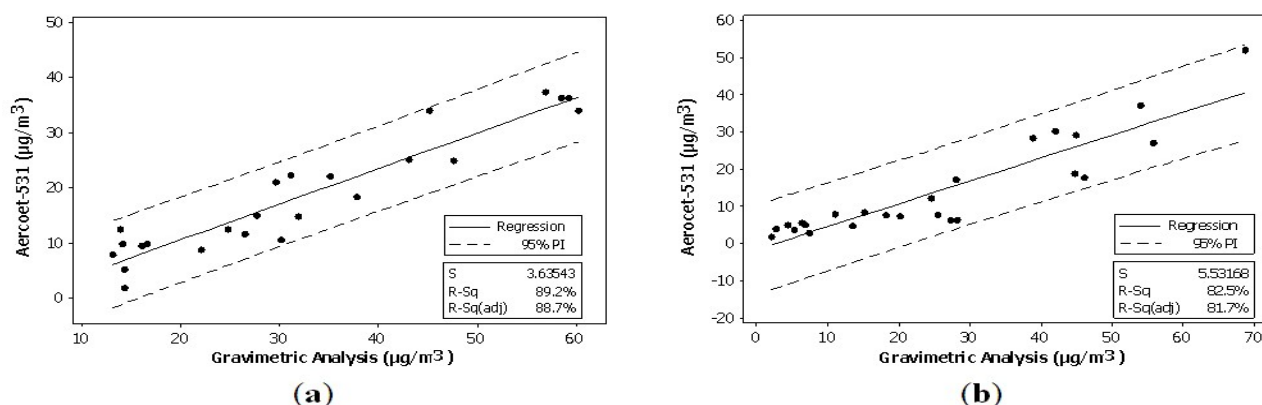
Measurements obtained from the optical light scattering technique (Aerocet-531) were compared, for quality control purposes, to the traditional particulate sampling method of gravimetric analysis.

Gravimetric analysis was carried out by pre and post-weighing a 47 mm diameter glass microfibre filter, with pore size 2 µm, on a Cahn C33 six figure microbalance which had an accuracy of ± 0.6 µg. The microbalance was calibrated before each weighing session using a 100 mg calibration weight as specified by the manufacturers. Filters were equilibrated prior to pre-weighing for at least 24 h and again after sampling for at least 24 h in a humidity and temperature controlled environment. On each occasion the filters were weighed a minimum of three times and the average weight was then taken. To ensure the validity of this average weight it was required that the three weights agreed to within 5 µg of each other. The laboratory and quality control procedures adopted during this element of the investigation followed closely those described by Koistinen *et al.* [21].

In total, 25 indoor and 25 outdoor comparisons (20% of the total samples) were carried out over 8 hour periods between the gravimetric method (Haz-Dust EPAM-5000) and the Aerocet-531. An acceptable level of accuracy was obtained and the PM₁₀ concentrations in the dataset for indoor and outdoor environments were subsequently adjusted separately according to the calibration equations shown in Figure A1a,b. Calibrations were carried out in indoor and outdoor environments to ensure that

the quality control procedures accounted for varying source types and levels of relative humidity, which are known to influence the accuracy of light-scatter based PM monitoring devices.

Figure A1. (a) Indoor calibration curve for Aerocet-531 and (b) Outdoor calibration curve.



The Aerocet was also tested with a flow meter before each sample to ensure flow was correct at $2.83 \text{ L/min} \pm 5\%$. It was also tested with a zero filter to identify any potential leaks in the intake of the instrument. Finally, the GPS was checked as well to ensure correct functioning and calibrated if required. In addition the Aerocet measurements were also adjusted using a correction factor (CF) for changes in relative humidity (RH) according to equation 1 when RH values exceeded 60% [22].

$$CF = 1 + 0.25 \frac{RH^2}{(1 - RH)} \quad (1)$$

By way of further illustrating the agreement between the Aerocet and gravimetric measurements, Bland and Altman plots of the indoor and outdoor calibration data is shown in Figure A2.

Figure A2. Bland and Altman Plot of data obtained from pair measurements of PM_{10} using the Aerocet and HazDust monitors in (a) Outdoor and (b) Indoor Environments. Outdoor statistics: $R = 0.7650$ ($p < 0.01$), Slope = 0.4034 ($p < 0.01$), Intercept = 3.403 ($p = 0.13$). Indoor statistics: $R = 0.6913$ ($p < 0.01$), Slope = 0.3863 ($p < 0.01$), Intercept = 3.935 ($p = 0.05$).

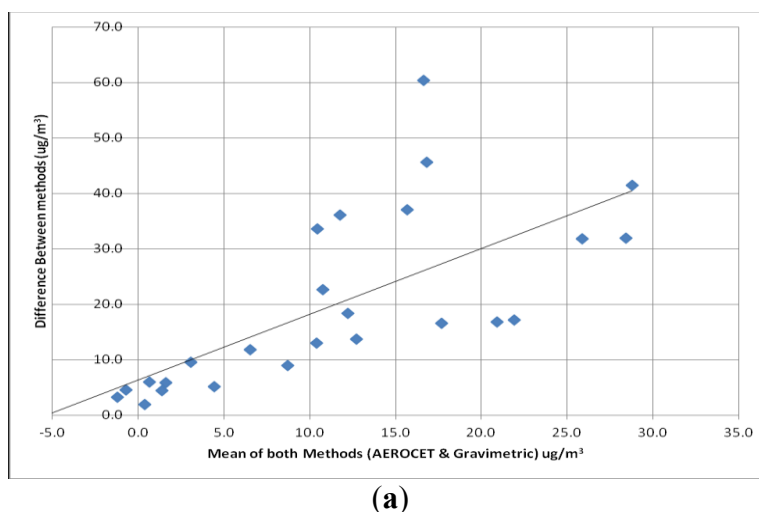
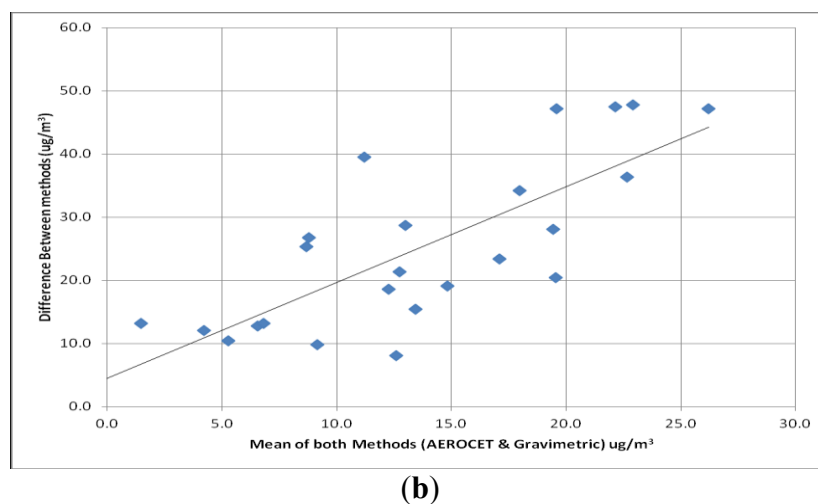


Figure A2. Cont.



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