Viitanen, Anna Kaisa; Kallonen, Kimmo; Kukko, Kirsi; Kanerva, Tomi; Saukko, Erkka; Hussein, Tareq; Hämeri, Kaarle; Säämänen, Arto

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Technical control of nanoparticle emissions from desktop 3D printing

Anna-Kaisa Viitanen[1] | Kimmo Kallonen[2,3] | Kirsi Kukko[4] | Tomi Kanerva[1] | Erkka Saukko[5] | Tareq Hussein[2,6] | Kaarle Hämeri[2] | Arto Säämänen[1]

[1]Finnish Institute of Occupational Health, Helsinki, Finland

[2]Institute for Atmospheric and Earth System Research (INAR), University of Helsinki, Helsinki, Finland

[3]Helsinki Institute of Physics (HIP), University of Helsinki, Helsinki, Finland

[4]Department of Mechanical Engineering, Aalto University, Espoo, Finland

[5]Pegasor Oy, Tampere, Finland

[6]Department of Physics, School of Science, University of Jordan, Amman, Jordan

Correspondence
Anna-Kaisa Viitanen, Finnish Institute of Occupational Health, P.O.Box 40, FI-00032 Työterveyslaitos, Finland.
Email: anna-kaisa.viitanen@ttl.fi

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Abstract

Material extrusion (ME) desktop 3D printing is known to strongly emit nanoparticles (NP), and the need for risk management has been recognized widely. Four different engineering control measures were studied in real-life office conditions by means of online NP measurements and indoor aerosol modeling. The studied engineering control measures were general ventilation, local exhaust ventilation (LEV), retrofitted enclosure, and retrofitted enclosure with LEV. Efficiency between different control measures was compared based on particle number and surface area (SA) concentrations from which SA concentration was found to be more reliable. The study found out that for regular or long-time use of ME desktop 3D printers, the general ventilation is not sufficient control measure for NP emissions. Also, the LEV with canopy hood attached above the 3D printer did not control the emission remarkably and successful position of the hood in relation to the nozzle was found challenging. Retrofitted enclosure attached to the LEV reduced the NP emissions 96% based on SA concentration. Retrofitted enclosure is nearly as efficient as enclosure attached to the LEV (reduction of 89% based on SA concentration) but may be considered more practical solution than enclosure with LEV.

KEYWORDS
contaminant control, desktop 3D printing, indoor air modeling, nanoparticle emission, risk management, ultrafine particles

1 | INTRODUCTION

Affordable material extrusion (ME) desktop 3D printers have gained wide popularity in recent decade with growing markets.[1] These printers are often used in educational institutions, libraries and enterprise engineering, marketing, and creative departments as well as by hobbyists. Concurrently as larger manufacturing companies are developing their own closed software printing systems, open software and hardware development is also underway.[2] With open-source 3D printers, users may change code, use different, perhaps completely new materials and printers such as RepRap can be modified by the user.[3] Even affordable open-source metal printers are possible in the future.[4] These trends are very meaningful especially when the number of people who have access to the 3D printing grows larger and larger and the need of knowledge on safety related to 3D printing grows.

Desktop 3D printers based on ME have been shown to emit nanoparticles in number of studies.[5-11] Also, gas-phase compounds, depending on the material, may be emitted during 3D printing.[10,12,13] Emissions are dependent mainly on the chemical composition of the 3D printing filament and nozzle temperature.[5,7,10] In addition, 3D printer malfunctions have been shown to affect the emissions.[9,10]

The need to control the exposure to emissions from 3D printers has been expressed in several studies. This is due to postulated negative health effects related to the exposure to nanoparticles. Long-term exposure to nanoparticles has been connected to, for example, cardiovascular diseases.[14] So far, only Gümberlein et al. (2018) have studied the acute health effects of 3D printing by exposing healthy volunteers to acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) emissions. Short time exposure (1 h) did not reveal acute changes but odor nuisance was reported.[15] Thus, the emissions are likely to have negative influence at least on workers' comfort and well-being. Office environments should also be suitable working environments for pregnant women and workers suffering from respiratory diseases such as asthma.

According to the theory and limited experimental data, conventional ventilation, engineered control measures, and filtration approaches should be applicable to nanoparticles.[16,17] In a survey made in USA, 83% companies utilizing carbonaceous nanomaterials reported that they were using chemical hoods and 71% were using local exhaust hoods. 40% were using ventilated enclosure or glove boxes and completely enclosed (isolated) production process 34%.[18]

A few studies reporting protective measures to control the emissions of 3D printers in controlled chamber conditions have been published.[19,20] Gu et al. studied commercial filter cover equipped with a fan connected to HEPA and an active carbon filters and air purifier with two different types of filters. The filter cover reduced the particle number concentration 93% and the air purifier 74%–90%. Kwon et al. reported removal effectiveness for enclosure, enclosure with a ventilation fan attached to different types of filters, and extruder suction fan. The removal effectiveness varied from 74% to close to 100% for enclosure with different configurations, whereas the extruder suction fan was not able to control the emissions at all. In a simulation study, the effectiveness of upgraded central HVAC filtration, stand-alone air cleaners, spot ventilation, and enclosure was modeled.[21] The most effective controls were achieved with spot ventilation and sealed enclosure.

In this paper, results of field measurements are presented. Here, four different engineered control measures for material extrusion desktop 3D printer in a common office room were tested: general ventilation, local exhaust ventilation (LEV), retrofitted enclosure, and retrofitted enclosure with LEV. Experimental measurement results were completed with indoor modeling. The need for protective measures in different office spaces based on modeling results is discussed along with the proper metrics to be used when protective measures are compared.

Practical implications

- Containment of the 3D printer is recommended to reduce the nanoparticle emissions to the room. Simple full enclosure over the printer reduces emissions significantly and even more if the enclosure is equipped with ventilation.
- If ME desktop 3D printers are used in office like spaces without containment, the ventilation commonly used in the office room is not sufficient in controlling NP emissions. This is true especially if the printing is regular or long-lasting and the room size is small. Locating the printer in the large space alleviates the conditions but still long-lasting printing causes high time-weighted concentration (8 h). Therefore, it is recommended that the 3D printer should be located to the unoccupied and well-ventilated space.

2 | METHODS

2.1 | Experimental setup

The measurements were performed in an office room with volume of 48.3 m^3 (3.5 × 4.6 × 3 m). There was some furniture (2 tables, bookshelves and chairs) in the room (Figure 1). The room was mechanically ventilated. The supply air was distributed to the room through a partly perforated ventilation duct. The room air was exhausted through two exhaust air grilles. Air flow rates of these general ventilation system were measured with iris type air flow measuring and balancing dampers (FläktGroup, Finland). In certain experiments, a local exhaust system (LEV) was used. It consists of ductwork, variable speed fan, and a HEPA 13 filter. The hood type varied depending on the system tested. The air was exhausted outdoor after filtration. The air flow rate of the LEV was controlled with variable speed fan and measured with orifice type meter (FläktGroup, Finland). During the measurements, the door and the windows were kept closed, and thus, the ventilation system accounted most significantly for the air change.

The 3D printer was placed on an office desk (Figure 1). For the study, the 3D printer (miniFactory Oy, Finland, model 3 Education Edition Single Extruder) based on the material extrusion technology (ME) was used. In ME, a polymer filament is heated to malleable state and extruded through a nozzle forming layers one top of another to create a 3D object.

Well prior the measurements, the printing surface was treated with hair spray to improve the attachment of the printed object. Significant particle formation during the heating of the printing bed that took place prior to the printing period was not observed. Still, hair spray may have minor influence on the emissions but was considered negligible here, because the focus was rather on engineering control methods than in emissions. Acrylonitrile butadiene styrene (ABS) (3D printing filament, 1.75 mm, color red) was used as printing material, while it is known to strongly emit nanoparticles. The printer was adjusted to heat the extruder to 240°C and the bed to 95°C throughout the study.

Four different scenarios were studied: general ventilation, LEV, retrofitted enclosure, and retrofitted enclosure with LEV (described

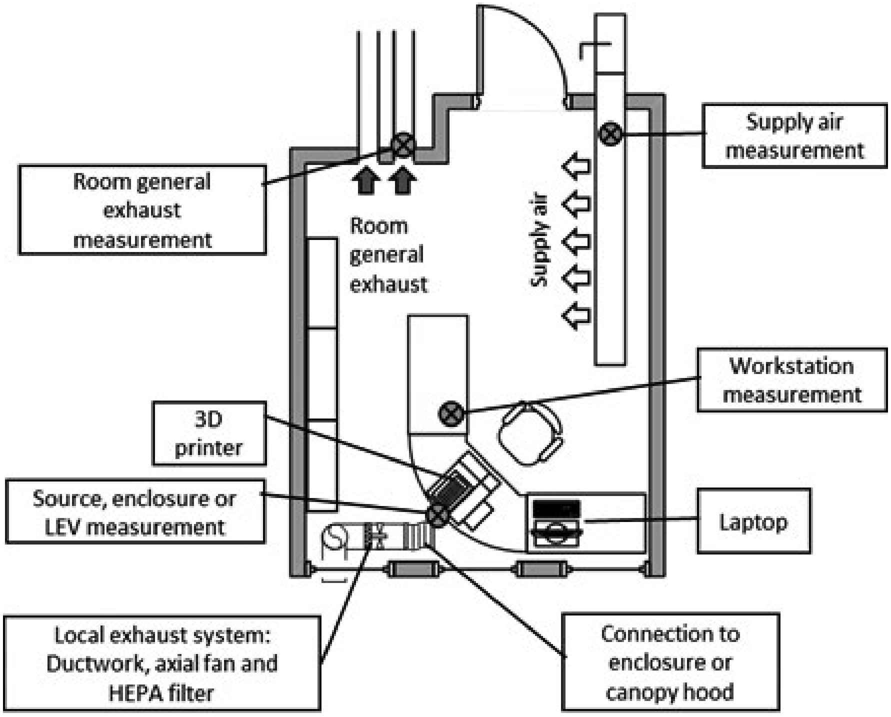

FIGURE 1 Layout of the test room and the location of the measurement points

more detailed below). The scenarios were studied with online nanoparticle measurement techniques. In case of mechanical ventilation, the measurement results were expanded to correspond to the situations where the printing times and the air change rates of the rooms with different volumes were varied by utilizing indoor aerosol modeling.

Every scenario was repeated two times. The duration of the printing period varied between 24 and 54 min, with 39 min being the average. A steady state was determined as a period of 10 min starting from 12 min and ending 2 minutes before the printing ended. Before and after the printing period, the background concentration was allowed to settle.

2.1.1 | General ventilation

The 3D printer was operated on the table in open space (Figure 2A). During the measurements, the supply air flow was 39 L/s (Q_s) and the exhaust air flow 32 L/s (Q_e). The air change of the room was 2.9 h^{-1}.

2.1.2 | Local exhaust ventilation

A canopy type local exhaust ventilation hood was placed above the 3D printer (Figure 2B). The distance from the edge of the hood to the 3D printer was app. 12–15 cm. The airflow of the LEV was set to 30 L/s (Q_{LEV}). To compensate the outgoing airflow in the room caused by the LEV, one of the room general exhaust air grilles was sealed resulting in the total exhaust airflow of 48 L/s, thus increasing the air change rate to 3.6 h^{-1}.

2.1.3 | Enclosure

The 3D printer was placed inside a custom-made plastic enclosure (Figure 2C). There was a maintenance door on one side and a route for the 3D printing filament through the sealing. The enclosure was not completely airtight, and some air change was plausible through the seams. The leakage of the enclosure was not studied *per se*. When the enclosure was used without LEV, general room ventilation was in use and the air change of the room was 2.9 h^{-1}.

2.1.4 | Enclosure with LEV

The 3D printer was placed inside a custom-made plastic enclosure attached with a LEV (Figure 2D). The exhaust airflow from the enclosure was adjusted to be 15 L/s (Q_{LEV}). To compensate the outgoing airflow in the room caused by the LEV, one of the room general exhaust air grille was sealed which resulted in the general room exhaust airflow of 18 L/s (Q_e) and the total exhaust airflow of 33 L/s. Air change rate was 2.5 h^{-1}.

The particle number size distributions from 2.02 to 63.8 nm were measured with a scanning mobility particle sizer (Q = 1.5 L/min, scanning time of 120 s; SMPS 3936 constructing of model 3080 N classifier and model 3776 Ultrafine Condensation Particle Counter, TSI Inc., Shoreview, MN, USA) and from 10 to 420 nm with NanoScan SMPS (model 3910, TSI Inc., Shoreview, MN, USA). The total number concentrations of the particles on the size range of 10 nm – 1 µm were measured with four identical diffusion chargers (Pegasor AQ^{TM} Indoor, CoorsTek Sensors, Tampere, Finland). Primary emission of the 3D printer was measured with the SMPS and Pegasor AQ^{TM} Indoor from the workstation next to 3D printer,

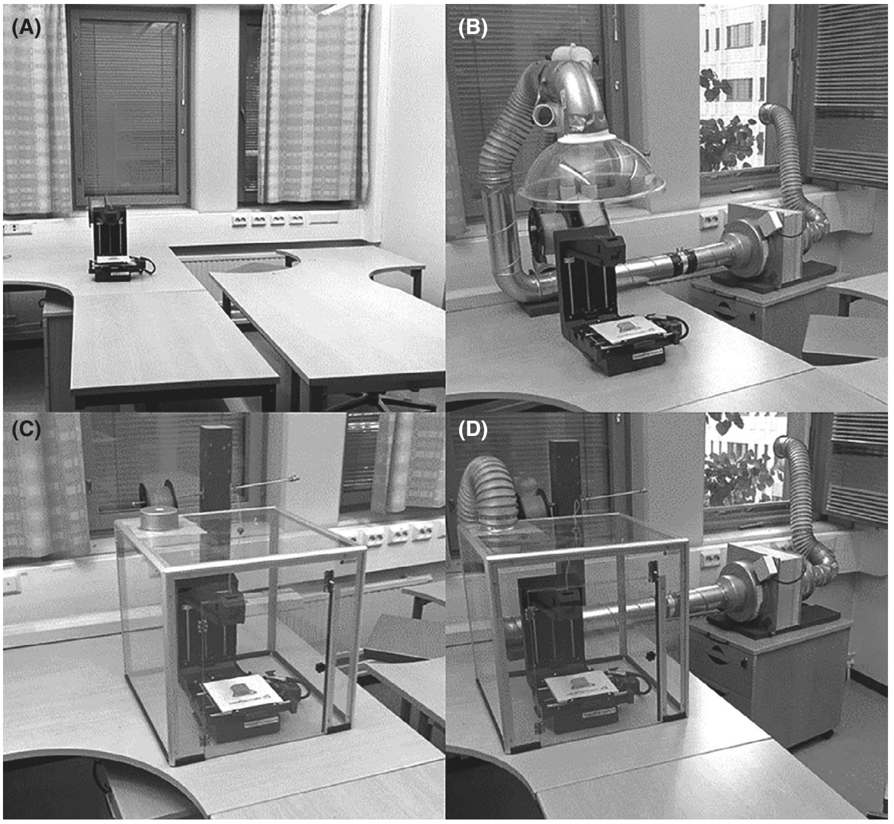

FIGURE 2 (A–D) The measurement setup with mechanical ventilation (A), local exhaust ventilation (B), enclosure (C), and enclosure with LEV (D)

inside the enclosure or, when the LEV was used, from the LEV duct. In addition, total particle number concentrations were measured from the incoming air inside the supply air duct (C_s), from the room general exhaust duct (C_e), and from the working space next to the 3D printer (C_{WS}) with diffusion chargers. The air from the working space next to the 3D printer was sampled directly without inlet tubing. Otherwise, conductive tubing was used as sampling line for SMPS and Tygon® tubing for diffusion chargers.[22] The sampling lines were kept as short as possible in order to minimize the losses.

2.2 | Statistical data analysis

Comparison of different control methods (treatments τ_i) was performed using analysis of variance with general linear model univariate procedure (IBM SPSS Statistics 25, IBM Corp.). Estimated marginal means was used to confirm the mean response for each treatment. Steady-state concentrations (y_{ij}) of particle number and surface area concentrations measured from the workstation and room general exhaust were calculated and used in the statistical analysis. Concentrations measured from supply air (x_{ij}) were used as a covariate in the model. This was done to eliminate the effect variations in background concentration.

To achieve normality and homogeneity of variances, the concentration values were ln-transformed before analysis. Post hoc pairwise comparisons of estimated marginal means were done using Bonferroni adjustment for multiple comparisons.

2.3 | Time-resolved indoor aerosol model

Indoor aerosol model (IAM) was used to simulate the time evolution of particulate matter (PM) concentrations in compartments of various sizes. In this study, single-compartment and size-resolved model was used.

The model is based on the mass-balance equation. The first-order differential equation accounts for the relevant physical processes describing the dynamics of indoor aerosols. The derivation and motivation of the equation have been illustrated extensively in previous studies.[23,24] The model used in this study numerically calculates the mass-balance equation in the form:

$$\mathrm{dI/dt} = \mathrm{P}\lambda\mathrm{O} - \left(\lambda + \lambda_{\mathrm{d}}\right) I + J_{\mathrm{coag}} + S \tag{1}$$

where I and O are, respectively, total PM concentrations indoors and outdoors; P is the penetration factor; λ is the ventilation rate; λ_d is the deposition rate; J_{coag} accounts for the coagulation of aerosol particles; and S is the emission rate of the aerosol source. The indoor air is assumed to be well-mixed, which means that there are no spatial variations in the indoor PM concentration within the compartment.

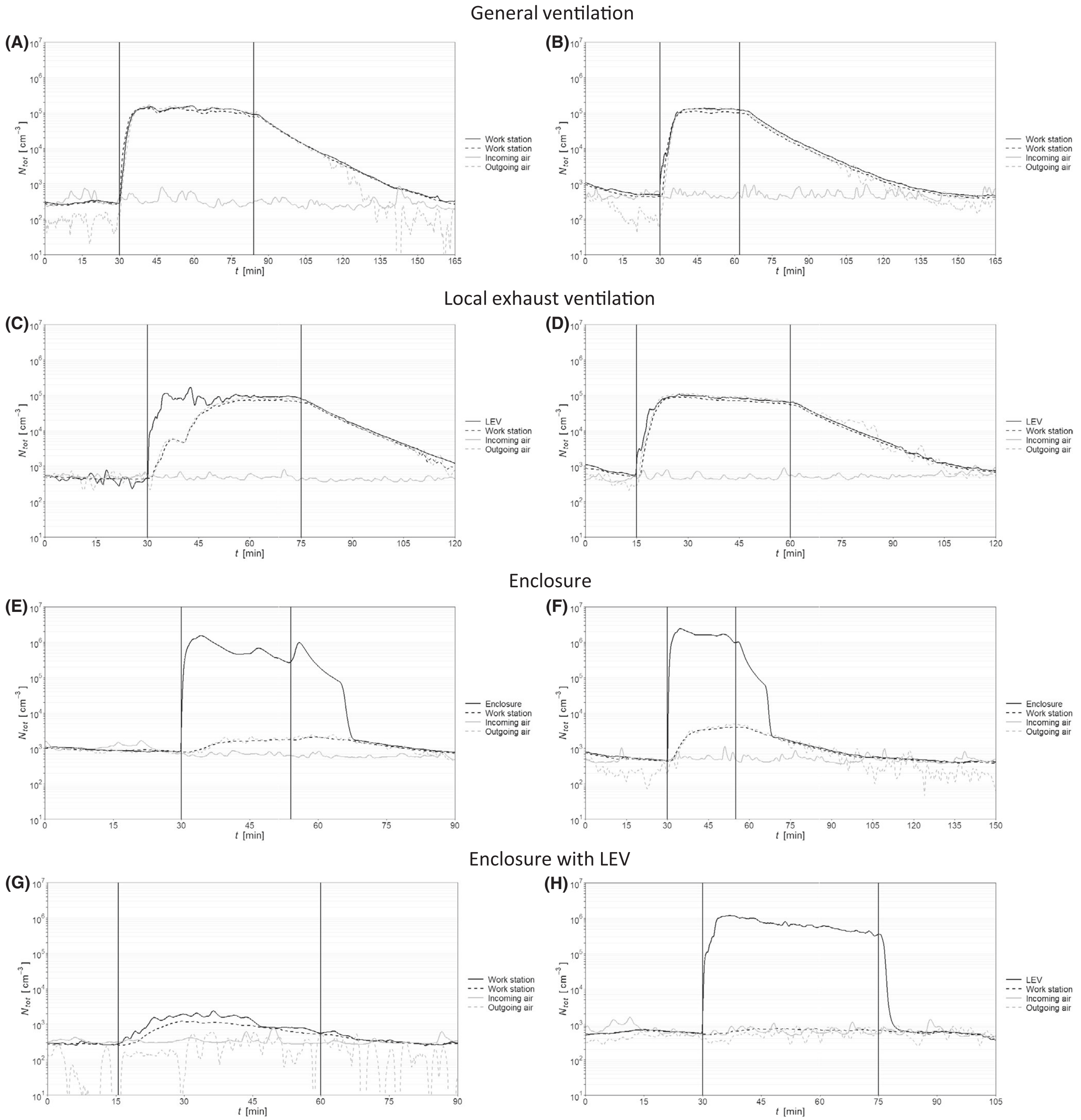

FIGURE 3 (A–H) Total particle number concentration measured from the emission source (black solid line), from the work station (black dashed line), from incoming air (gray solid line), and from outgoing air (gray dashed line) with general ventilation (A,B), LEV (C,D), enclosure (E,F), and enclosure with LEV (G,H). When measuring with the enclosure, it was kept closed 10 min (E) or 11 min (F) after the printing period. After the enclosure was opened, the dilution accelerated as seen in Figure E,F

The particle emission rate of the 3D printer was determined from a measurement in a controlled office environment using the IAM. The volume of the room and the ventilation rate was known. The penetration factor and outdoor PM concentration were determined by first considering the equation without the source term and fitting the model to match the background particle concentration observed in the measured data. Then with the source term added to the model, the deposition rate and the source emission rate were iterated until the model fit the measured data. With the knowledge of the emission rate, the effect of the 3D printer to the indoor air quality could be examined. The IAM enabled us to vary the room size, ventilation, and printing time. In this study, the examination was limited to three case studies corresponding to an average office room (48 m^3) and two larger rooms (108 and 168 m^3). The ceiling height was assumed

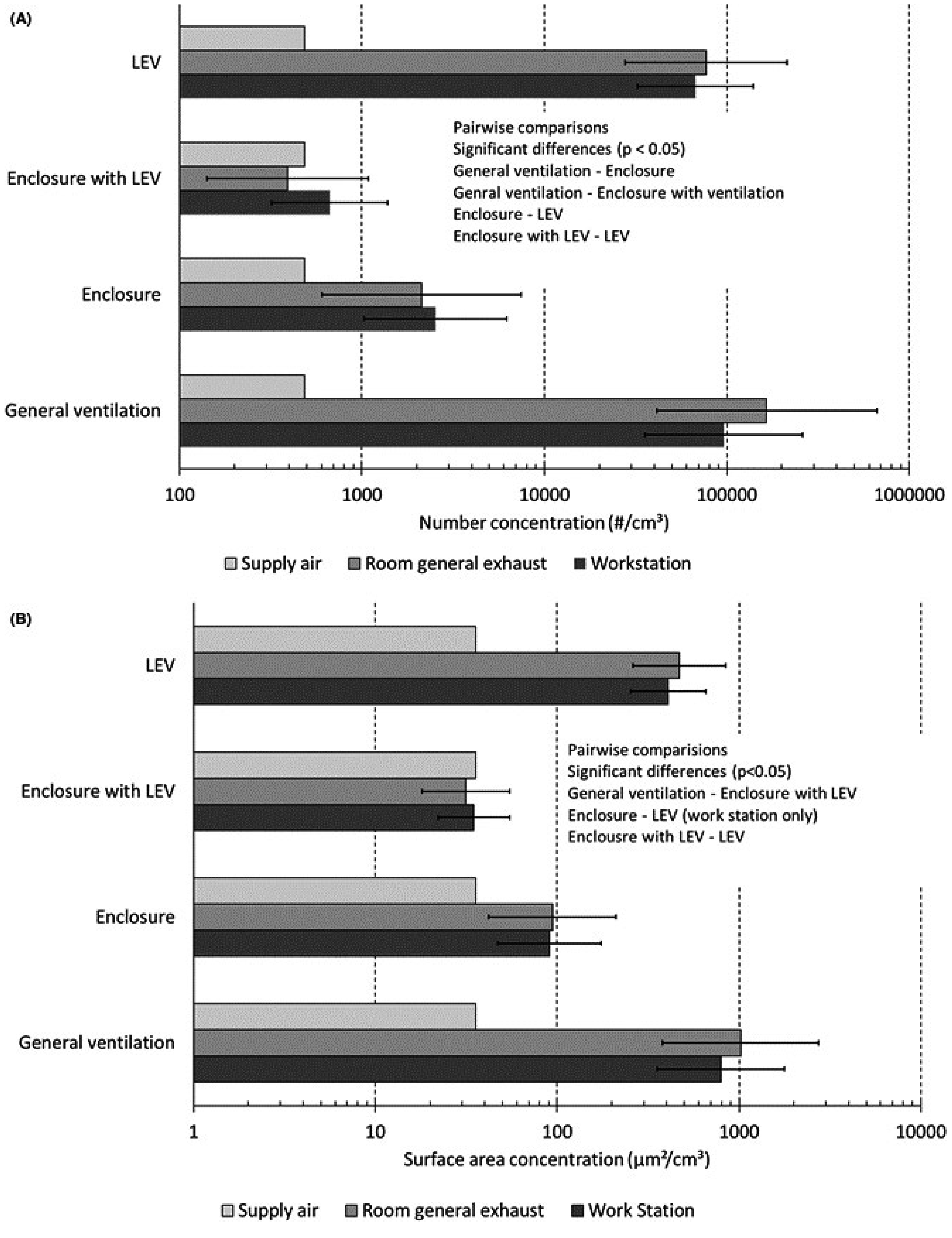

FIGURE 4 (A,B) Estimated marginal means and 95% confidence interval bars for different control approaches based on number (A) and SA (B) concentrations. Significant differences of the pairwise comparison of estimated marginal means with Bonferroni test are also shown for room general exhaust and workstation measurement points

to be 3 meters in all cases. The background particle concentration was subtracted from the total particle concentration, so that the effects of a 3D printer could be examined in isolation.

3 | RESULTS

Time series of the total particle number concentrations measured during different scenarios are shown in Figure 3A–H. During the measurements, the particle concentration measured from the supply air duct (incoming air) remained relatively constant during the 3D printing periods. The mean value of the steady-state concentrations during different printing events varied between 300–700 cm^{-3} and 20–50 $\mu m^2/cm^3$ for number and surface area concentrations, respectively (Table S1). Estimated marginal means for different control methods were calculated using SPSS GLM and considering the values for supply air as a covariate. When there was no activity in the room, particle concentrations measured from working space and from supply air followed each other relatively closely (data not shown). This indicates that there were no considerable nanoparticle sources in the room and that the influence of the leakage air from doors and windows were negligible to the nanoparticle concentrations.

The concentration measured from the general exhaust of the room and the concentration level measured from the working space followed the trend without major delays throughout the measurements. Thus, it can be concluded that the air in the test room was well-mixed.

3.1 | General ventilation

When the 3D printer was operated in the room with general ventilation, the nanoparticle concentration at the workstation elevated rapidly reaching mean steady-state concentrations (Table S1). Estimated marginal means for steady-state concentrations in the workstation measurement point were 96 200 cm^{-3} (95% CI: 35 500–260 700 cm^{-3}) and 794 $\mu m^2/cm^3$ (95% CI: 355–1774 $\mu m^2/cm^3$; Figure 4).

The measurements of the particle size distributions show that the emitted particles are in the nanoparticle size range (below 50 nm), and the mode of the distribution is between 10 and 20 nm (Figures S2A,B and S3B).

3.2 | Local exhaust ventilation

A local exhaust ventilation system (LEV) with canopy hood was attached above the 3D printer. The particle concentrations measured from the workstation were somewhat lower than those measured with the general ventilation (Table S1). Estimated marginal means for number concentration (67 200 cm^{-3}; 95% CI 32 300–139 600 cm^{-3}) and for surface area concentration (408 $\mu m^2/cm^3$; 95% CI 254–657 $\mu m^2/cm^3$) were 30% and 49% lower than that of general ventilation but the difference was not statistically significant (*p*-values 1.00 and 0.803; Figure 4, Table 1).

TABLE 1 Reduction in room air concentrations compared to general ventilation case when using the control methods

	Number concentration	Surface concentration
Enclosure	97%	89%
Enclosure with LEV	99%	96%
LEV	30%	49%

During the first measurement period, the concentration on the workstation was controlled by the LEV at first but, as the printing period proceeded, the concentration at the workstation reached the level measured from the LEV duct (Figure 3C). Also, the particle size distributions (Figure S2C) showed similar behavior. During the second measurement period, such effect was not seen, and the mean particle concentrations measured from the LEV, from the workstation, and from the outgoing air were relatively close to each other (Figure 3D). This indicates quite poor influence of the LEV to the air quality in the room. The size distributions measured from the workstation (Figure S2D) and from the LEV duct (Figure S3C,D) resemble the size distributions measured with the general ventilation (Figures S2B and S3B). There might be several reasons for the observed difference between tests. The air flow of the LEV was quite low which means that the effective distance of the LEV is quite small. Thus, the distance between the LEV and the extruder is significant, and minor changes in the position of the LEV may have drastic impact on the removal effectiveness. Also, the emission source is warm creating an emission plume that rises. Even though the conditions are controlled, the plume might fluctuate and escape from the reach of the hood. Most likely, the LEV has been closer to the nozzle at first, even though the distance was tried to keep as constant as possible. This demonstrates the importance of the positioning of the LEV proportional to the emission source.

3.3 | Enclosure

When a custom-made plastic enclosure was placed on the 3D printer, drastic decrease of nanoparticle emissions was seen on the workstation compared to the emissions measured from inside the enclosure and also to the scenarios where general ventilation and LEV were used (Figure 3E,F, Table S1). Estimated marginal means in the workstation were 2540 cm^{-3} (95% CI: 1030–6230 cm^{-3}) for number concentration and 91 $\mu m^2/cm^3$ (95% CI: 47–174 $\mu m^2/cm^3$) for SA concentration. Number concentration means were significantly lower compared to both general ventilation and local ventilation scenarios (p = 0.032 and 0.016; Figure 4). However, the comparison results for SA concentration were not so distinct (p = 0.079 and 0.040).

The steady-state mean number and SA concentrations measured from the workstation (Table S1) were about 0.3% and 0.4% from the

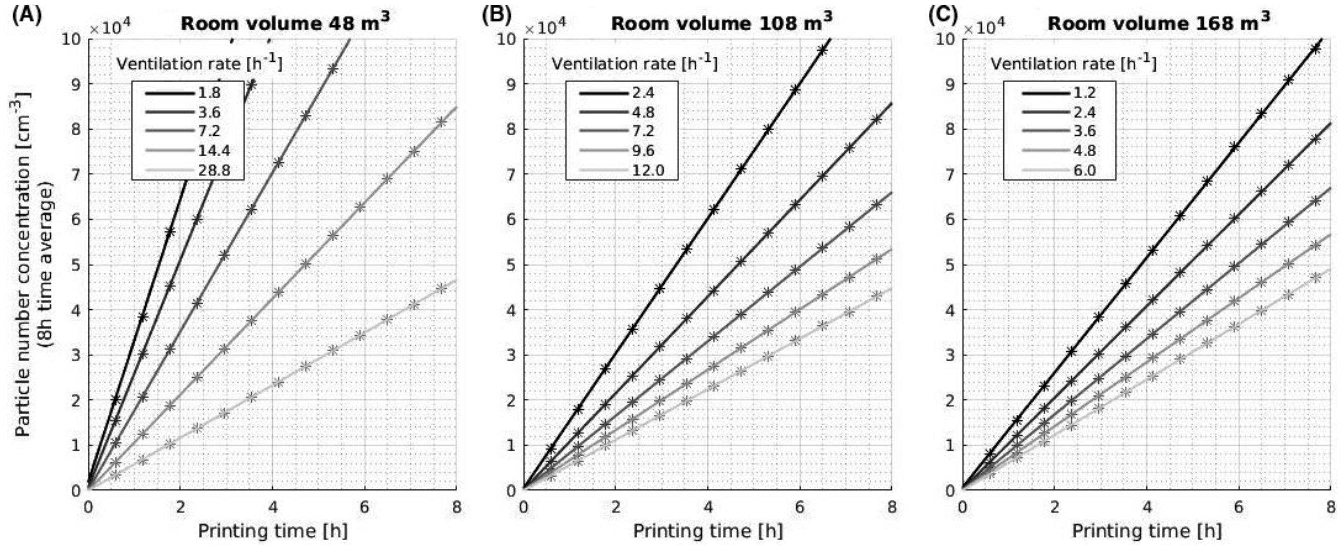

FIGURE 5 (A–C) Dependence of the 8-hour average particle number concentration depending on the size of the room (A–C) and ventilation rate (from black to light gray curves) of the printing time

concentrations measured from inside the enclosure, respectively. Estimated marginal means for number concentration at the workstation were 97% lower compared to the general ventilation scenario. For SA concentration, the reduction was 89% (Table 1).

Size distributions measured from the workstation show that the diameter of the nanoparticles slightly grew during the 3D printing event (S2E-F). Here, nucleation mode particles were not as intensively present as those are in case of general ventilation (S2A-B). Number size distributions measured inside the enclosure (Figure S3E,F) show how the nanoparticles coagulate inside the enclosure during the printing. The nanoparticles have had time to coagulate before those were released outside the enclosure via thermal convection when the temperature inside the enclosure rose, which was seen from the size distributions. The coagulation might explain the difference in exposure reduction seen between the number concentration and surface area concentrations.

3.4 | Enclosure with LEV

Attachment of a LEV to the enclosure decreased further the concentrations measured from the workstation compared to the scenario where only enclosure was used. During the first measurement period, some elevation of the concentration was seen on the workstation (Figure 3G, Table S1). During the second measurement period, the concentration on the workstation was comparable to the concentration measured from the incoming air duct (Figure 3H, Table S1). Estimated marginal means for this scenario in the workstation measurement point was 665 cm^{-3} (95% CI 320–1380 cm^{-3}) and 35 $\mu m^2/cm^3$ (95% CI: 22–55 $\mu m^2/cm^3$; Figure 4). The mean number concentration at the workstation was reduced by 99% and the surface concentration by 96% compared to general ventilation scenario (Table 1).

Particle size distribution measured from the workstation (Figure S2G,H) showed slight increase of particles below 20 nm during the printing. Particle size distribution measured from the LEV duct (Figure S3H) showed an intensive increase of nanoparticles during printing. The mode of the distribution was around 10 nm. This shows how the LEV is able to capture the nanoparticles that are being formed during the printing very effectively.

3.5 | The effect of the printing time, the room size, and the air change rate

By utilizing the indoor aerosol modeling, it was studied how the room size and air change rate effects on the particle number concentration. The results will help in decision making when other protective measures than general ventilation, such as LEV or enclosure, is needed.

A good fit for the background particle concentration was achieved with a constant outdoor concentration of 2000 cm^{-3} and penetration rate $p = 0.8$ (Figure S1). Deposition rate λ_d and the emission rate S were initially unknown, thus the values were iteratively determined. The deposition rate was found to be $\lambda_d = 2.1\ h^{-1}$, and during the printing process, the emission rate was found to be $S = 7.0 \times 1013\ h^{-1}$ (app. $1.2 \times 1012\ min^{-1}$).

Figure 4 shows the particle concentration in three different simulated rooms (48, 108, and 168 m^3) with varying printing durations. In the case of the office room with volume of 48 m^3, it was found out that with realistic ventilation rates, the particle concentration reaches very high levels even with printing processes that last only a few hours. In the larger spaces, the particle concentration levels remain moderate if the ventilation is efficient and only one printer is in use. Figure 5 also shows the influence of the printing time to overall air quality.

4 | DISCUSSION

In this study, four different technical control measures were compared in reducing the nanoparticle concentrations originating from the operation of one ME desktop 3D printer in an office room. The containment of the 3D printer nanoparticle emissions with a retrofitted enclosure was found to be an effective control measure with the reduction of 97% and 89% for the particle number and surface area concentrations, respectively. When the local exhaust ventilation system was attached to the enclosure and the exhausted air was vented outdoor through the HEPA filter, the reduction was even better, for particle number concentrations 99% and for SA concentration 96%. In Exposure Control Efficacy Library (ECEL) database, the estimated efficacy for enclosure is stated to be 86% (95% CI 30%–97%) and for the enclosures with local exhaust ventilation 86% (95% CI 69%–94%)[25] showing good agreement with the present study. Accordingly, Lo et al. studied ventilated enclosures in furnace operations producing nanoparticles and reported a nanoparticle reduction of 79% based on number concentration[26] being slightly lower than found in this study.

Also, results from 3D printer-specific studies support the removal effectiveness found in this study. Gu et al. studied commercial filter cover equipped with a fan connected to HEPA and active carbon filters.[20] The filter cover was reported to reduce both the particle number and surface area concentrations 93% even the air flow rate out of the enclosure was low (app. 2.5 L/s). Similarly, Kwon et al. found that the enclosure combined with a high-efficiency particulate air (HEPA) filter had the removal effectiveness nearly 100% for nanoparticles based on number concentration. When less efficient particle filters were in use, the removal effectiveness varied between 76% and 96%, and the removal effectiveness for enclosure without a ventilation was reported to be 74%.[19] Stefaniak et al. evaluated a custom-built ventilated enclosure at industrial 3D printing facility and found 99.7% reduction in particle number concentration.[27] In addition, Azimi et al. modeled the 95% removal efficiencies of an enclosure with gas and particle filtration.[21]

Yi et al. and Azimi et al. measured 3D printer emissions using enclosures that were not air tight resulting to clearly poorer reduction of the nanoparticle emissions than in the case of the above-mentioned studies including this one.[7,9] In this study, some leakage of the enclosure mainly due to thermal convection caused by the heated nozzle and printing bed was observed when the 3D printer was operated inside a retrofitted enclosure without any air change or LEV. If the printing time would increase most likely also the convection outside the enclosure would increase. Thus, design of the enclosure has a significant role when enclosure without an air exchange is used as a control method. Possible leakage should be taken into account when selecting suitable engineering methods for 3D printers. On the other hand, elevating temperature inside the enclosure may harm the electronics and lead to malfunction of the 3D printer.

Local exhaust ventilation (30 L/s) using canopy type hood was found to be inefficient in this study. The air flow rate of the LEV system was quite low but was comparable, for example, to the movable LEV systems used in soldering. The LEV air flow rate was selected taken into consideration what can be realistic in normal office room without unbalancing the air flows in the building too much. Reduction in the workstation number and SA concentrations was 30% and 49%, respectively. Azimi et al. modeled the removal efficiencies of spot ventilation systems with different flows.[21] According to their results, the high-flow spot ventilation (500 L/s) resulted to 100% removal effectiveness value where as low-flow spot ventilation (25 L/s) comparable with the one used in this study (30 L/s) resulted to the removal effectiveness of <10% in the near field of the 3D printer.[21] Similarly, Kwon et al. found that the extruder suction fan (0.27 L/s) resulted in poorer removal effectiveness than the reference condition when no control method was applied.[19]

The design of the 3D printer sets requirements for the LEV. If the 3D printer is designed so that the position of the printing bed is fixed and the nozzle is allowed to move vertically (as in this study), the positioning of the LEV close enough to the moving nozzle is extremely challenging. With 3D printer designs where the position of the nozzle is fixed and the bed is allowed to move, the use of LEV could be more effective. Also, the air flow of the LEV is in essential role. Here, the airflow was not strong enough, and with stronger airflow, better capture efficiency is most likely achieved. Also, some practical issues when using LEV were faced. Strong airflow from LEV can cause troubles with 3D printing when filament is cooling down too fast and not bonding with previous layer or the nozzle might not be able to keep its temperature decreasing the printing quality.

The general dilution ventilation (supply air flow rate 2.4 $L/s/m^2$; air change rate 2.9 h^{-1}) in the office room used in this study was not able to control nanoparticle emission from the 3D printer. During the 3D printing, nanoparticle concentrations were measured in the office room which were clearly higher than concentrations measured typically in the offices.[28] Also, Yi et al. measured nanoparticle concentrations in an office room and ended up to similar results.[9]

The influence of the room volume and the air change rate to the room air concentration was investigated with indoor aerosol modeling. Based on the results achieved with the model, concentration levels close to typical nanoparticle concentrations were not possible to reach with achievable air exchange rates in typical office rooms. In larger spaces (>100 m^3), the need for engineering control measures is not as essential as in the small office if the room ventilation is highly efficient and the durations of printing processes are moderate. However, with multiple printers and/or continuous printing processes, control measures are necessary also in larger spaces to maintain the nanoparticle concentration close to the background level and minimize the human exposure.

In general, the efficiency of the control measures has been investigated mainly based on particle number concentrations but in few studies also mass concentration has been used.[29-31] In their study, Zhang et al. used multiple metrics when studying nanoparticle exposure from gas metal arc welding process.[32] They found out that the presence of the engineering control measures influences more to the mass concentration than for the number and SA concentrations. They explained that the engineering control measure in use had higher efficiency to remove the larger-size welding particles than nanoparticles. In this study, the observed reduction of SA concentrations was lower than those measured with number concentrations. Coagulation seems to play an important role here. Based on these findings, studying the efficiency of the control methods based on the difference of particle number concentration may overestimate the reduction if the generated nanoparticles are able to coagulate, for example, in the case of enclosure. Thus, the SA metric is considered more reliable here and should be studied more to generalize the finding.

Altogether, this study supports the findings of previous studies that traditional engineer control measures are still effective to decrease nanoparticle levels in workplaces.[16,17,26,32,33] Finally, it is important to note that quite often, the 3D printers without enclosures are the least expensive ones, which may be used in schools and among hobbyists.

5 | CONCLUSION

With the online measurements and the indoor aerosol modeling, it was shown that during the 3D printing of ABS in a typical office room, nanoparticle concentration close to the typical level in the office environments may not be reached with achievable air change rates of the general ventilation. Canopy hood type LEV was found to poorly decrease the emissions with the airflow used here. From studied engineering control measures, enclosure attached to the LEV was found to most effectively prevent the nanoparticle emissions. However, according to the results, enclosure without LEV was found nearly as effective. The advantage of the plain enclosure is its low expenses compared to the enclosure with LEV.

While evaluating the performance of the technical control measure, the particle surface area concentration was found to be the best measure to study the difference of the efficiency of different engineering control measures. However, its utilization should be studied more to generalize the finding.

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CONFLICT OF INTEREST

Erkka Saukko works as a Senior R&D Engineer at Pegasor Ltd, the manufacturer of AQ Indoor. Otherwise, the authors declare no conflict of interest.

AUTHORS' CONTRIBUTION

Anna-Kaisa Viitanen equally contributed to conceptualization, data curation, formal analysis, investigation, methodology, resources, supervision, validation, visualization, and writing—review and editing and lead the funding acquisition, project administration, and writing—original draft preparation. Kimmo Kallonen equally contributed to data curation, formal analysis, methodology, writing—review and editing, and writing—original draft preparation. Kirsi Kukko equally contributed to conceptualization, writing—review and editing, and writing—original draft preparation and supported in funding acquisition, project administration and resources. Tomi Kanerva equally contributed to conceptualization, investigation, methodology, resources, and writing—review and editing and supported in writing—original draft preparation. Erkka Saukko supported in investigation and resources and equally contributed in writing—review and editing. Tareq Hussein equally contributed to conceptualization, formal analysis, methodology, supervision, validation, and writing—review and editing and supported in writing—original draft preparation. Kaarle Hämeri equally contributed to funding acqusition and supported in supervision and writing—review and editing. Arto Säämänen equally contributed to conceptualization, data curation, formal analysis, investigation, methodology, resources, supervision, validation, visualization, and writing—review and editing, and writing—original draft preparation.

DATA AVAILABILITY STATEMENT

Author elects to not share data. Research data are not shared.

ORCID

Anna-Kaisa Viitanen https://orcid.org/0000-0002-1677-6917
Kirsi Kukko https://orcid.org/0000-0002-7533-908X

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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