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TITLE: Exposure to particles from laser printers operating within office workplaces

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ABSTRACT: While recent research has provided valuable information as to the composition of laser printer particles, their formation mechanisms, and explained why some printers are emitters whilst others are low emitters, fundamental questions relating to the potential exposure of office workers remained unanswered. In particular, (i) what impact does the operation of laser printers have on the background particle number concentration (PNC) of an office environment over the duration of a typical working day?; (ii) what is the airborne particle exposure to office workers in the vicinity of laser printers; (iii) what influence does the office ventilation have upon the transport and concentration of particles?; (iv) is there a need to control the generation of, and/or transport of particles arising from the operation of laser printers within an office environment?; (v) what instrumentation and methodology is relevant for characterising such particles within an office location? We present experimental evidence on printer temporal and spatial PNC during the operation of 107 laser printers within open plan offices of five buildings. We show for the first time that the eight-hour time-weighted average printer particle exposure is significantly less than the eight-hour time-weighted local background particle exposure, but that peak printer particle exposure can be greater than two orders of magnitude higher than local background particle exposure. The particle size range is predominantly ultrafine (< 100nm diameter). In addition we have established that office workers are constantly exposed to non-printer derived particle concentrations, with up to an order of magnitude difference in such exposure amongst offices, and propose that such exposure be controlled along with exposure to printer derived particles. We also propose, for the first time, that peak particle reference values be calculated for each office area analogous to the criteria used in Australia and elsewhere for evaluating exposure excursion above occupational hazardous

chemical exposure standards. A universal peak particle reference value of 2.0×10^4 particles cm^{-3} has been proposed.

1. Introduction

Recent studies have concluded that laser printers can be significant sources of ultrafine particles (< 100nm diameter) [1-3], the particles are volatile and of secondary nature, being formed in the air from volatile organic compounds originating from both the paper and hot toner, and that the difference between a high and low emitting printer lies in the speed and sophistication of the temperature control [3]. Whilst such information is essential for the design of low emitting printers, information is also needed regarding the pattern of the printer particle emissions within actual office locations and the subsequent exposure of office workers so as to guide decision making regarding implementation of particle exposure controls. Destaillats et al [4] concluded human exposure to potentially harmful pollutants emitted from office equipment has not been systematically evaluated and is currently not well understood. Koivisto et al [5] found printer-emitted particles increased office 6-h averaged particle concentration over eleven times compared to background particle concentration. Hanninen et al [6] concluded daily uptake and lung deposition of printer particles can occur and that associated risk to health was low, and also substantially lower than the estimated risks due to exposure to ambient particles. In summary the objectives of our study included the measurement of particle mass and number concentrations arising from laser printers, the assessment of the impact of ventilation on particle spatial and temporal characteristics, and the assessment of human exposure to the particles. We have recommended a method for characterising exposure of office workers to printer generated ultrafine particles. Because this study was primarily one of particle exposure measurement rather than a study of the toxicology of the particles and because the scientific literature is inconclusive regarding the actual toxicity of the particles, guidance rather than recommendations has been provided on selection of particle exposure controls, along with examples of control strategies. Whilst the measurement of particles is relatively simple, what is crucial is the analysis of the data so as to demarcate non-printer particle exposure from printer particle exposure, so as to inform exposure control decisions.

2. Materials and methods

Temporal and spatial particle number and mass concentration was characterised for laser printers operating within office environments in order to estimate particle exposure to office occupants, and importantly to provide guidance on particle exposure control reflective of actual exposure. To achieve this aim, the study was designed to cater for (i) the most common minimum distance between an office worker and a laser printer; (ii) the average breathing zone height of a seated office worker; (iii) the influence of local ventilation upon the transport of particles from the laser printer; (iv) the influence of low, medium, and high emitting printers on particle concentration within an office; (v) differing air movement both within and between office locations; and (vi) background particle number and mass concentrations.

2.1 Instrumentation

Particle number and mass concentration. Three TSI Incorporated (St. Paul, MN) Condensation Particle Counters (CPCs) were used for measurements of particle number concentration: a TSI Model 3025A with a sampling time of 1 second and particle size range of 0.007 - 3 µm was used for continuous measurement of particles from the printers, and a TSI Model 3781 CPC, with a sampling time of 5 seconds, and particle size range of 0.006 - 3 µm was used to measure outdoor particle number concentration. A TSI Model 8525 P-Trak Ultrafine Particle Counter was used to measure total particle number concentration (sample time 1 second) in the size range 0.02 - 1 µm. Particle size distribution in six channels between 0.3 µm to 10 µm was measured by a TSI Model AeroTrak 9306 hand-held optical particle counter (OPC). Particle mass concentration was measured by a TSI Model 8520 DustTrak Aerosol Monitor using a 2.5 µm impactor at the aerosol inlet.
Air temperature, relative humidity (RH) and carbon dioxide (CO_2). These were monitored using a TSI Q-Trak Plus Indoor Air Quality Monitor. This data allowed the identification of the automated start-up and shut-down times of the building ventilation systems.
Air velocity. The velocity of air through room air supply inlet ducts was measured by a TSI Velocicheck Model Anemometer.

The calibration of the three CPC's was checked against a standard CPC in the laboratory prior to conducting the measurements, whilst the OPC and DustTrak had both undergone factory calibration within the previous 12 months.

2.2 Selection of offices and printers

For part one of the study, discrete business units located in five buildings within the central business district of Brisbane, Australia, were selected for particle measurement. 107 laser printers were identified during a walk-through survey of open plan work areas. Since it is known that a large proportion of printers emit low concentrations of particles [1], and in order to reduce unnecessary particle measurement, printers for inclusion in the study were selected based upon: criteria (a) **particle emission status** where a hand-held condensation particle counter (CPC), in this case a P-Trak, was used to measure the PNC arising from the operation of *all* laser printers within the office area of the business unit and at all potential particle emission points of each printer during the printing of a single page. The background office PNC was measured when the printer was not printing and the measurement was then repeated immediately during and after the printer had printed one page. The P-Trak was set to record one data reading per second and the total duration for each test was between 2-3 min. The ratio of the peak PNC, measured during the one page printing event, to the background PNC was calculated. All printers with ratios > 2 were selected for further investigation. This printer emission classification system is in keeping with that used by He et al [1], who used a P-Trak to catalogue printers into four different classes, in terms of the ratio of particle emission concentration to background, including: non-emitters (ratio ≤ 1); low emitters (ratio > 1 and ≤ 5), medium emitters (ratio > 5 and ≤ 10 to background); and high emitters (ratio > 10 to background); and criteria (b) **accessibility** where the trolley containing the measurement equipment was required to be located at the predetermined particle exposure measurement position of 1 m from the printer. Some printers that met criteria (a) had to be excluded because the furniture configuration in the office area would not allow the trolley to be located at this distance. Of the 107 printers assessed, 45 were classified as emitters, with 26 meeting both selection criteria and therefore admitted to this part of the study.

Part two of the study involved selecting two additional printers that meet selection criteria (a), and evaluating the response of handheld instruments, namely the P-Trak, OPC, and DustTrak, to laser printer particles. This measurement data was used to inform our recommendations regarding instrumentation and methodology for characterising laser printer particles at office locations.

The 107 printers included in the initial survey included three manufacturers and of these, 32 printer models.

All buildings were serviced by heat, ventilation and air-conditioning (HVAC) systems with outdoor air entrained into air handling units, filtered, and delivered to each occupied area through central ventilation ducting, along with remixed air. The predominant design of all the office locations was open plan with one laser printer typically shared amongst up to 6 computer work stations in each work pod, with the laser printer/s located amongst the workstations. Such a configuration typically resulted in varying distances between the laser printer and the various computer work stations, ranging from approximately one to three metres. Some laser printers were located in enclosed offices that were connected to the open plan areas by a single doorway.

2.3 Study design

Following observation of the typical distances the initial 107 printers were located from computer work stations, 1 m was identified as a typical minimum distance between an occupant of a computer workstation and a desk-located laser printer. Therefore, part one of the investigation focused upon the potential worst case exposure scenario for office workers defined as a work station at 1 m from an emitting printer. Measurement equipment, consisting of a TSI CPC 3025, DustTrak, and Q-Trak, was therefore located on a trolley one metre away from each laser printer and at an orientation to the printer such that the airflow in the room was most likely to transport particles to the equipment. To assist with this artificial smoke was generated so as to visualise the likely predominant direction particles would move away from the printer. This then allowed the measurement equipment to be located so as to characterise worst case exposure at 1 and 2 m from the printers. The air inlets of the measurement instruments were situated on the trolley at a height of 1.15 m from the floor to represent the height of the mouth/nose (potential entry route of particles to the respiratory system) of a seated office worker.

The height of 1.15 m is the approximate 50th percentile “sitting eye height” anthropometric data of British adults aged 19-65 years [7].

In addition, for five laser printers, a P-Trak was also located at a distance of 2 m from the printer to simultaneously compare PNC at 1 and 2 m from the printer in order to investigate the influence of distance, local ventilation, and dilution upon PNC and office worker exposure.

For an additional printer, particle concentration was measured simultaneously at 0.1 m from the paper exit tray and at one metre from the printer so as to further evaluate the influence of local ventilation upon particle transport.

During part two of the study, for an additional two printers, only handheld instruments were used so as to evaluate the utility of such instruments in characterising the emission and transport of particles arising from the operation of laser printers. A handheld P-Trak and OPC were used to simultaneously characterise PNC in the size range of 20 to 10,000 nm at the printer particle source, and at varying distances from the printers. A handheld DustTrak was also used to characterise particle mass in the size range of less than 2.5 µm (2500 nm).

The instrumentation on the trolley was operated during office hours and also over the previous night to characterise the office hours and 24-hour real-time background PNC. Q-Trak data (changes in temperature and relative humidity) was used to identify the approximate times the HVAC system commenced and stopped operation for each day. For the overnight measurements, as printers were not operating, other likely sources of particle generation such as cleaner activity were identified were possible. Measurements then continued throughout the working day and were stopped at the end of the working day, typically around 4.30pm. As observation of the working patterns of the office workers revealed 8.30am to 4.30pm as being the time period the majority of office workers occupied the offices, this time period was selected for calculation of eight-hour office hour printer particle exposures. During office hours other sources of particle emission, such as the operation of microwave ovens and sandwich toasters, were confirmed using a P-Trak and recorded in a diary.

Initially, persons using each printer were asked to record, on a form located at each printer, the time and number of pages printed for each printing episode. However due to a lack of consistency in such record keeping this changed to the investigator recording this data.

Particle number and mass concentration data was also simultaneously collected using a CPC 3781 and DustTrak located in the plant room through which the office area received its outdoor air intake in order to distinguish between outdoor particle events, and indoor particle emission events such as that arising from the operation of laser printers.

To identify the influence of the air-conditioning system upon the transport of particles the duct face velocity and face area of the air inlet and outlet ducts in the immediate vicinity of the printers, and the distance between the ducts and the printers were measured. Artificial smoke was generated at varying distances between ventilation inlet and outlet ducts and the laser printer so as to visualise and measure the zone of influence of the ducts upon particle movement from the printers. More quantitative data on the operation of the air-conditioning system, such as room air supply volumes, percentage of mixed and outdoor air were not available from the building maintenance managers.

For the purposes of reporting printer measurement results the printers were coded LJ1 through to LJ26 for part one of the study, and LJ27 and 28 for part two.

2.4 Data analysis

All statistical analyses (t-test, and analysis of covariance [ANCOVA]) were conducted using Microsoft Excel, and R (R Development Core Team, 2010). A level of significance of $p = 0.05$ was used for all statistical procedures. When the data was not normally distributed, a robust analysis (trimming off the maximum and minimum) or logarithmic transformation was employed.

3. Results

3.1 Time series of particle number concentrations in the offices

Shown below are several selected time-series plots of the PNC measured as part of the study. These graphs provide data on the ultrafine particle (UFP) and $PM_{2.5}$ mass concentration. The plotted measurement values reflect both the office particle background and the particle concentrations during the discrete print episodes so as to illustrate specific aspects of particle behaviour.

Figure 1 illustrates UFP and $PM_{2.5}$ mass concentration time-series for high-emitting printer LJ17. Concentration peaks for UFP associated with discrete printing events are identified against a steady background of 3.0×10^3 particles cm^{-3}. Concentration peaks exceeded the detection limit of 1.0×10^5 particles cm^{-3} for 6 out of 15 events and varied widely for the events recorded. $PM_{2.5}$ peak values did not differ from the background values and were not associated with print jobs.”

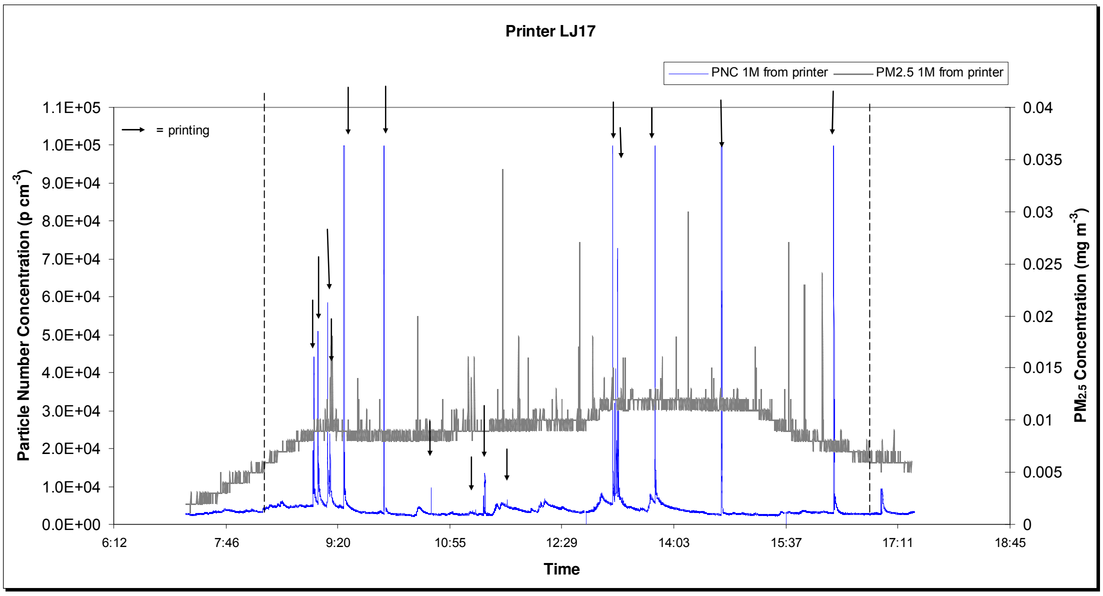

Figure 1: Particle number and mass concentration measured from printer LJ17 which was classified as a high-emitter. The vertical dotted lines demarcate the time period used for calculating office hour particle exposures.

In some offices printer PNC was not distinguishable from background PNC. For example, for printer LJ2, which was classified as a low-emitting printer, the background PNC is seen to fluctuate between about 1.5 x 10^3 particles cm^{-3} and 7.5 x 10^3 particles cm^{-3}. There were nine print jobs during the period under consideration. The PNC peaks during each of these print jobs were relatively small and only just distinguishable over the background. Again, $PM_{2.5}$ peak values did not differ from the background values and were not associated with print jobs. Figure S1 (Supporting Information) shows the corresponding graph for printer LJ2.

The PNC inside the office areas and outdoor was measured simultaneously so as to identify any influence of stronger particle sources upon the indoor PNC. Figure S2 (Supporting Information) shows a comparison of the typical PNC concentration measured over a 24-hour period inside an office, and immediately outdoor the plant room vent that providing outdoor air to the office. The outdoor PNC is clearly higher during the day compared to night and reflects the central business district location of the office with vehicle traffic patterns a major influence on the strength of outdoor PNC. The office background PNC is clearly higher (p-value < 0.01) during office hours compared to overnight. This is because the ventilation system provides outdoor air to the office during office hours compared to at night when the ventilation system is typically not delivering air to the office. Because the building ventilation system typically does not filter all the vehicle particles from the office air supply, office workers are constantly exposed to a background or ambient PNC.

3.2 Contribution of particles from printing activities to the overall office background average particle number concentration

For each printer/office, a time series of the PNC and $PM_{2.5}$ was plotted for the hours 8.30am to 4.30pm. The beginning and end points of each printing peak PNC were identified so as to demarcate the contribution of printer particles from the background PNC. (see Supporting Information Text S1 for further information regarding this).

To determine if there were any differences between the mean CPC data that included and excluded printer PNC peaks, the PNC data during printing and between printing was grouped and a two sample t-test was performed using the means of these groups. Table S1 (Supporting Information) summarises the average PNC at 1 m both with and without the print PNC, and the calculated p-values for all 25 printers. A 5% significance level was used. (see Supporting Information Text S2 for a further description of the t-test)

Of the 25 printers studied, 18 showed a statistically significant increase in PNC associated with printing, at 1 m from the printer, over the background PNC, indicating these 18 printers made a statistically significant contribution to the normal background PNC for that office area.

3.3 Eight-hour time-weighted average exposure of office workers to particles arising from printing activities

In the absence of an exposure standard for laser printer particle emissions an approach needed to be developed so as to evaluate printer particle exposure. Therefore the eight-hour TWA *local background particle exposure* to which office workers are subjected to has been used as the comparative for exposure to laser printer particles. The *local background particle exposure* for each office was calculated by subtracting the average PNC associated with printing from the total PNC for each office hour period and applying an eight hour weighting period.

This eight-hour TWA *local background particle exposure* value, as shown in column nine of Table 1, reflects the exposure to particles arising from <u>non</u>-printer sources such as from vehicle emissions outdoor the building that subsequently infiltrate the building ventilation system and to which the workers in that office are constantly exposed.

In addition, for those 18 printers shown by t-test to contribute significantly to the office background PNC, the eight-hour time-weighted average (TWA) *printer particle exposure* has been calculated for office workers whose computer work station places them at one meter from the printer during their working day, and are summarised in column six of Table 1. This value reflects the printer particle exposure that was additional to the *local background particle exposure* for the office workers. Although the measured values are not personal exposure measurements, the location of the measurement instruments to replicate a seated worker at the computer work stations give a reliable estimate of the maximum average exposure.

Table 1: summary of data used for evaluating peak particle exposure and 30 minute short-term exposure

Printer ID	Total Number of printing events for the 8-hour office hours period	Total number of printing events for which a *peak particle exposure* was > 15 % of background PNC@	Total time period, during 8-hr office hours period, for which PNC associated with print events was elevated above the *local background particle exposure* [minutes]	Total number of pages printed for the 8-hour office hours period	8-hr TWA *printer particle exposure* at one meter from printer [particles cm^{-3}]	Highest *peak particle exposure* of all printing events [particles cm^{-3}]	Median of *peak particle exposure* for all printing events for the office hours period [particles cm^{-3}]	8-hour TWA *local background particle exposure* $^{\Delta}$ [particles cm^{-3}]
LJ1	3	2	1	8	5.1×10^{1}	7.1×10^{3}	4.8×10^{3}	3.0×10^{3}
LJ2	15	8	9	47	6.8×10^{1}	6.9×10^{3}	3.3×10^{3}	3.9×10^{3}
LJ3	9	Cannot distinguish printer events from background PNC		23	Cannot distinguish printer events from background PNC			4.0×10^{3}
LJ4	3	3	2	5	2.4×10^{2}	9.9×10^{4}*	2.3×10^{4}	1.7×10^{3}
LJ5A^	23	23	*50*	129	4.0×10^{3}	9.9×10^{4}*	9.9×10^{4}	2.2×10^{3}
LJ5B^	48	48	*40*	101	1.6×10^{3}	9.9×10^{4}*	9.9×10^{4}	5.8×10^{3}
LJ6	8	7	5	18	#	3.3×10^{3}	2.3×10^{3}	2.2×10^{3}
LJ7	11	3	2	28	#	5.5×10^{3}	4.3×10^{3}	6.5×10^{3}
LJ8	33	21	21	85	8.1×10^{1}	1.2×10^{4}	9.7×10^{3}	8.0×10^{3}
LJ9	39	37	25	116	8.2×10^{1}	8.6×10^{4}	1.4×10^{4}	4.0×10^{3}
LJ10	39	21	22	168	4.1×10^{2}	7.5×10^{3}	6.0×10^{3}	4.8×10^{3}
LJ11	45	30	*32*	143	7.3×10^{1}	9.9×10^{4}*	1.4×10^{4}	3.4×10^{3}
LJ12	13	11	10	73	6.3×10^{2}	1.9×10^{4}	7.5×10^{3}	4.9×10^{3}
LJ13	12	7	8	23	4.3×10^{1}	7.5×10^{3}	4.0×10^{3}	3.6×10^{3}
LJ14	10	8	4	16	#	1.6×10^{4}	5.8×10^{3}	4.1×10^{3}
LJ15	36	36	*33*	92	2.1×10^{2}	2.1×10^{4}	1.1×10^{4}	6.1×10^{3}
LJ16	11	7	12	63	1.5×10^{2}	3.8×10^{4}	2.2×10^{4}	4.0×10^{3}
LJ17	16	22	18	97	6.1×10^{2}	9.9×10^{4}*	5.1×10^{4}	3.6×10^{3}
LJ18	10	9	7	14	#	6.5×10^{3}	2.7×10^{3}	2.5×10^{3}
LJ19	26	11	18	59	1.3×10^{2}	1.9×10^{4}	9.1×10^{3}	4.0×10^{3}
LJ20	25	13	22	133	2.8×10^{1}	6.7×10^{4}	3.0×10^{4}	7.6×10^{3}
LJ21	20	16	*43*	122	3.0×10^{3}	6.4×10^{4}	2.8×10^{4}	1.0×10^{4}
LJ22	24	16	17	55	#	1.7×10^{4}	1.2×10^{4}	1.0×10^{4}
LJ23	15	10	18	38	#	1.7×10^{4}	1.4×10^{4}	1.2×10^{4}
LJ24	19	15	18	42	3.6×10^{2}	5.1×10^{4}	2.2×10^{4}	8.4×10^{3}
LJ25	8	8	5	39	3.4×10^{2}	9.9×10^{4}*	9.9×10^{4}	4.8×10^{3}

@ see text in section 3.2 for explanation of the significance of the 15% value

Δ these values are the exposure to ultrafine particles arising from *non-printer* sources such as from vehicle emissions outdoor the building that subsequently infiltrate the building ventilation system and to which the workers in that office are constantly exposed.

^ this printer was measured on two separate days

* these values represent particle saturation for the CPC so real values are likely higher

Not calculated as printer was shown by t-test to not contribute significantly to the office background PNC

From Table 1 it can be seen that 16 of the eight-hour TWA *printer particle exposures* were less than 20% of the *local background particle exposure*, two were 28% (printers LJ5B and LJ21), and one was 175% (printer LJ5A).

However it is clear that such results are relative to the local background particle concentration for that office area. This is illustrated in the following example.

From Table 1 the eight-hour TWA *printer particle exposure* arising from printer LJ5A was calculated as 4.0 x 10^3 particles cm^{-3}, and the eight-hour TWA *local background particle exposure* as 2.2 x 10^3 particles cm^{-3}, leading to a conclusion that *printer particle exposure* was greater than the *local background particle exposure*. However, had printer LJ5A been operated in an office with a higher eight-hour TWA *local background particle exposure*, for example the office for Printer LJ8 where the eight-hour TWA *local background particle exposure* was 8.0 x 10^3 particles/cm^3, the conclusion would have been that eight-hour TWA *printer particle exposure* was less than the eight-hour TWA *local background particle exposure*.

Clearly, as indicated by the values in Table 1, the eight-hour TWA *printer particle exposures* are a small fraction of the eight-hour TWA *local background particle exposure* indicating that the majority of the average particle exposure experienced by workers in these offices came from sources other than printers, such as vehicle particle emissions infiltrating the building.

3.4 Peak and 30 minute short-term exposure to particles arising from printer activities

For the first time, to evaluate peak exposure to laser printer particles the guidance on general variability in the concentration of airborne substances, as described in the documents *Exposure Standards for Atmospheric Contaminants in the Occupational Environment Guidance Note* [8] and the *Threshold Limit Values for Chemical Substances and Physical Agents* [9], has been utilised in keeping with the normal occupational hygiene approach to such evaluation. Therefore, this novel approach in utilising the guidance in the two documents listed above on excursions of airborne substances above reference concentrations, considers a printing process to not be under reasonable control if:

1. short term exposures exceed three times the eight-hour TWA *local background particle exposure* for more than a total of 30 minutes per eight-hour working day, or
2. a single short term value exceeds five times the eight-hour TWA *local background particle exposure*.

To evaluate peak exposure to particles arising from the operation of laser printers, the data in column seven of Table 1 was calculated.

It can be seen from column seven of Table 1 that a peak greater than the *local background particle exposure* was identified for most printing events. The reason some printer particle emissions were not characterised is because (i) relatively high PNC background in some offices likely occluded the printer

PNC, and (ii) particle emission from laser printers is variable, which has been shown by Morawska et [3] to occur.

No printer particle exposure greater than three times the *local background particle exposure* for a period of ≥ 30 minutes was recorded for any printer. The closest printer particle exposure to this excursion guidance limit was for Printer LJ5A for which total *printer particle exposure* over the eight-hour office period was twice the *local background particle exposure*.

From Table 1 it can been seen that 11 of the printers (LJ4, 5, 9, 11, 16, 17, 19, 20, 21, 24, 25) caused *peak particle exposures* greater than five times the eight-hour TWA *local background particle exposure* . This indicates that at one meter from these printers *peak particle exposure* was in excess of the excursion guidance. In addition, eleven printers (LJ1, 2, 6, 8, 10, 12, 13, 14, 15,18, 23) contributed a *peak particle exposure* at between one and four times the eight-hour TWA *local background particle exposure*. Printer LJ7 was the only printer that contributed a *peak particle exposure* below the eight-hour TWA *local background particle exposure*, whilst the peak particle emission for printer LJ3 could not be distinguished from the *local background particle exposure*.

3.5 Difference in spatial particle exposure at one and two metres from printers

For five printer/offices, a time series of the PNC was plotted for the hours 8.30am to 4.30pm at both 1 and 2 m from the printer and all peaks corresponding to printing episodes were identified.

Figure 2 compares the PNC measured at two distances, 1 and 2 m from printer LJ24. The PNC at the time of each print event at both distances from the printer was higher than the background PNC between printing events. Note that the measurements at 1 m were carried out with CPC 3025A, while those at 2 m were done with a P-Trak. The minimum and maximum measurement size ranges of the two instruments differ. Therefore a correction factor, $F_{P\text{-}Trak}$, for the P-Trak PNC data was calculated (see Supporting Information Text S3 for description of calculation method).

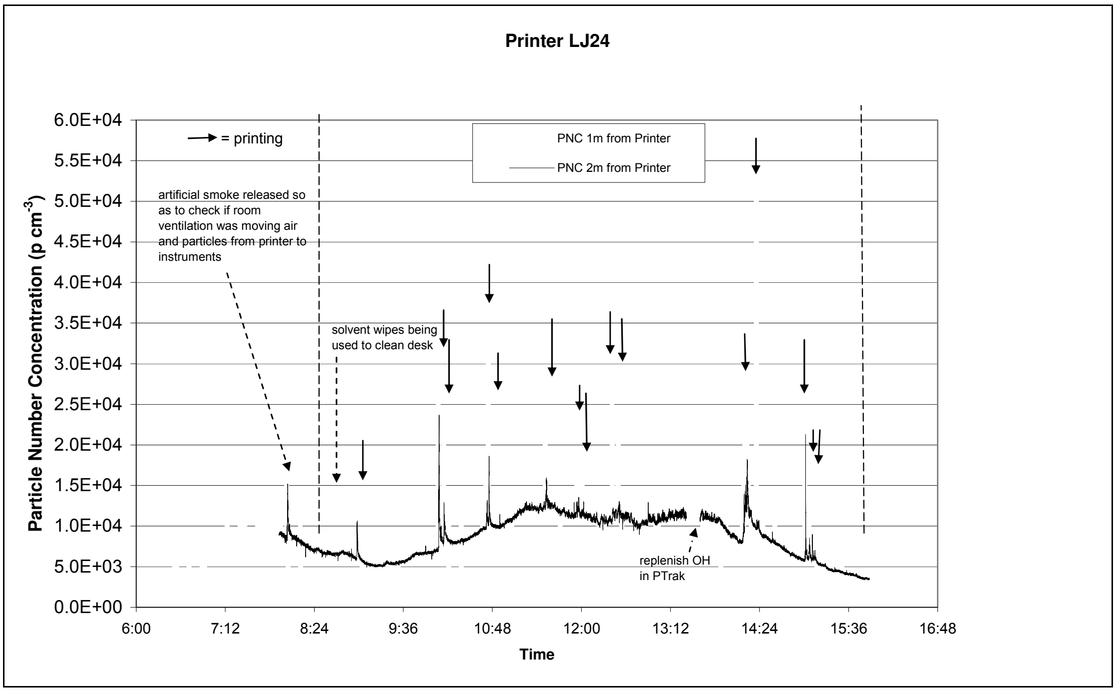

Figure 2: Particle number concentration measured at printer LJ24, a high-emitter. The P-Trak data are $CTC_{P\text{-}Trak}$ *values*. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

Figure 2 clearly shows that the peak particle exposure at 1 m as measured with CPC 3025A was greater than that at two metres as measured with the P-Trak. The figure also shows a clear difference in the heights of the PNC peaks during the print episodes with the peak particle exposure at 1 m being up to an order of magnitude greater than at 2 m. The difference in particle number concentration was due to the distance.

To determine if the PNC corresponding to each print event was statistically different to the *local background particle exposure*, the beginning and end points of each PNC printing peak was identified. Table S2 (Supporting Information) provides the p-value results for the t-test of any differences between 1) the mean PNC including printer particles, and 2) the mean PNC with printer PNC subtracted, at both one and two metres from five printers. The corrected P-Trak values, $CTC_{P\text{-}Trak}$ have been used to inform these differences in spatial PNC associated with printing.

Of these five printers, three (LJ5B, LJ21, LJ24) showed a statistically significant increase in particle exposure associated with printing over the *local background particle exposure*, at both 1 and 2 m indicating that at both distances from the printer the *printer particle exposure* was greater than the *local background particle exposure*. For Printer LJ22 the *printer particle exposure*, at both one and two meters, was not statistically significant and this result reflects the influence of the relatively high *local background particle exposure* for this office.

For Printer LJ23, *printer particle exposure* was statistically significant at two meters but not at one meter. The reason for this is likely due to the influence of local ventilation conditions that may have dispersed the particles predominantly to the position of the P-trak at two metre location in contrast to the CPC 3025 at the 1 m location.

The *printer particle exposure* is lower at 2 m than at 1 m (p-value <0.01) for printers LJ 21, 22, and 24 reflecting the spatial change over the 1 m distance. However, for printer LJ5B the *printer particle exposure* at 2 m is higher (p-value <0.01) than at 1 m. This is because printer LJ5B emitted high particle concentrations resulting in the CPC 3025A located at a distance of 1 m experiencing particle saturation at 1.0×10^5 particles cm^{-3} for nearly every printing event, whilst the P-Trak located at the 2 m distance registered higher PNC associated with the same printing events because of its higher particle saturation point. This also indicates that the *printer particle exposure* associated with printing at 1 m was likely to be much higher than that recorded by the CPC 3025A.

3.6 Utility of hand-held instruments to characterise the particles

In order to assess the utility of hand-held particle instruments in characterise particle number, mass, and size across the submicrometre and supermicrometre range, the PNC emission for two printers, coded as printers LJ27 and LJ28, were measured simultaneously using an Optical Particle Counter (OPC), P-Trak, and DustTrak. Figure S3 (see Supporting Information) illustrates the real-time PNC size response for printer LJ28 in the particle bin sizes of 20 to 1000 nm (as measured by the P-Trak), 300 to 500 nm and > 500 nm (as measured by the OPC). PNC > 300 nm was extremely low and not associated with print events, whilst PNC recorded by the P-Trak was four orders of magnitude higher and associated with print events. This indicates the predominant particle size associated with printing is less than 300 nm and concurs with the findings of Morawska et al [3] who concluded the particle size range associated with printing was within the ultrafine particle size range.

This finding of insignificant particle size in the supermicrometre size range is supported by Figures 1 and 2 which show typical printer $PM_{2.5}$ values do not differ significantly from background and are not associated with print jobs.

The findings also indicate a hand-held P-Trak (or similar CPC) can be used to characterise particle emission arising from the operation of laser printers.

3.7 Effect of type of printing upon particle number concentration

To determine if the variation in the *peak printer emission* can be explained using selected explanatory variables an analysis of covariance (ANCOVA) model was conducted (See Supporting Information Text S4 for further description of the ANCOVA method).

Colour was the only significant variable found to explain the variation in peaks of printer emissions based on the ANCOVA, with the colour printing modes associated with higher PNC than black printing. All other variables, and the interactions between these variables, were also tested for their impact on PNC values. The ANCOVA showed them to be insignificant and thus not useful in explaining the variation on maximum PNC value.

This indicates that the factors contributing to particle emission from printers are more complex than these variables and supports the conclusions from Morawska et al [3] that the causes are complex in nature. Qualitative analysis of the PNC associated with colour printing for the two printers with colour printing ability revealed peak PNC > than 1.0×10^5 particles cm^{-3} for each colour print event.

4.0 Discussion

The results of the experiments conducted upon 28 printers classified as particle emitters and located in open plan work areas of the five buildings will now be combined to address the key questions related to the exposure of office workers to ultrafine particles.

4.1 What are the sources of particle exposure to office workers within office environments?

The measurement data clearly showed office workers are continually exposed to a background PNC within their office environment, predominantly within the ultrafine size range. All eight-hour time-weight average (TWA) *printer particle exposures* except one were below the eight-hour TWA *local background particle exposure* for each office area, indicating that the majority of the average ultrafine exposure experienced by workers in these offices over the course of a working day came from sources other than printers, such as vehicle emissions infiltrating the building.

The study identified that not all printers were sources of particle emission in concentrations significantly greater than background. Morawska et al [3] concluded that the difference between a high and low emitting printer lies in the speed and sophistication of the temperature control. However during the course of a working day, some printers are sources of peak particle exposure at both one and two metres from the printers in concentrations statistically greater than the background, with the total printer particle exposure directly influenced by the duration and frequency of printer events and the position of the printer relative to occupied work stations.

4.2 What impact does local ventilation have upon laser printer particle exposure?

The ventilation provided by HVAC systems was found to have delayed influence on diluting the PNC arising from printer emissions, except in one case where an unusually high air velocity at the face of an inlet grill directed toward a printer had an immediate effect. However because the typical grill face velocity range is in the range of 0.2 to 0.5 m/s and are usually many metres above the printer, there is general lack of immediate ventilation influence on the particles. This is not surprising as HVAC systems are designed to provide a gradual replacement of office air with filtered air and are not designed as mechanical dilution ventilation systems. The release of artificial smoke revealed particles were found to disperse upwards from the printers and to fan out in fairly uniform pattern in all directions from the printer and to disperse from sight over the distance of approximately 1 to 2 m, reflecting dilution within the air volume of the office area.

The exception to this was with Printer LJ20 where the release of smoke at the printer resulted in immediate movement in a direction away from the inlet grill. The configuration of the office in which printer LJ20 was located was such that the occupied computer work station was located *between* the printer and the unusually high velocity inlet ventilation grill, with the inlet grill approximately two metres on one side of the computer work station, and the printer approximately one metre from and on the opposite side of the computer work station. For this printer a P-Trak was positioned for several hours at 0.1 m from the paper exit tray of the printer, and the CPC 3025 at the computer workstation (one metre from the printer), both in a straight line with the inlet grill. The result indicates that whilst a PNC of up to almost 7.0×10^4 particles cm^{-3} was generated during printing events, the particles were not transported to the computer work station 1 m from the printer and “upwind” from the printer. The results of these simultaneous real time measurements are graphed in Figure S4 (Supporting Information).

4.3 What criteria should be used in controlling particle laser printer particle exposure?

Although little direct toxicological data exists regarding ultrafine particles associated with laser printer operation, there is a wide body of literature regarding the link between ultrafine particles in general and cardiovascular and respiratory health effects [10, 11]. Health based arguments for controlling the *local background particle exposure* of office workers in addition to particle exposure arising from the operation of laser printers are contained within the scientific literature [12, 13]. Therefore consistent with a precautionary approach, exposure to ultrafine particles in general and those arising from the operation of laser printers should be controlled.

We propose that peak particle exposure relative to five times the local particle background exposure be used to guide particle exposure control decisions. Average printer particle exposure is not useful for the reasons provided in section 4.1.

Airborne particles are abundant within the environment and arise from both natural and anthropogenic sources. Therefore our finding of a constant non-printer local background particle exposure to office workers is therefore not surprising.

However, an important finding from our measurement data is the order of magnitude difference in such background particle exposure amongst the 5 office locations.

Options for establishing a particle reference value that will guide exposure control decisions include establishing a single particle reference value based upon the office eight-hour TWA local background particle exposures using (i) the median value of a representative sample of office locations; or (ii) the value from each individual office.

Common to both these options is the need to ensure the operation of the office ventilation system consistently achieves the target local background particle exposure. This will achieve two things. One, ensuring *local background particle exposure* of occupants of all office workplaces is consistent, minimised, and given equal priority to that of particle printer emission; and two, providing a stable background particle concentration upon which to evaluate printer particle emission.

> Option (i) involves adopting peak particle reference values limiting exposure at the occupied work stations to below a peak particle exposure concentration of 2.0×10^4 particles cm^{-3}, and 1.2×10^4 particles cm^{-3} as averaged over any 30-minute period. This proposal is based upon three concepts:

1) the guidance on general variability in the concentration of airborne substances, as described in the document *Exposure Standards for Atmospheric Contaminants in the Occupational Environment Guidance Note* [8], which can be interpreted such that printer particle exposure controls may be required in the following circumstances:

   - Where the 30 minute short-term printer particle exposures exceed three times a *particle reference value* for more than a total of 30 minutes per eight-hour working day, and/or where a single peak value exceeds five times a *particle reference value*.

2) A *particle reference value* of 4.0 x 10^3 particles cm^{-3}, which is the median value of the *local background particle exposures* estimated for the 25 office environments included in this study. As such this is not a health based standard but rather reasonably precautionary guidance based upon the typical office (non-printer related) background particle exposures.

3) The absence of a universal *particle reference value* or National Exposure Standard for nanoparticles arising from the operation of laser printers.

Option (ii) involves adopting a particle reference value for each office, based upon the local background non-printer particle exposure for each office, and implementing exposure controls in accordance with the guidance on general variability in the concentration of airborne substances [8] outlined above.

As both these options require particle measurement to be conducted a third option is to skip measurement and implement exposure controls as outlined below.

4.4 What particle exposure control options could be used?

In line with a precautionary approach, where the *particle reference values* are exceeded or likely to be exceeded, the following exposure control options are available: (a) Replace the laser printer with a lower emitting printer such that exposure at the occupied work stations is below the excursion criteria; (b) Move the printer such that distance, frequency of exposure, and/or local ventilation conditions dilute the printer particles before they reach a PNC at the occupied work station in excess of the excursion criteria. Examples of such include: Locating the printer in proximity to a ventilation inlet or outlet grill. The release of artificial smoke can aid in visualising local air movement. Note the potential movement of the printer should not then result in printer particles increasing exposure to occupants of other work stations; reducing the number of laser printers located amongst work stations and locating remaining laser printers in a dedicated printer room, or an area of the office a sufficient distance away from occupied work stations. Ideally the local ventilation to either of these areas should have a higher flow rate so as to provide a greater fresh air velocity to the area compared to the rest of the office. Printer manufacturers also have a role to produce new generations of printers with negligible particle emissions.

4.5 What instrumentation can be used to characterise particle exposure?

The study showed that the airborne particle size within the offices was predominantly < 300nm. This finding is supported by that of Morawska et al [3] who concluded that the initial count median diameter of submicrometre particles during a print run was approximately 63 nm, which gradually decreased to approximately 28 nm. Comparison of the data in columns one and two of Table 1 shows that 79% of print events where characterised by both the use of a CPC and the measurement method utilised. Therefore the use of a CPC that has a lower particle measurement range of ≤20 nm can be used to characterise laser printer particle exposure within office environments. Spatial variations in particle exposure should be accounted for by ensuring measurements are conducted at worker breathing zone height and location when seated at work stations.

Literature Cited

1. **He, C.; Morawska, L.; Taplin, L.; Particle emission characteristics of office printers. *Environmental Science and Technology*, 2007. *41*(17); 6039-6045.**
2. **He, C.; Morawska, L.; Wang, H.; Jayaratne, R.; McGarry, P.; Johnson, G.; Bostrom, T.; Gonthier, S.; Ayoko, G.; Quantification of the relationship between fuser roller temperature and laser printer emissions. *Journal of Aerosol Science*, 2010. *41*; 523-530.**
3. **Morawska, L.; He, C.; Johnson, G.; Jayaratne, R.; Salthammer, T.; Wang, H.; Uhde, E.; Bostrom, T.; Modini, R.; Ayoko, G.; McGarry, P.; Wensing, M.; An Investigation into the Characteristics and Formation Mechanisms of Particles Originating from the Operation of Laser Printers. *Environmental Science and Technology*, 2009. *43*(4); 1015 -1022.**
4. **Destaillats, H.; Maddalena, R.; Singer, B.; Hodgson, A.; McKone, T.; Indoor pollutants emitted by office equipment: A review of reported data and information needs. *Atmospheric Environment*, 2008. *42*; 1371-1388.**
5. **Koivisto, A.; Hussein, T.; Niemela, R.; Tuomi, T.; Hameri, K.; Impact of particle emissions of new laser printers on modelled office room. *Atmospheric Environment*, 2010. *44*; 2140-2146.**
6. **Hanninen, O.; Bruske-Hohlfeld, I.; Loh, M.; Stoeger, T.; Kreyling, W.; Schmid, O.; Peters, A.; Occupational and consumer risk estimates for nanoparticles emitted by laser printers. *J Nanopart Res*, 2010. *12*; 91-99.**
7. **Grandjean, E., *Problems of Body Size*, in *Fitting the task to the man: a textbook of occupational ergonomics*. 1988, Taylor & Francis: London.**

8. *Exposure Standards for Atmospheric Contaminants in the Occupational Environment - Guidance Note [NOHSC:3008(1995)]*, National Occupational Health and Safety Commission, Editor, Australian Government Publishing Service: Canberra.

9. The American Conference of Governmental Industrial Hygienists, *Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices*. 2010, Signature Publications.

10. Delfino, R.; Sioutas, C.; Malik, S.; Potential Role of Ultrafine Particles in Associations between Airborne Particle Mass and Cardiovascular Health. *Environmental Health Perspectives*, 2005. *113*; 934-946.

11. Pope, C.; Burnett, T.; Thurston, G.; Thun, M.; Calle, E.; Krewski, D.; Godleski, J.; Cardiovascular Mortality and Long-Term Exposure to Particulate Air Pollution: Epidemiological Evidence of General Pathophysiological Pathways of Disease. *Circulation*, 2004. *109*; 71-77.

12. Knol, A.; de Hartog, J.; Boogaard, H.; Slottje, P.; van der Sluijs, J.; Lebret, E.; Cassee, F.; Wardekker, A.; Ayres, J.; Borm, P.; Brunekreef, B.; Donaldson, K.; Forastiere, F.; Holgate, S.; Kreyling, W.; Nemery, B.; Pekkanen, J.; Stone, V.; Wichmann, H.E.; Hoek, G.; Expert elicitation on ultrafine particles: likelihood of health effects and causal pathways. *Particle and Fibre Toxicology*, 2009. *6*(19).

13. Weichenthal, S.; Dufresne, A.; Infante-Rivard, C.; Indoor ultrafine particles and childhood asthma: exploring a potential public health concern. *Indoor Air*, 2007. *17*; 81-91.

Supporting Information – for uploading separately to main article

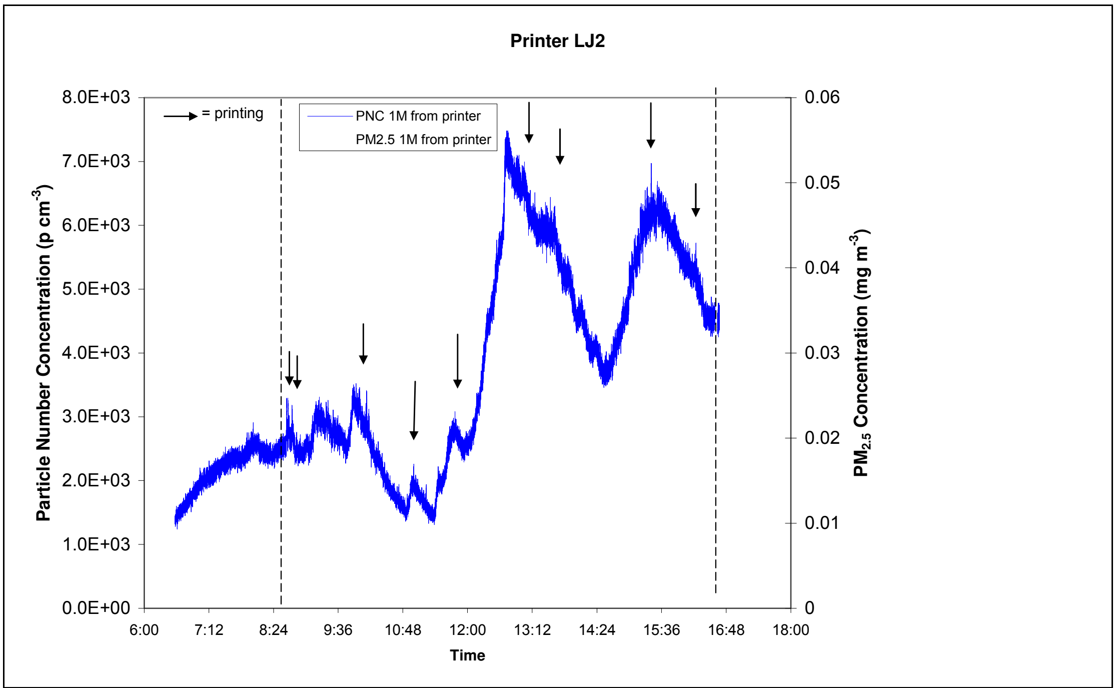

Figure S1: Particle number and mass concentration measured from printer LJ2 which was classified as a low-emitter. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

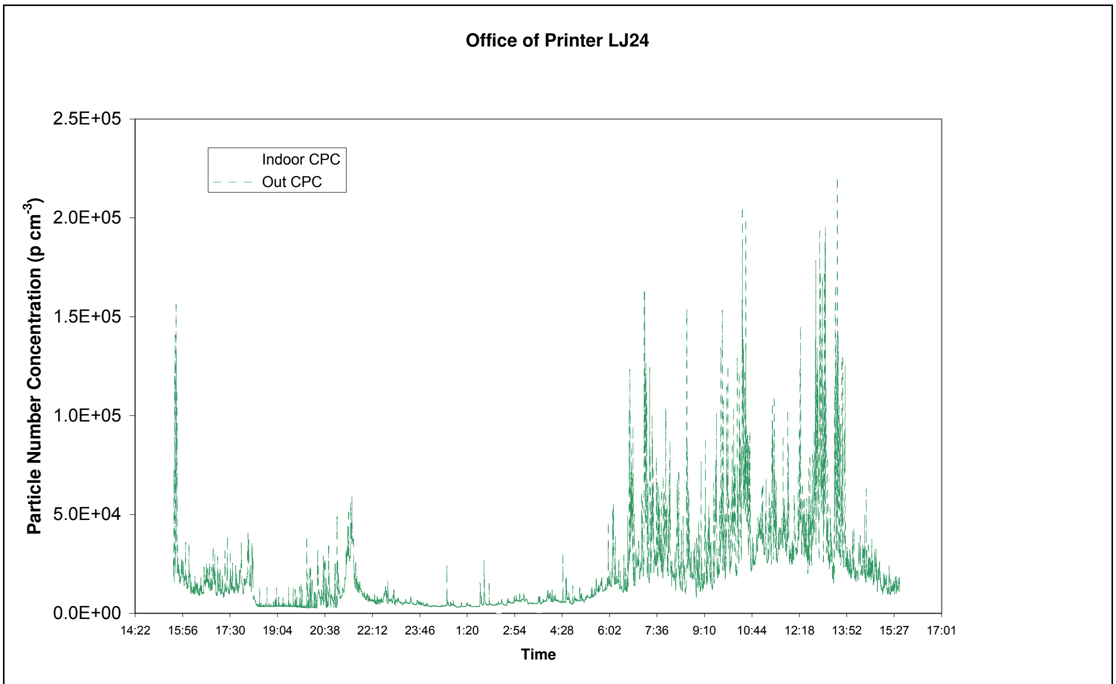

Figure S2: Comparison of indoor and outdoor particle number concentration for a 24 hour period

Supporting Information Text S1

The beginning time of the printing peak was identified by the sharp and sudden rise from background in the PNC associated with each print episode. In general, the measured PNC increased to its maximum value within five seconds and then decreased slowly over a period that ranged from about one to four minutes.

For some printers there was no obvious peak in PNC on the real-time data graph associated with the print times recorded on the log sheet. Therefore in order to capture all peak PNC associated with printing events, increases in PNC of 15% or more than the background immediately preceding the recorded printing time were counted as contributing to the total printing PNC. A time series sample was taken for five printers and the ratio of one standard deviation of the background PNC to the average of the background PNC was calculated. This ratio, the coefficient of variation, was found to be consistently 0.05 (or 5%) for these printers. This shows that the variability of these five printers is similar. Furthermore, increases of 15% or more are outdoor three standard deviations of the mean for the printers, indicating that less than 1% of CPC measurements not relating to printing will be included as being related to printing jobs (assuming background PNC is normally distributed).

The end of the printing peak PNC was determined visually as the time at which the PNC first attained an approximate steady value over several seconds or when it drew level with the previous background value, whichever came first.

The determination of this end point, naturally, involved some uncertainty. In order to quantify this procedure, a time series sample with five print jobs was selected. For each of these printer PNC peaks, the end point cut-off was defined as the time at which the printer-induced PNC fell back to 2% of its pre-peak value. The average PNC values for (i) the entire data set and (ii) the data set excluding the printer PNC peak values, defined by the 2% cut-off, were calculated. These values were found to be very close, well-within 1%, of the corresponding values calculated from the manual identification method described in the previous paragraph. As such, the manual method was adapted for all the data analysed.

Table S1: Average PNC at one metre from printers with and without print PNC and associated p-values, plus 8-hr TWA printer particle exposure calculations

Printer identification code	t-test p-values	Average total office hours PNC including particle contribution from printing events [particles cm^{-3}]	Average office hours PNC with printer PNC subtracted (= office hours 8-hr *local background particle exposure*) [particles cm^{-3}]	Sample period
LJ1	*0.01*	3.1×10^3	3.0×10^3	08:30-16:30
LJ2	*<0.01*	4.0×10^3	3.9×10^3	08:30-16:30
LJ3	0.99	4.0×10^3	4.0×10^3	08:36-16:30
LJ4	*<0.01*	1.9×10^3	1.7×10^3	08:30-16:25
LJ5A*	*<0.01*	6.3×10^3	2.2×10^3	08:30-16:36
LJ5B*	*<0.01*	7.6×10^3	5.8×10^3	08:30-15:59
LJ6	0.60	2.2×10^3	2.2×10^3	08:30-16:27
LJ7	0.93	6.5×10^3	6.5×10^3	08:30-15:59
LJ8	*<0.01*	8.1×10^3	8.0×10^3	08:30-16:18
LJ9	*<0.01*	4.1×10^3	4.0×10^3	08:30-15:42
LJ10	*<0.01*	5.2×10^3	4.8×10^3	08:30-16:27
LJ11	*<0.01*	3.5×10^3	3.4×10^3	08:30-16:05
LJ12	*<0.01*	5.5×10^3	4.9×10^3	08:30-16:30
LJ13	*<0.01*	3.6×10^3	3.6×10^3	08:30-12:43
LJ14	0.49	4.1×10^3	4.1×10^3	08:30-16:32
LJ15	*<0.01*	6.3×10^3	6.1×10^3	08:30-16:30
LJ16	*<0.01*	4.2×10^3	4.0×10^3	08:30-16:30
LJ17	*<0.01*	4.2×10^3	3.6×10^3	08:30-16:29
LJ18	0.14	2.5×10^3	2.5×10^3	08:38-16:30
LJ19	*<0.01*	4.2×10^3	4.0×10^3	08:30-16:30
LJ20	*<0.01*	7.6×10^3	7.6×10^3	13:14-15:32
LJ21	*<0.01*	1.3×10^4	1.0×10^4	08:30-16:29
LJ22	0.29	1.0×10^4	1.0×10^4	08:30-15:48
LJ23	0.94	1.2×10^4	1.2×10^4	08:30-15:45
LJ24	*<0.01*	8.8×10^3	8.4×10^3	08:31-15:52
LJ25	<0.01	5.2×10^3	4.8×10^3	08:30 -16:27

Supporting Information Text S2

For the Student t-test the CPC data was log transformed to ensure the normality assumption of the test was valid. The t-test is such that unequal variance between the two samples is assumed. The t-test assumes independence between samples whereas in this case the CPC data not associated with printing is found in both samples. A two sided t-test was conducted i.e.

$$H_0 : \mu_{all} = \mu_{no\_peaks}$$

$$H_1 : \mu_{all} \neq \mu_{no\_peaks} .$$

At the 5% significance level, those printers with p-values < 5% from the associated t-tests are deemed to have significantly contributed to the office background.

Table S2: Average PNC at 1 and 2 metres from printers with and without print PNC, and t-test p-values

Printer identification code	One metre			Two metres			Sample period
	t-test p-values (of columns 3 & 4)	Average total office hours PNC including printer PNC values [particles cm^{-3}]	Average PNC with printer PNC values subtracted [=*local background particle exposure*] [particles cm^{-3}]	t-test p-values (of columns 6 & 7)	Average PNC including printer PNC values [particles cm^{-3}]	Average PNC with printer PNC values subtracted [=*local background particle exposure*] [particles cm^{-3}]	
Printer LJ5B	*<0.01*	7.6 x 10^3	5.8 x 10^3	*<0.01*	8.5 x 10^3	5.4 x 10^3	8:30 – 15:59
Printer LJ21	*<0.01*	1.3 x 10^4	1.0 x 10^4	*<0.01*	1.2 x 10^4	1.0 x 10^4	8:30 – 16:22
Printer LJ22	0.29	1.0 x 10^4	1.0 x 10^4	*0.12*	9.9 x 10^3	9.9 x 10^3	8:30 – 15:48
Printer LJ23	0.94	1.2 x 10^4	1.2 x 10^4	*<0.01*	1.2 x 10^4	1.1 x 10^4	8:30 – 15:46
Printer LJ24	*<0.01*	8.8 x 10^3	8.4 x 10^3	*<0.01*	8.6 x 10^3	8.5 x 10^3	8:30 – 15:52

The slight difference in background PNC at one and two metres likely reflects the spatial influence of the office ventilation system between printing events. However the temporal differences associated with printing events at both one and two metres are statistically significant reflecting the strength of the printers as sources of particles compared to other office particle sources.

Supporting Information Text S3

$$F_{P-Trak} = \frac{TC_{P-Trak}}{TC_{CPC3025}} \qquad \text{Eq.2}$$

where $F_{P\text{-}Trak}$ is the correction factor for the P-Trak, and $TC_{P\text{-}Trak}$ and $TC_{CPC3025}$ are the total number concentrations measured by the P-Trak and CPC 3025, respectively, during selected periods for the printer emission measurements.

The corrected measurements for the P-Trak readings were then calculated as:

$$CTC_{P-Trak} = \frac{TC_{P-Trak}}{F_{P-Trak}} \qquad \text{Eq.3}$$

where, $CTC_{P\text{-}Trak}$ is the corrected total number concentration P-Trak data.

A $F_{P\text{-}Trak}$ correction factor of 0.78 was calculated for the P-Trak using ambient particle concentration time series data with both CPC's operated simultaneously and side by side. All P-Trak data is presented as the $CTC_{P\text{-}Trak}$.

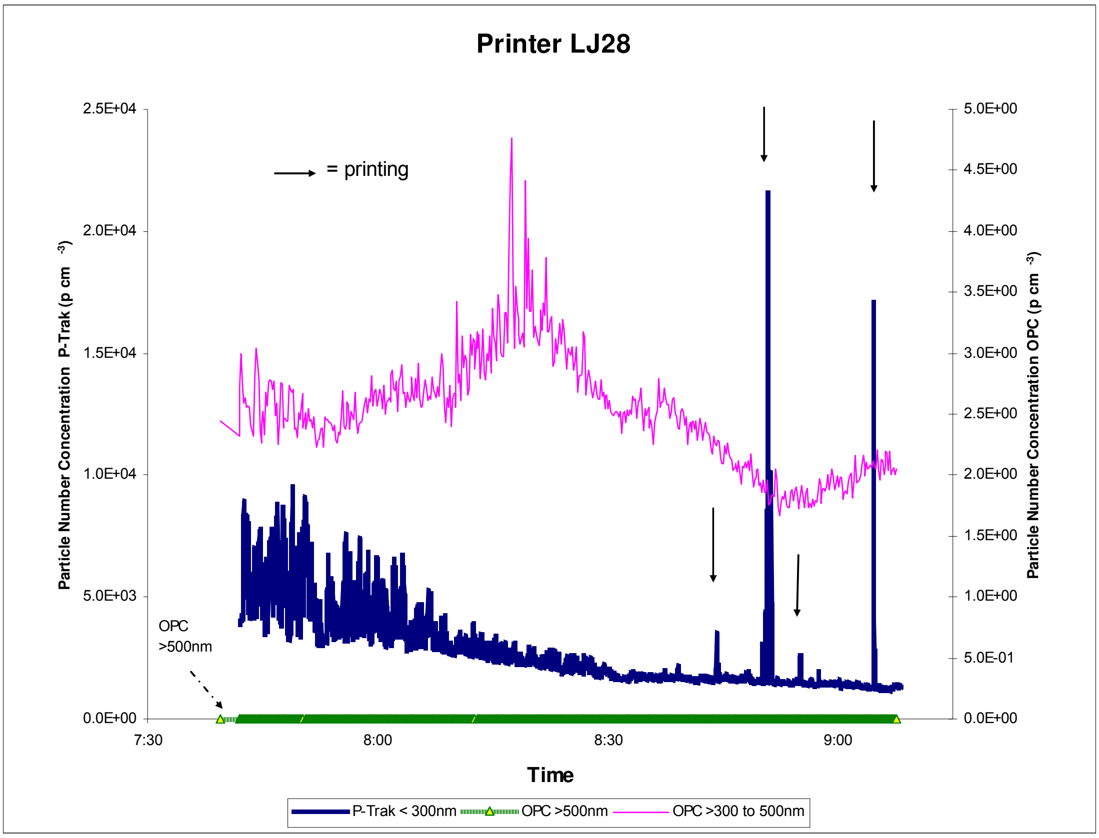

Figure S3: Supermicrometre and submicrometre particle number concentration. The PNC > 300nm recorded by the OPC does not change in response to recorded printing events in contrast to the PNC < 300nm as recorded by the P-Trak. The higher PNC > 300nm for period prior to 8.30am reflects the ventilation system starting up for the day and automatically venting the room with outdoor air.

Supporting Information Text S4

The dataset consisted of variables associated with emissions during printing jobs. The six variables used were:

- Peak – the maximum PNC value from the printing job.
- Printer – which of the 25 sampled printers the peak is associated with.
- Type – whether the printer is classified as a high, medium or low emitter.
- Colour – whether the print job was colour or black and white.

- Sided – whether the print job was single or double sided.
- Pages – the number of pages in the print job.

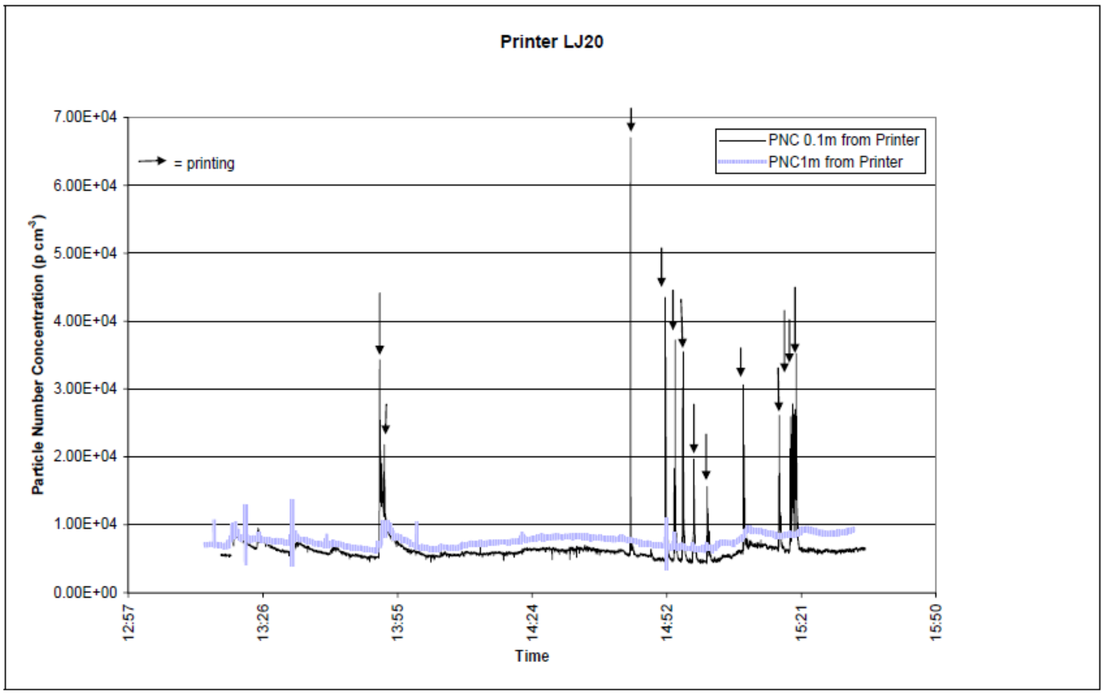

Figure S4: Influence of office local ventilation upon the movement of printer particles.