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Microplastics in the surgical environment

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ABSTRACT

Atmospheric microplastics (MPs) have been consistently detected within indoor and outdoor air samples. Locations with high human activity are reported to have high MP levels. The aim was to quantify and characterise the MPs present within the surgical environment over a one-week sampling period. MPs were collected in samplers placed around an operating theatre and adjoining anaesthetic room at 12 h intervals. Particles were filtered onto 0.02 μm membranes and analysed using micro-Fourier-transform infrared spectroscopy. The number of MPs identified during the working day sampling period varied, with a mean of 1,924 ± 3,105 MP m^{-2} day^{-1} and a range of 0 – 9,258 MP m^{-2} day^{-1} observed in the theatre, compared with a mean of 541 ± 969 MP m^{-2} day^{-1} and a range of 0 – 3,368 MP m^{-2} day^{-1} for the anaesthetic room. Across both rooms and at all sampling points, an increase in levels with a decrease in MP size was observed. Identified particles consisted of mainly fragment shaped MPs (78 %) with polyethylene terephthalate (37 %), polypropylene (25 %), polyethylene (7 %) and nylon (13 %) representing the most abundant polymer types. MPs were not detected in the theatre during non-working hours. The results provide novel information on defining polymer levels and types, in a room environment where the use of single plastics has been regarded as beneficial to practice. These results can inform cellular toxicity studies, investigating the consequences of human MP exposure as well as represent a potentially novel route of exposure for humans for this emerging contaminant of concern, via surgery.

1. Introduction

Microplastics (MPs) are typically defined as plastic particles of a size range from 1 μm to < 5000 μm/5 mm (Frias and Nash, 2019). With the rise in plastic usage globally, MPs have been detected ubiquitously including in the outdoor (Hidalgo-Ruz et al., 2012; Hale et al., 2020; Chen et al., 2020) and indoor environments (Jenner et al., 2021), as well as in foodstuffs meant for human consumption (for review (Danopoulos et al., 2020) and drinking water (for review: (Danopoulos et al., 2020).

Recent research has also reported the presence of MPs in human tissue samples, including cadaver (Amato-Lourenço et al., 2021) and living lung (Jenner et al., 2022), blood (Leslie et al., 2022) and colon (Ibrahim et al., 2021). Detection in such tissues have been attributed to exposure for humans via gastrointestinal ingestion and atmospheric inhalation (Domenech and Marcos, 2021). The presence of MP in colonic tissue and faeces can be attributed to degradation and subsequent direct contamination from packaging (e.g. drinking water and food) or by trophic transfer to humans, via diet such as seafood: crustaceans and molluscs, which take up MPs from contaminated water (Carbery et al., 2018). Emerging evidence has also demonstrated MP contamination in fruits and vegetables (Oliveri Conti et al., 2020). Globally, it has been estimated that humans could ingest up to 5 g of MPs weekly (Senathirajah et al., 2021). Inhalation of MPs into the respiratory system and subsequent detection in lung tissue likely results from atmospheric particles with a primary source identified as polymer textiles (Amato-Lourenço et al., 2021; Pimentel et al., 1975). Inhalation can also provide downstream gastrointestinal ingestion mediated by the mucociliary escalator (Lippmann et al., 1980), whereby inhaled particles of larger size are transported from the respiratory tract by cilia to the upper airways and swallowed. Detection of MPs in blood suggests absorption from the mucosa to the blood stream within the lungs and/or gastrointestinal tract (Leslie et al., 2022). The role those mucosal environments play in this process have yet to be determined in humans (Hussain, 2001). More recent evidence, albeit representing small sample

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sizes, suggest that downstream deposition of MPs in organs (such as liver, kidney and spleen) is also a possibility (Horvatits et al., 2022).

The biological impacts of MP exposure investigations using human cell and tissue approaches have started to be characterised; with inflammatory and oxidative stress type responses reported (for review: (Danopoulos et al., 2022). The clinical implications of MPs within the human body have yet to be fully determined. New evidence is starting to emerge however, for example, MP concentrations in inflammatory bowel disease sufferers' faeces was determined to be significantly higher than healthy individuals (Yan et al., 2021). Although not a proven causality, such pathologies that are influenced by the outside/inside world interface (i.e. the gastrointestinal mucosa and the luminal contents), raises interesting avenues of questioning regarding the potential health hazards of MPs (Tyler et al., 2016).

Plastics are not only ubiquitous in everyday lives but also form a core part of medical equipment. A vast amount of medical equipment used in the general hospital environment is either made from plastic or comes in plastic wrapping (Harding et al., 2021; Lee et al., 2002; McGain et al., 2008). The SARS-CoV-2 (COVID-19) pandemic also resulted in increases in personal protective equipment usage, predominantly made from plastics (Harding et al., 2021). The development of plastic was revolutionary for the medical world since it provided single use equipment that optimised sterility to ensure patients are protected against infective agents. Plastic wastage is a significant global issue and that also applies within the health care setting. For instance, it has been estimated that the UK National Health System (NHS) contributed over 130,000 tonnes of plastic waste annually with a recovery rate of only 5 % (NHS England, 2019; NHS Scotland, 2017). As a result, NHS England enacted the 'Single-Use Plastics Reduction Campaign Pledge' in 2019 to take steps to tackle this issue and NHS Scotland has made similar pledges (NHS England, 2019; NHS Scotland, 2017). An environment which sees a particularly concentrated amount of equipment are surgical environments, particularly operating theatres. Being comparatively small rooms with concentrated use of single-use plastic equipment it is plausible that MP generation is very high. Furthermore, since many surgical procedures require incisions and exposure of internal body tissues to the external environment, the content of the atmosphere is therefore an important area for quantification. While studies have looked at atmospheric MP content in the home indoor environment, revealing high levels, with a mean value of 1,414 ± 1,022 across 20 households of contamination (Jenner et al., 2021), the hospital/surgical environment has yet to be investigated. Much attention has been paid to the atmospheric quality in the operating environment with particular concern of surgical site infections (SSI) (Tan et al., 2021) and surgical smoke effects on theatre staff (Mowbray et al., 2013). With the growing evidence regarding MP exposure and cellular level impacts, the aims of this study were to therefore:

a) Determine and compare MP abundance in both the operating theatre and adjoining anaesthetic room.
b) Determine the MP type profile in these environments and correlate this to potential theatre sources.
c) Determine the MP parameters including size and shape to ascertain the distribution of potentially clinically significant MPs.
d) Compare MP abundance during working hours and non-working hours.

The rationale for comparing the operating theatre and anaesthetic room was based on the hypothesis that if MPs are originating from the use of single use plastic products, the relatively equipment intense operating theatre should have a greater abundance of MP compared with the anaesthetic room. To further test this hypothesis, working and non-working hours were compared where the expected abundance of MPs would be greater during the hours plastic equipment is being used.

2. Methods

2.1. Pre-Sampling preparation

The methodology for detecting and characterising atmospheric MP content has been employed and validated in previous indoor and outdoor studies (Jenner et al., 2021; Jenner et al., 2022; Jenner et al., 2022) (Fig. 1). Briefly, 1 L volume glass sampling beakers (with an equivalent base surface area of 0.0095 m^2) were prepared. To eliminate possible background MP contaminants, beakers were hand washed with water, placed in a distilled water dishwasher for 30 min with detergent (Lombard P10 powder detergent) at 70–75 degreesC, and finally, rinsed three times with triple-filtered (using glass fibre (GF6) filters, GE Healthcare Life Sciences, Marlborough MA, U.S.A.) distilled water. Aluminium foil was used to tightly seal each beaker during periods where the glassware was not in use and at the end of preparation. All preparation, outside of the dishwasher, took place within a fume cupboard and undertaken by the same researcher to ensure preparation standardisation.

2.2. Sample collection

Covered prepared sampling beakers (n = 28) were transferred to a tertiary teaching hospital. At the start of the sampling period, a single beaker (n = 1) was placed at eye level (approximately 1–1.8 m) on the anaesthetic machine in a cardiothoracic theatre. Standard cardiothoracic cases are routinely performed in the theatre including coronary artery bypass grafts (with cardiopulmonary bypass), lobectomies, and surgical tracheostomies. The machine was not moved from its position during the study period. Initial attempts at placing the beaker near the surgical field were unsuccessful and provided an unacceptable risk to the protection of the sterile field and patient safety. Theatre staff were informed of the study and a notice was posted on the sampling beaker to reduce the risk of movement and interference of the sample. At 8am on Monday of the study week, the beaker was placed into position and the foil removed. The sampling beaker remained open until 8 pm the same day, providing a 12-hour exposure period, after which fresh foil was used to seal it. At the same time, a fresh sampling beaker replaced the initial one with the foil removed. At 8am the following morning (Tuesday), foil was used to cover the beaker and a fresh beaker replaced it. The beakers collecting atmospheric samples from 8am to 8 pm were classed as 'working' hours whereas the 8 pm to 8am samples were classed as 'non-working' hours. The 8am to 8 pm period during the Saturday and Sunday were regarded as non-working hours as the rooms were not in use during these times. The process was repeated for a 7-day period until the last beaker was covered on the following Monday at 8am. In total, n = 14 samples were collected from the theatre environment over the 7-day sampling period. Simultaneously, the same process was repeated in the adjoining anaesthetics room with the sampling beaker placed on a shelf at eye-level and another n = 14 samples collected. In the theatre, ventilation over the surgical field was provided by an EXFLOW^{TM}32 Ultra Clear Ventilation (UCV) canopy (Howorth Air Technology, Bolton, U.K).

2.3. Sample filtration

Sampling beakers were transported to the laboratory, stored at room temperature in the dark until bulk processing was conducted. The foil was removed and the beakers rinsed with 200 mL of pre-filtered distilled water. The rinsate was passed through an Anodisc filter of 47 mm, 0.2 μm pore size, aluminium oxide composition (Anodisc inorganic filter membrane, Whatman, Buckinghamshire, U.K.) in a closed glass vacuum filtration system. The Anodisc filter uses aluminium oxide to produce pores of a 0.2 μm with a surface porosity of 25–50 % and a water flow rate of 10.2 at 25 degrees and 10 psi. The beakers were rinsed twice more and passed through the same filter. The filter was then removed,

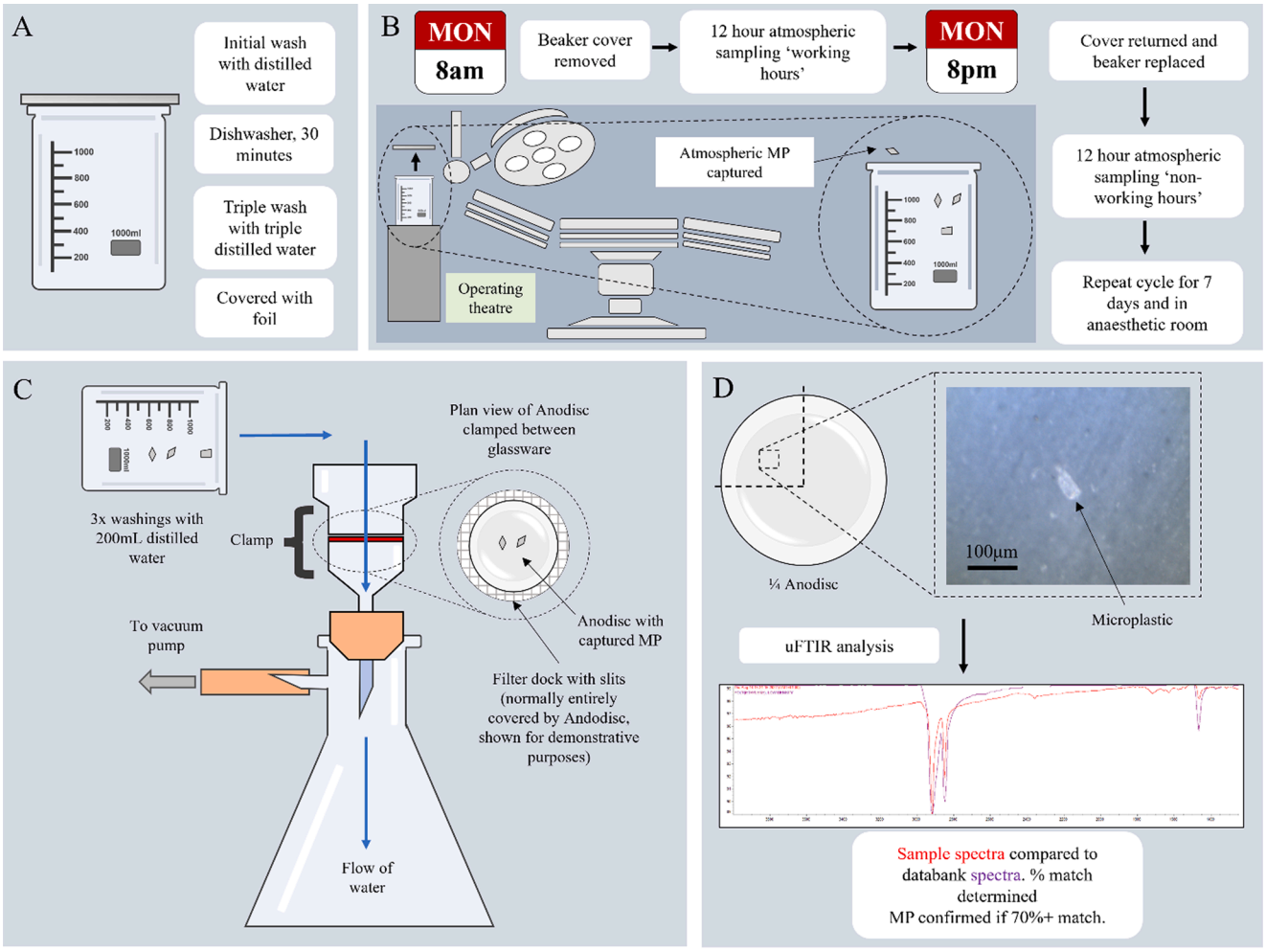

Fig. 1. Schematic of the methodology for detecting MPs in the surgical environment, (A) sampling beaker preparation, (B) atmospheric sampling, (C) sample filtration and MP capture onto Anodisc filter, (D) analysis of MP using µFTIR. Abbreviations: MP, microplastic; µFTIR, micro-Fourier-transform infrared spectroscopy.

covered in a glass Petri dish, and left to air dry for a minimum of 24-hours. A pre-filtration digestion stage was omitted because the sampling beakers were opened to the surgical environments for only 12-hour time periods. The total amount of particle fallout was predicted to be low relative to studies sampling for a week indoors (Jenner et al., 2021) or externally for two weeks outdoors (Jenner et al., 2022).

2.4. Particle level quantification and characterisation

Filters were analysed using micro-Fourier-transform infrared spectroscopy (µFTIR, Nicolet iN10 ThermoFisher, Waltham MA, U.S.A). All particles, including natural polymer particles and MPs, were counted in one quarter of the filter, with an assumption that even particle distribution had occurred during the filtration process.

µFTIR analysis was undertaken in transmission mode and with a liquid nitrogen cooling system. Width and length measurements for a particle of interest were ascertained by the spatial resolution box using the software (Omnic Software Package, ThermoFisher, Waltham MA, U.S.A). The length (largest side of particle) and width (second largest side) was recorded, as well as the shape (Free et al., 2014). Particle dimensions were categorised between lengths 10–1000 µm, and width: 10->50 µm. Particles > 1 mm were disregarded to focus on the standard MP size range (Hartmann et al., 2019). Particles with dimensions of < 10 µm were excluded due to the limitations of the µFTIR analysis capabilities below this size. The same spatial resolution was used to analyse a background reference prior to particle spectra determination. All spectra were obtained over a period of 12 s with a spectral range of 4000–1250 cm^{-1}, compared to a polymer spectra database (Omnic polymer library) and a match index calculated. A value of ≥ 70 % and above was regarded as confirmatory. Three attempts for each particle were undertaken to gain a spectrum of 70 % or above. Particles below the 70 % threshold were not included in the results.

Fig. 1A, 1B, 1C, 1D.

2.5. Quality assurance and control

Strict quality assurance measures were used to restrict background MP contamination using validated methods described in previous work (Jenner et al., 2021; Jenner et al., 2022; Jenner et al., 2022). The laboratory used for analyses has a focal interest in MP research and a culture of contamination avoidance purveys throughout all processes. All equipment and glassware used were first washed by hand before a dishwasher cycle using distilled water and finally a triple rinse using MilliQ water. The MilliQ water was prepared by filtering using glass fibre (GF6) filters (GE Healthcare Life Sciences, Marlborough MA, U.S.A.). All reagents and equipment were covered with aluminium tin foil lids and a small opening made when pouring. During pouring and filtering of samples, triple rinsing of containers with MilliQ water was conducted to avoid sample particle loss. A fume cupboard was used during most stages of the laboratory processing, with the power off to minimise air flow. Safety goggles, nitrile gloves, and plastic equipment was avoided by using an all-glass vacuum filtration kit, glass petri

dishes, a cotton laboratory coat and glass or metal laboratory equipment. Laboratory work was conducted at times of low activity and μFTIR analysis conducted in a single-person room. Windows and doors were closed with no other ventilation. Three random new Anodisc filters were chosen for μFTIR analysis, in which no particles were identified to rule these out as a source of contamination. All sampling and sample-preparations were conducted by the primary researcher. To ensure environmental contamination during beaker preparation was accounted for, a blank filter was placed in the laboratory during the period of preparation. Finally, to account for environmental contamination during analysis, a blank filter was placed next to the μFTIR microscope during particle quantification, when the sample filter was exposed to the atmosphere so was this filter. A new filter was used for each separate sample and particles counted on a quarter of the filter.

2.6. Statistical analysis

All particles, including MPs, were counted per quarter of the filter for each sample and multiplied by four to give a value for the whole filter. To compare with other studies, the MP abundance was calculated per m^{-2} by multiplying the MP count per filter by 105.2264 (conversion factor from the area of the bottom of the beaker surface area to m^2). The outcome is then multiplied by a factor of two to convert the particle level per day (given sampling occurred over a 12-hour period). A Shapiro-Wilk test confirmed the data was not normally distributed and a Mann-Whitney *U* test applied. The significance level was set at 0.05. All abundance values are given as mean particle abundance m^{-2} day^{-1} ± the standard deviation. Statistical analyses were conducted using version 28 of SPSS (IBM, Armonk, New York, U.S.A).

3. Results

3.1. Control and laboratory blanks

A total of 65 particles were identified from the 30 controls. From these, none were identified as MPs, which was significantly different to the number of MPs identified within samples ($p = 0.00039$). Non-MP particles in controls consisted primarily of zein (corn starch) (68 %) and cellulose/cellophane (27 %). Due to the low contamination rates of MPs within each sample it was decided not to subtract contamination rates from results (Vianello et al., 2019).

3.2. Total particle fallout and characterisation

When combining both rooms, the mean total particle abundance was 13,048 ± 14,283 particles m^{-2} day^{-1}. The total number of particles collected from the operating theatre environment during the sampling period varied, with a mean of 16,957 ± 18,622 particles m^{-2} day^{-1} and a range of 842–62,294 particles m^{-2} day^{-1} (Fig. 2). Variation was also seen in the total particle fallout in the anaesthetic room with a mean of 9,140 ± 6,636 particles m^{-2} day^{-1} and a range of 2,525 – 29,463 particles m^{-2} day^{-1}.

The mean total particle abundance for working hours in the operating theatre was 37,882 ± 15,950 particles m^{-2} day^{-1} and 5,332 ± 3,260 particles m^{-2} day^{-1} for non-working hours. Total particle abundance was significantly higher in the working hours compared to the non-working hours in the theatre samples ($p = 0.003$). The working hours mean total particle fallout in the anaesthetics room was 14,648 ± 8,700 particles m^{-2} day^{-1} whereas this was 6,080 ± 2,052 particles m^{-2} day^{-1} for the non-working hours. Like the theatre, the total particle abundance was significantly higher during the working hours for the anaesthetics room ($p = 0.007$).

When combining the two rooms, a similar pattern was observed with a mean particle abundance of 26,265 ± 17,224 particles m^{-2} day^{-1} during working hours and 5,706 ± 2,671 particles m^{-2} day^{-1} during non-working hours. The difference in total particle abundance between the two time periods was significantly higher in the working hours samples ($p = 0.000043$). When comparing total particle abundance between the two rooms, regardless of working versus non-working hours, there was no significant differences in concentrations ($p = 0.747$). Of the total particles, most were fragments (78 %) (Fig. 3A), and clear in colour (84 %) (Fig. 3B). An increase in particle abundance with a decreasing particle length was observed (Fig. 4A). Particles in the size range 10–250 μm accounted for the majority (94 %) (Fig. 4B).

3.3. Non-MP particle composition

Non-MP particles (natural and artificial particles not of a petroleum derived nature) accounted for 89 % and 94 % of particles sampled from the operating theatre and anaesthetics room, respectively. Non-MP fractions for each working day ranged from 80 to 100 % and from 88 to 100 % for non-working days. Of the non-MP fraction, the most abundant compound was zein accounting for 60 % of particles. The remaining non-MP particles were comprised of cellulose/cellophane, wood, silicon dioxide and zinc acetate (24 %, 2 %, 1 % and 1 % respectively), and others.

3.4. MP abundance

MPs were detected in the operating theatre during all 12-h sampling periods within the working day, and four out of the five working day 12-h samples from the anaesthetic room. For both locations combined, including both working and non-working hours the mean MP atmospheric abundance was 1,233 ± 2,364 MP m^{-2} day^{-1} with a range of between 0 and 9,569 MP m^{-2} day^{-1} (Fig. 2). When comparing between the working and non-working hours for both rooms combined, the MP abundance during working hours was 3,367 ± 2,970 MP m^{-2} day^{-1}. During non-working hours this value was 47 ± 198 m^{-2} day^{-1}. There were significantly higher MP levels in the working hours compared to the non-working hours ($p = 0.000009$).

In the operating theatre alone, the number of MPs identified during the sampling period varied, with a mean of 1,924 ± 3,105 MP m^{-2} day^{-1} and a range of 0 – 9,258 MP m^{-2} day^{-1}, compared with a mean of 541 ± 969 MP m^{-2} $day^{-1}$and a range of 0 – 3,368 MP m^{-2} day^{-1} for the anaesthetic room. The variation in MP abundance overall between the operating theatre and anaesthetic room were not statistically significant even when adjusted for working or non-working hours ($p = 0.555$).

Breaking this down further in the operating theatre, when separating by working versus non-working hours, the mean MP abundance was 5,388 ± 2,830 MP m^{-2} day^{-1} during working hours and no MPs were detected during non-working hours. A statistically significant difference ($p = 0.00047$) indicating higher MP levels in theatre during working hours. The highest MP abundance in the operating theatre was observed on Monday (involving one coronary artery bypass graft procedure with cardiopulmonary bypass) with an abundance of 9,260 MP m^{-2} day^{-1}. Thursday (involving a single surgical tracheostomy) saw the lowest abundance at 1,684 MP m^{-2} day^{-1}.

Working hours in the anaesthetics room saw a mean MP abundance of 1,347 ± 1,277 MP m^{-2} day^{-1} and 94 ± 281 MP m^{-2} day^{-1} for non-working hours. A significantly higher MP abundance was observed during the working hours ($p = 0.01$). The highest MP abundance observed in the anaesthetics room was 3,368 MP m^{-2} day^{-1} (on Tuesday, involving four separate thoracic surgical procedures) and the lowest abundance was zero MP m^{-2} day^{-1} (on Thursday, involving one surgical tracheostomy). Of note, compared to the operating theatre, one non-working sample did detect MP (Monday night).

3.5. MP particle composition

Synthetic MPs, including semi-synthetic nylon, accounted for 11 % and 6 % of the particles identified within the operating theatre and anaesthetics room samples respectively (Fig. 5A). PET was present in 43

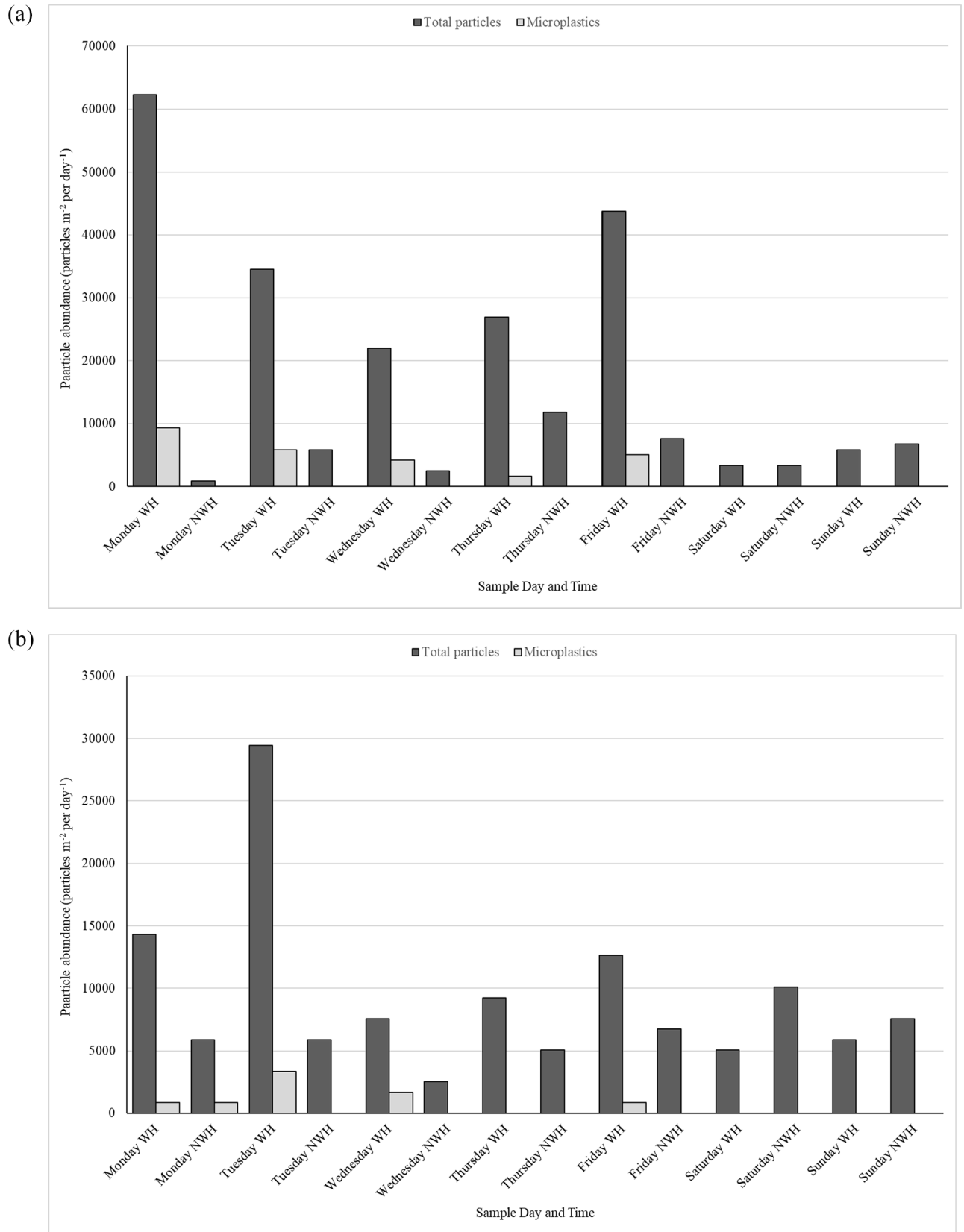

Fig. 2. Bar chart displaying mean total particle and microplastic abundance per sampling period for both theatre (A) and the anaesthetic room (B). Abbreviations: WH, working hours; NWH, non-working hours.

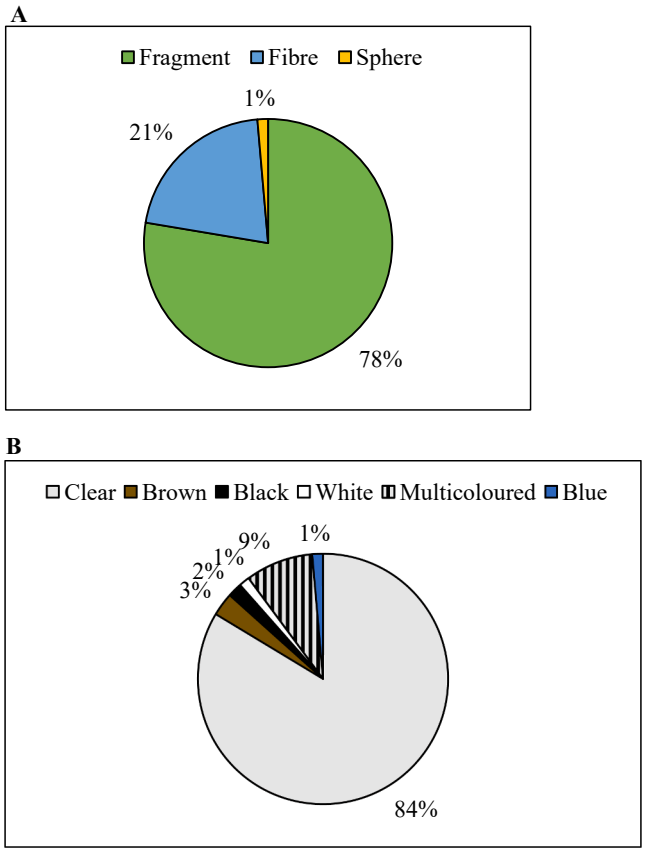

Fig. 3. Total particle A. shape and B. colour. All particles represented, from operating theatre and anaesthetic room combined, sampled over the entire 7-day period and during working and non-working hours.

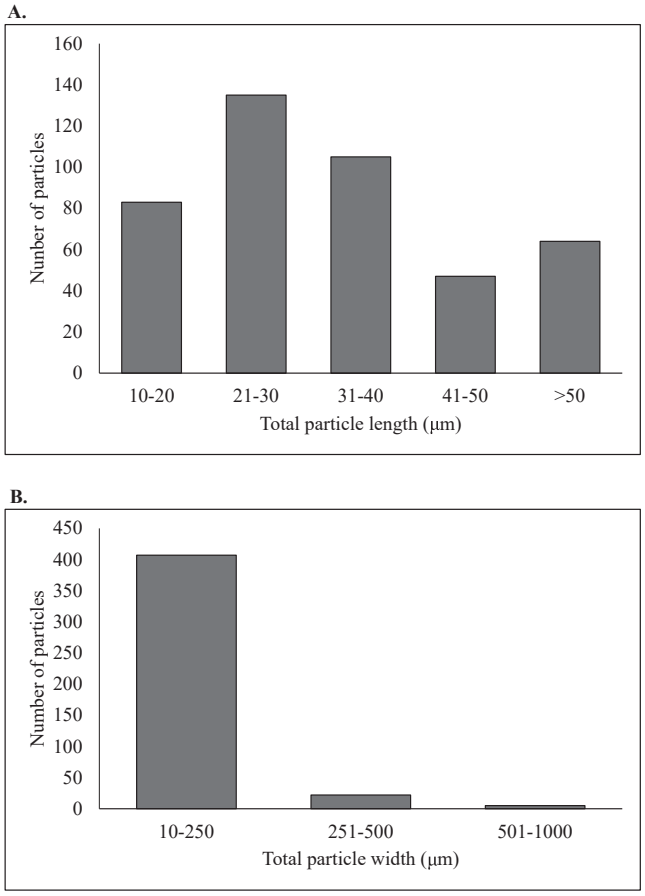

Fig. 4. Bar chart showing the particle size distributions of the entire total particle fallout. A. Particle length categories and abundance, B. Particle width categories and abundance. Operating theatre and anaesthetic room data combined, over the entire 7-day sampling period, during working and non-working hours.

% of samples and accounted for 37 % of the total synthetic fraction (Fig. 5A). Other MP polymer types identified were polypropylene (PP), nylon, polyethylene (PE), and polytetrafluoroethylene (PTFE) (25 %, 13 %, 7 %, 5 %, respectively) (Fig. 5A). The mean width and length of MP in samples was 29.8 ± 14 μm and 92 ± 136 μm (mean ± SD) respectively. The range of widths of MP were 10 – 73 μm and the range of lengths were 28 – 800 μm. An increase in abundance as particles decreased in size was noted (Fig. 5C and 5D). 85 % of identified MPs were clear in colour with black, blue, and brown composing the remainder (7 %, 5 % and 3 % respectively) (Fig. 5E). 78 % of the MP were classified as fragment in shape with fibres and spheres composing 20 % and 2 % respectively (Fig. 5F).

4. Discussion

The results of this study are the first, to our knowledge, to report of atmospheric MP contamination in a hospital environment and fills in the gap in knowledge about the composition and levels of MP contamination that humans (both staff and patients) are exposed to in such environments. Previous studies into atmospheric particulate contamination in the operating environment have investigated anaesthetic gases (Molina Aragonés et al., 2015), surgical smoke (Romano et al., 2017) and general PM_{10}/PM_5 levels (Tan et al., 2021; Whyte et al., 2019; Romano et al., 2020),. It is logical to predict that an abundance of single use plastic in the environment involving intense disruption (opening and ripping of the packaging) will cause particle release into the atmosphere. In terms of comparisons for a surgical environment, airborne MP levels have not previously been studied and only spallation of plastic tubing in cardiopulmonary bypass (CPB) circuits, where levels of 929 particles per 200 mL for particles of Tygon < 50 μm after 180 min of CPB running, have been reported (Kim and Yoon, 1998; Ippoleti et al., 2019). The CPB roller pump compresses the plastic tubing leading to shearing and spallation of plastic particles into the circuit. This is analogous to the disruption of plastic upon opening packaging and subsequent 'spallation' into the atmosphere. In comparison to the limited number of indoor environment studies, including household values of 1,414 ± 1,022 MP m^{-2} day^{-1} (mean ± SD) (Jenner et al., 2021), and office area (1,800 MP m^{-2} day^{-1}) or corridors (1,500 MP m^{-2} day^{-1}) (Zhang et al., 2020), the operating theatre working day values for MP levels observed are relatively high.

With respect to significantly higher levels of MPs, and total particles in general, during working hours, this is consistent with other studies investigating particulate matter in the operating environments as follows. Longer operating time has been positively correlated with overall operating theatre atmospheric particulate concentration (Sicat et al., 2022; Kirschbaum et al., 2020), and mock operating theatres prior to operating room setup, have significantly less particles than during operating set-up and operation period (Marsault et al., 2021). Direct correlation between increased particulate numbers and movement of staff in the operating room has also been reported (Tateiwa et al., 2020; Pasquarella et al., 2020). Similarly, our findings indicate that MPs make up a proportion of the operating room atmospheric particulate contamination in addition to surgical smoke, bioaerosols and anaesthetic gases, and that the working day pattern results in higher levels compared to non-working hours. The size distribution of MP identified in our study mirrors the distribution seen in surgical smoke production; (Kondo et al., 2021) reported a greater abundance of smaller particles

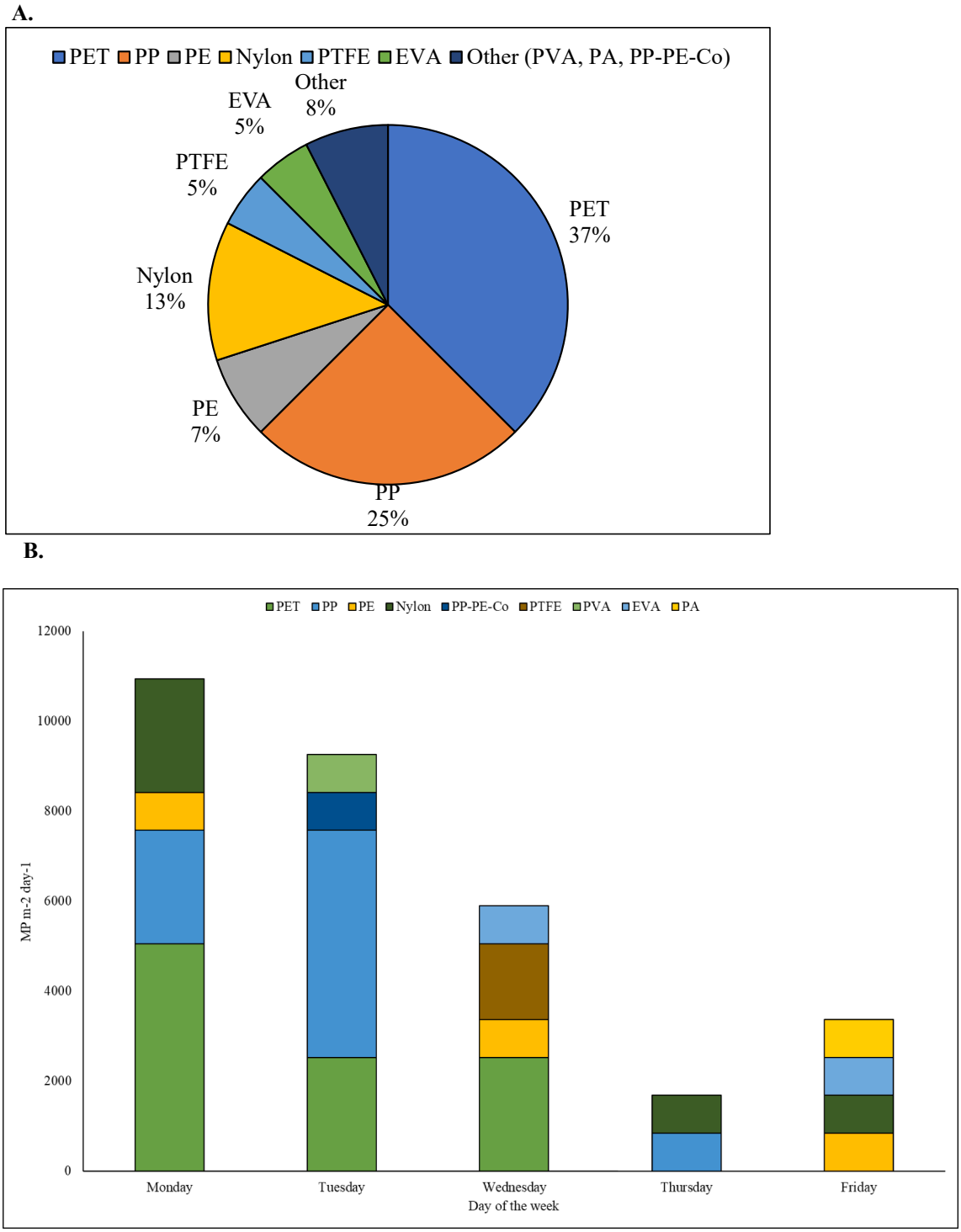

Fig. 5. MP particle characteristics: A. chemical composition types and abundances; B. daily level of each polymer type (working and non-working hours combined, Saturday and Sunday excluded due to no MP detection); C. widths; D. lengths; E. colours, and F shapes. Abbreviations: PET - polyethylene terephthalate, PA - nylon, PP - polypropylene, PP-PE-Co - polypropylene-polyethylene co-polymer, PE - polyethylene, PTFE - polytetrafluoroethylene, EVA - ethylene–vinyl acetate, PVA - polyvinyl alcohol, PA - polyacetal. Data is for the operating theatre and anaesthetic room combined for the entire 7-day sampling period, and for working and non-working hours.

(Fig. 5C, 5D).

To attempt to relate the MPs observed to sources, the data available on plastic composition and waste in operating theatres can be used. A large retrospective study including five hospitals in Massachusetts, U.S. A, identified that the operating theatres contributed to 33.2 tons per year of plastic waste representing 21 % of the total plastic waste for the whole hospital (Lee et al., 2002). Focusing on the two most detected MP polymers, PET represented 38 % of the MP content with a mean concentration of 451 MP m^{-2} day^{-1}. It is a synthetic thermoplastic, stable, with high tensile strength and transparent, making it a popular plastic worldwide. Outside of the medical context, PET is used in food wrapping, bottles, and textiles (Rodríguez-Hernández et al., 2019). PET use in

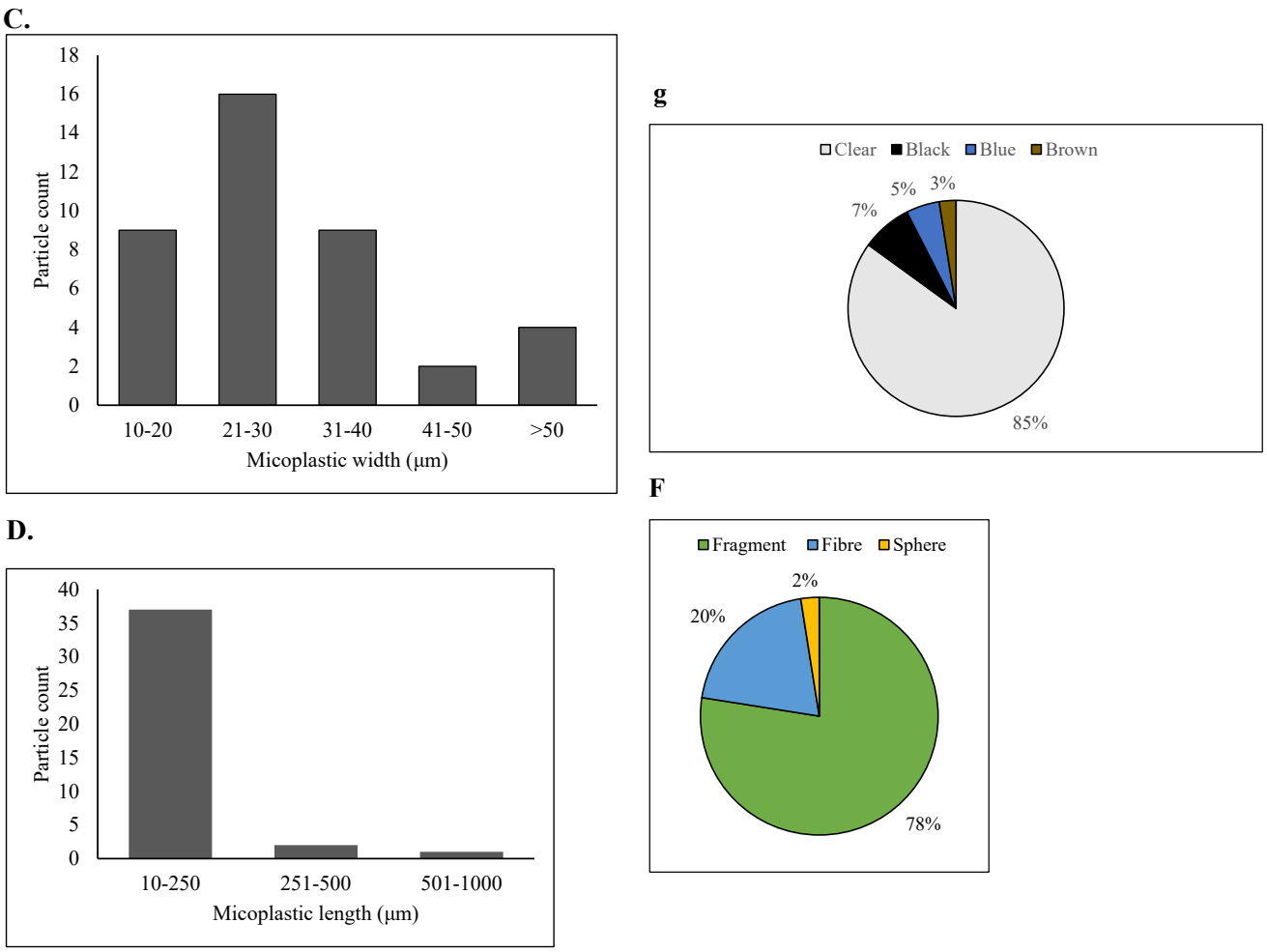

Fig. 5. (*continued*).

hospitals can be categorised into two groups: medical implants/materials and packaging. PET in its fibre form, referred to as Dacron®, is used as a vascular grafting and suture material (Roll et al., 2008; Jaffe, 1981). Due to its strength, transparency and sterility, PET is ideal for single use plastic for medical instrument and equipment packaging such as blister packs. Most MPs detected in this study were fragment-shaped suggesting a packaging rather than suture/implant source. A study in Brisbane operating theatres extrapolated PET usage to ~ 1,700 kg per year (Wyssusek et al., 2020), with laparoscopic and bariatric surgeries contributing the most, and sources noted as staplers, cutters, clip applicators and packs for central and arterial lines. Only 16 cardiothoracic cases were performed in in this study period, however the equipment similarities are evident. To explore the source of MPs further, packaging from thoracic operative cases were analysed: all blister packs containing laparoscopic instrumentation (staplers) were composed of PET.

The second most common MP detected in our study was PP at 25 % of MPs observed, with a mean concentration of 301 MP m^{-2} day^{-1}. Studies of hospital waste have reported 9–21 % of plastic waste in the operating theatre as PP (McGain et al., 2008), one neurosurgical department reported a PP usage of 566 kg (over a 39-day period) (Babu et al., 2018), and a Belgian waste reduction study identified PP being a large contributor of plastic waste in the operating environment (Harding et al., 2021). The main uses of PP in the surgical environment are as a mesh material for vaginal prolapse or hernias (Improvement and England, 2018; Amid et al., 1996) and various surgical packaging and clothing. Disposable scrub caps, surgical gowns, surgical drapes and instrument wrapping are often formed of nonwoven PP fibres (Babu et al., 2018; van Straten et al., 2021; Albert and Rothkopf, 2015). For wearable items, PP provides lightweight, flexible and breathable characteristics with the ability to repel fluids. The sterility and disposability justify its use for surgical drapes where the reduction in external contamination into the surgical field is paramount. Surgical procedures involve high throughputs of such material with new gowns being used for each case. PP is also moulded into blister packs for surgical equipment however our analysis of the blister packs used during thoracic cases did not demonstrate its use for this purpose in the study department.

5. Clinical significance

To date, there are few investigations that relate to the clinical significance of MPs. Recent studies show MP presence in human tissues (Jenner et al., 2022; Leslie et al., 2022; Ibrahim et al., 2021) as well as detrimental lung health impacts in occupational exposure settings whereby synthetic fibres have been observed in lung tissue samples from nylon flock factory workers (Pauly et al., 1998; Burkhart et al., 1999). In parallel, various cell/tissue culture and/or animal models variously report sub-cellular level detrimental impacts such as oxidative stress, inflammation responses and membrane stability impact following MP exposure (reviewed in (Danopoulos et al., 2022). PET was the most common MP detected in blood samples from 22 healthy donors (Leslie et al., 2022) and 11 colectomy samples (Ibrahim et al., 2021), PP and PET the most common in 13 lung tissue samples (Jenner et al., 2022). In lungs, MP levels were significantly higher in the lower regions of the lung and the median length and width of measure particles were 223 μm and 22 μm respectively evidencing that larger size MP reach distal lung

tissue (Jenner et al., 2022). The most common MP polymer types and sizes detected in the surgical environment are like that identified in human samples.

From an operating environment perspective, these results identify a potential new route of exposure for MPs in humans. Operating theatre air quality has been studied extensively focussing on the lower micro- and nanoplastic size range applied to preventing SSI and joint infections in orthopaedic surgery (Romano et al., 2017; Marsault et al., 2021; Pasquarella et al., 2020; Lansing et al., 2021). Data from stimulated operating environments and post-operative analysis has shown conflicting evidence for SSI incidence and atmospheric particulate levels and/or different behaviours in the theatre (Sadrizadeh et al., 2021). The identification of MP in the atmosphere offers a potential novel source for microorganism contamination of a surgical wound in that bacteria can adhere to plastic for prolonged periods of time, including PET, PP and PE identified herein (Cai et al., 2019). Of note, *Staphylococcus* and *Enterococci* species, were shown to survive for over 22 days on PE surfaces with many surviving $>$ 90 days (Neely and Maley, 2000). The presence of airborne MPs and wound contamination is hypothetical, but this study highlights a new potential source of microbial contamination in the operating theatre.

While a validated methodology has been employed to measure MPs, limitations do exist. Only a proportion (one quarter) of the particles were characterised, it is based on a single one-week sampling period and a relatively small number of locations used. It is the norm in MP investigations to use a digestion phase before filtration to break down organic matter and focus analysis on the synthetic particles. This step was not conducted herein to allow a compositional analysis and characterisation of the overall particulate matter in a surgical environment, given the complete lack of such data in the literature.

6. Conclusion

The results of this study quantify, for the first time, MP atmospheric contamination in the hospital surgery environment. The abundance of MP was greatest during the working-hours of the theatre and PET and PP made up the most abundant polymer types. Having established that MPs are present in the surgical environment, thus providing a novel dataset on their levels and characteristics, this now serves as an important proof of concept foundation for more in-depth investigations to determine MP levels and types, as well as potential implications for human health, in future work.

CRediT authorship contribution statement

Daniel T. Field: Conceptualization, Methodology, Investigation, Data curation, Visualization, Formal analysis. **Jordan L. Green:** Conceptualization, Methodology, Investigation, Data curation, Visualization, Formal analysis. **Robert Bennett:** Conceptualization, Methodology, Investigation, Data curation, Visualization. **Lauren C. Jenner:** Formal analysis. **Laura.R. Sadofsky:** Conceptualization, Funding acquisition, Project administration, Supervision. **Emma Chapman:** Formal analysis. **Mahmoud Loubani:** Conceptualization, Funding acquisition, Project administration, Supervision. **Jeanette M. Rotchell:** Conceptualization, Funding acquisition, Project administration, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Ethics statement: This work involved analysis of dust particles from a surgical environment (with no sampling from patients) and was approved by the Faculty of Science and Engineering Ethics Committee, reference number FEC_2020_106.

References

Albert, M.G., Rothkopf, D.M., 2015. Operating room waste reduction in plastic and hand surgery. Plastic Surg. 23, 1000941.
Amato-Lourenço, L.F., Carvalho-Oliveira, R., Júnior, G.R., et al., 2021. Presence of airborne microplastics in human lung tissue. J Hazard Mat. 416, 126124.
Amid, P.K., Shulman, A.G., Lichtenstein, I.L., 1996. Open "tension-free" repair of inguinal hernias: the Lichtenstein technique. Eur J Surg. 162, 447–453.
Babu, M.A., Dalenberg, A.K., Goodsell, G., et al., 2018. Greening the operating room: results of a scalable initiative to reduce waste and recover supply costs. Neurosurgery 85, 432–437.
Burkhart, J., Jones, W., Porter, D.W., et al., 1999. Hazardous occupational exposure and lung disease among nylon flock workers. Am J Ind Med. 36, 145–146.
Cai, L., Wu, D., Xia, J., et al., 2019. Influence of physicochemical surface properties on the adhesion of bacteria onto four types of plastics. Sci Tot Environ. 671, 1101–1107.
Carbery, M., O'Connor, W., Palanisami, T., 2018. Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environ Int. 115, 400–409.
Chen, G., Feng, Q., Wang, J., 2020. Mini-review of microplastics in the atmosphere and their risks to humans. Sci Tot Environ. 703, 135504.
Danopoulos, E., Jenner, L.C., Twiddy, M., et al., 2020. Microplastic contamination of seafood intended for human consumption: a systematic review and meta-analysis. Environ Health Perspect. 128, 126002.
Danopoulos, E., Twiddy, M., Rotchell, J.M., 2020. Microplastic contamination of drinking water: A systematic review. PLOS ONE 15, e0236838.
Danopoulos, E., Twiddy, M., West, R., et al., 2022. A rapid review and meta-regression analyses of the toxicological impacts of microplastic exposure in human cells. J Hazard Mat. 427, 127861.
Domenech, J., Marcos, R., 2021. Pathways of human exposure to microplastics, and estimation of the total burden. Curr Opin Food Sci. 39, 144–151.
NHS England. NHS Single-Use Plastics Reduction Campaign Pledge - NHS England - Citizen Space. www.engage.england.nhs.uk. Available from: https://www.engage.england.nhs.uk/survey/dee161d9/. 2019.
Free, C.M., Jensen, O.P., Mason, S.A., et al., 2014. High-levels of microplastic pollution in a large, remote, mountain lake. Mar Pollut Bull. 85, 156–163.
Frias, J.P.G.L., Nash, R., 2019. Microplastics: finding a consensus on the definition. Mar Pollut Bull. 138, 145–147.
Hale, R.C., Seeley, M.E., La Guardia, M.J., et al., 2020. A global perspective on microplastics. J Geophys Res: Oceans 125 (1), 014719.
Harding, C., Van Loon, J., Moons, I., et al., 2021. Design opportunities to reduce waste in operating rooms. Sustainability 13, 2207.
Hartmann, N.B., Hüffer, T., Thompson, R.C., et al., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ Sci Technol. 53, 1039–1047.
Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., et al., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol. 46, 3060–3075.
Horvatits T, Tamminga M, Liu B, et al. Microplastics detected in cirrhotic liver tissue. *eBioMedicine*. 2022;82:104147.
Hussain, N., 2001. Recent advances in the understanding of uptake of microparticulates across the gastrointestinal lymphatics. Adv Drug Del Rev. 50, 107–142.
Ibrahim, Y.S., Tuan Anuar, S., Azmi, A.A., et al., 2021. Detection of microplastics in human colectomy specimens. JGH Open. 5, 116–121.
NHS Improvement and NHS England. Vaginal Mesh: High Vigilance Restriction Period: Immediate Action Required, All Cases Should be Postponed If it is Clinically Safe to Do So Available from: [https://i.emlfiles4.com/cmpdoc/9/7/2/8/1/1/files/47633_mesh-letter-to-acute-ceos-and-mds.pdf] 2018.
Ippoleti, F., Piscioneri, F., Sartini, P., et al., 2019. Comparative spallation performance of silicone versus Tygon extracorporeal circulation tubing. Interact Cardiovasc Thorac Surg. 29, 685–692.
Jaffe, N.S., 1981. Polyethylene terephthalate (Dacron®) in intraocular surgery. Ophthalmology 88, 955–958.
Jenner, L.C., Sadofsky, L.R., Danopoulos, E., et al., 2021. Household indoor microplastics within the Humber region (United Kingdom): Quantification and chemical characterisation of particles present. Atmos Environ. 259, 118512.
Jenner, L.C., Sadofsky, L.R., Danopoulos, E., et al., 2022. Outdoor atmospheric microplastics within the Humber Region (United Kingdom): Quantification and chemical characterisation of deposited particles present. Atmos. 13, 265.
Jenner, L.C., Rotchell, J.M., Bennett, R.T., et al., 2022. Detection of microplastics in human lung tissue using μFTIR spectroscopy. Sci Tot Environ. 831, 154907.

Kim, W.G., Yoon, C.J., 1998. Roller pump induced tubing wear of polyvinylchloride and silicone rubber tubing: phase contrast and scanning electron microscopic studies. Artif Organs. 22, 892–897.
Kirschbaum, S., Hommel, H., Strache, P., et al., 2020. Laminar air flow reduces particle load in TKA—even outside the LAF panel: a prospective, randomized cohort study. Knee Surg Sports Traumatol Arthrosc. 29, 3641–3647.
Kondo, A., Watanabe, Y., Ishida, M., et al., 2021. Particle size distributions in surgical smoke generated by advanced energy devices. Annals Surg. 273, e168–e170.
Lansing, S.S., Moley, J.P., McGrath, M.S., et al., 2021. High number of door openings increases the bacterial load of the operating oom. Surg Infect. 22, 684–689.
Lee, B.-K., Ellenbecker, M.J., Moure-Eraso, R., 2002. Analyses of the recycling potential of medical plastic wastes. Waste Manag. 22, 461–470.
Leslie, H.A., van Velzen, J.M., Brandsma, S.H., et al., 2022. Discovery and quantification of plastic particle pollution in human blood. Environ Int. 163, 107199.
Lippmann, M., Yeates, D.B., Albert, R.E., 1980. Deposition, retention, and clearance of inhaled particles. Occup Environ Med. 37, 337–362.
Marsault, L.V., Ravn, C., Overgaard, A., et al., 2021. Laminar airflow versus turbulent airflow in simulated total hip arthroplasty: measurements of colony-forming units, particles, and energy consumption. J Hosp Infect. 115, 117–123.
McGain, F., Clark, M., Williams, T., et al., 2008. Recycling plastics from the operating suite. Anaesth Intensive Care Med. 36, 913–914.
Molina Aragonés, J.M., Ayora, A.A., Ribalta, A.B., et al., 2015. Occupational exposure to volatile anaesthetics: a systematic review. Occup Med. 66, 202–207.
Mowbray, N., Ansell, J., Warren, N., et al., 2013. Is surgical smoke harmful to theater staff? A systematic review. *Surg Endoscopy* 27, 3100–3107.
Neely, A.N., Maley, M.P., 2000. Survival of enterococci and staphylococci on hospital fabrics and plastic. J Clin Microbiol. 38, 724–726.
Oliveri Conti G, Ferrante M, Banni M, et al. Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population. *Environ Res.* 2020;187:109677.
Pasquarella, C., Balocco, C., Colucci, M.E., et al., 2020. The influence of surgical staff behavior on air quality in a conventionally ventilated operating theatre during a simulated arthroplasty: a case study at the University Hospital of Parma. Int J Environ Res Public Health. 17, 452.
Pauly, J.L., Stegmeier, S.J., Allaart, H.A., et al., 1998. Inhaled cellulosic and plastic fibers found in human lung tissue. Cancer Epidemiol Biomark Prev. 7, 419–428.
Pimentel, J.C., Avila, R., Lourenço, A.G., 1975. Respiratory disease caused by synthetic fibres: a new occupational disease. Thorax 30, 204–219.
Rodríguez-Hernández, A.G., Muñoz-Tabares, J.A., Aguilar-Guzmán, J.C., et al., 2019. A novel and simple method for polyethylene terephthalate (PET) nanoparticle production. Environ Sci Nano. 6, 2031–2036.
Roll, S., Müller-Nordhorn, J., Keil, T., et al., 2008. Dacron® vs. PTFE as bypass materials in peripheral vascular surgery – systematic review and meta-analysis. BMC Surg. 8, 22.
Romano, F., Gustén, J., De Antonellis, S., et al., 2017. Electrosurgical smoke: ultrafine particle measurements and work environment quality in different operating theatres. Int J Environ Res Public Health 14, 137.
Romano, F., Milani, S., Ricci, R., et al., 2020. Operating theatre ventilation systems and their performance in contamination control: "At Rest" and "In Operation" particle and microbial measurements made in an Italian large and multi-year inspection campaign. Int J Environ Res Public Health 17, 17197275.
Sadrizadeh, S., Aganovic, A., Bogdan, A., et al., 2021. A systematic review of operating room ventilation. J Build Eng. 40, 102693.
NHS Scotland. NHS Scotland Waste Management Action Plan Available from: https://www.sehd.scot.nhs.uk/dl/DL(2017)03.pdf. 2017.
Senathirajah, K., Attwood, S., Bhagwat, G., et al., 2021. Estimation of the mass of microplastics ingested – A pivotal first step towards human health risk assessment. J Hazard Mat. 404, 124004.
Sicat, C.S., Schwarzkopf, R., Slover, J.D., et al., 2022. Comparison of operating room air quality in primary versus revision total knee arthroplasty. J Arthroplasty. 37, S297–S300.
Tan H, Wong K, Nyakuma BB, et al. Systematic study on the relationship between particulate matter and microbial counts in hospital operating rooms. *Environ Sci Pollut Res.* 2021;29:6710-6721.
Tateiwa T, Masaoka T, Ishida T, et al. Impact of surgical clothing and footwear on operating room contamination during standstill and intraoperative stepping motion. *J Orthop Surg.* 2020;28:2309499020976232.
Tyler, A.D., Kirsch, R., Milgrom, R., et al., 2016. Microbiome heterogeneity characterizing intestinal tissue and inflammatory bowel disease phenotype. Inflam Bowel Dis. 22, 807–816.
van Straten, B., van der Heiden, D.R., Robertson, D., et al., 2021. Surgical waste reprocessing: Injection molding using recycled blue wrapping paper from the operating room. J Cleaner Prod 322, 129121.
Vianello, A., Jensen, R.L., Liu, L., et al., 2019. Simulating human exposure to indoor airborne microplastics using a Breathing Thermal Manikin. Sci Reports. 9, 8670.
Whyte, H.E., Raillard, C., Subrenat, A., et al., 2019. Influence of environmental parameters on the photocatalytic oxidation efficiency of acrylonitrile and isoflurane; two operating room pollutants. Built Environ. 154, 97–106.
Wyssusek, K., Keys, M., Laycock, B., et al., 2020. The volume of recyclable polyethylene terephthalate plastic in operating rooms – A one-month prospective audit. Am J Surg. 220, 853–855.
Yan, Z., Liu, Y., Zhang, T., et al., 2021. Analysis of microplastics in human feces reveals a correlation between fecal microplastics and inflammatory bowel disease status. Environ Sci Technol. 56, 414–421.
Zhang, Q., Zhao, Y., Du, F., et al., 2020. Microplastic fallout in different indoor environments. Environ Sci Technol. 54, 6530–6539.