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Particle and Volatile Organic Compound Emissions from 3D Printers and Their Potential Exposure Risks

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1 Introduction

Desktop fused filament fabrication (FFF) 3D printers are being widely used in indoor environments where substantial exposures to emissions are possible. These include schools, offices and residential homes, leading to concerns on possible adverse health impacts of desktop 3D printer emissions on vulnerable populations, like children. Previous studies have found that ultrafine particles (less than 100 nm in size) and a range of volatile organic compounds (VOCs) are emitted from operating FFF 3D printers, and these emissions depend on the print filament materials utilized, like acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and nylon. However, the potential health impacts from both particle and gas phase emissions are not well known. This study systematically characterized particle and VOC emissions from desktop 3D printers using a standardized testing method. The potential health hazards in different indoor environments were estimated by applying various toxicity assays and an indoor exposure model.

2 Methods

Particle and VOC emissions from 3D printers were studied using special exposure chambers (ASTM, 2013; UL, 2014). Particles from ultrafine to coarse sizes were measured by a scanning mobility particle sizer and an optical particle counter. Air samples were collected onto sorbent tubes and analysed by gas chromatography mass spectrometry and high-performance liquid chromatography for VOCs and aldehydes separately. The testing procedures and emission calculation methods followed the standard protocols of ANSI/CAN/UL 2904 (ANSI, 2019). Particle chemical composition was measured by aerosol mass spectroscopy and inductively coupled plasma mass spectrometry, and the composition of particles collected onto filters during printing were contrasted to the bulk filament material by pyrolysis gas chromatography mass spectrometry. Particle toxicity analysis via various assays based on oxidative stress responses was assessed for particles also collected on filters. Exposure levels of particles and specific VOCs were estimated by an indoor exposure model based on calculated emission rates from the chamber study and different indoor environment scenarios. Multiple commercially available desktop 3D printers were studied with typical print filament materials from different vendors, including ABS, PLA, and nylon, and filaments with additives, such as metals.

3 Results and Discussion

A typical 3D printing particle emission profile showed a peak of particle numbers at the beginning of the printing process, which was associated with a new particle formation process from semi-volatile compounds emitted from the heated filament. A majority (average of about 70%) of particle emissions were found to be ultrafine particles, which are associated with specific health concerns as they can transport deep into the lung, pass into the bloodstream and through cell membranes. High particle emitters from specific manufactures were identified using the same bulk filament material, indicating minor additives may drive particle emissions for some filaments. VOC concentrations increased from when printing started and reached steady state levels later into the printing process. Approximately 200 individual VOCs were detected from 3D printing air samples. Particle emission levels and sizes, total VOC (TVOC) and specific VOC concentrations depended on print conditions, among which the most important ones included extrusion temperature and filament material (Table 1).

Table 1. Summary of average particle and VOC emissions from 3D printing. (ER=emission rate)

	ABS	PLA
Particle ER (h^{-1})	5.6×10^{11}	8.7×10^{10}
Particle size (nm)	73	53
TVOC ER (µg/h)	840	190
Top 3 VOCs	Styrene Benzaldehyde Ethylbenzene	Lactide Acetaldehyde 1-butanol

Cytotoxicity of 3D printer emitted particles was assessed by in vitro cell viability, cell death and intracellular reactive oxygen species (ROS) generation assays, using human lung epithelial cells and rat alveolar macrophages. All assays showed toxic responses after exposure to 3D printer emitted particles. Cell viability assay showed PLA emitted particles were more toxic than ABS emitted particles at similar doses. In vivo animal exposures also showed inflammatory responses in mice lungs after exposure. Oxidative potential (OP) was assessed using a chemical (dithiothreitol, DTT) assay, which indicted ABS, PLA and nylon-emitted particles all induced toxic responses. Measured OP results were combined with model estimated exposure levels of particles, and results showed ABS emitted particles to be more harmful due to their typically higher emissions, comparing to the PLA filament.

Some of the detected VOCs are hazardous to humans, including the most detected VOC species listed in Table 1. Notably, styrene, ethylbenzene, and acetaldehyde are carcinogens according to the Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65) and/or Candidate Chemical List by California Department of Toxic Substances Control. Other frequently detected VOCs like formaldehyde and methyl methacrylate are also carcinogens. The highest concentration VOC detected from nylon filaments, caprolactam, has an ocular and respiratory toxicity. Exposures to chemicals of concern were estimated using a model, and exposure concentrations of some VOCs, like benzene and formaldehyde, can exceed recommended levels in residential settings.

4 Conclusions

High levels of ultrafine particles and various VOCs were found to be emitted during 3D printing via chamber studies following an existing standard test method. Emitted particles were found to induce toxic responses; some detected VOCs are known carcinogens. Combining laboratory and model results showed potential exposure hazards to 3D printer emissions when operating in office or residential environments. Practices should be adapted to minimize exposure. These include printing at the lowest temperature feasible, selecting low emitting filament materials and filament brands, reducing the time of close contact with operating 3D printers, and placing printers in well-ventilated locations.

5 Acknowledgement

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6 References

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