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The effect of activity and face masks on exhaled particles in children

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ABSTRACT

Importance: Despite the high burden of respiratory infections among children, the production of exhaled particles during common activities and the efficacy of face masks in children have not been sufficiently studied.

Objective: To determine the effect of type of activity and mask usage on exhaled particle production in children.

Methods: Healthy children were asked to perform activities that ranged in intensity (breathing quietly, speaking, singing, coughing, and sneezing) while wearing no mask, a cloth mask, or a surgical mask. The concentration and size of exhaled particles were assessed during each activity.

Results: Twenty-three children were enrolled in the study. Average exhaled particle concentration increased by intensity of activity, with the lowest particle concentration during tidal breathing (1.285 particles/cm^3 [95% CI 0.943, 1.627]) and highest particle concentration during sneezing (5.183 particles/cm^3 [95% CI 1.911, 8.455]). High-intensity activities were associated with an increase primarily in the respirable size ($\leq$ 5 μm) particle fraction. Surgical and cloth masks were associated with lower average particle concentration compared to no mask ($P = 0.026$ for sneezing). Surgical masks outperformed cloth masks across all activities, especially within the respirable size fraction. In a multivariable linear regression model, we observed significant effect modification of activity by age and by mask type.

Interpretation: Similar to adults, children produce exhaled particles that vary in size and concentration across a range of activities. Production of respirable size fraction particles ($\leq$ 5 μm), the dominant mode of transmission of many respiratory viruses, increases significantly with coughing and sneezing and is most effectively reduced by wearing surgical face masks.

KEYWORDS
Aerosol, Face masks, Respiratory particles

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INTRODUCTION

Respiratory viruses, including severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), are transmitted via respiratory droplets and aerosols generated by all activities that involve exhalation, including tidal breathing, speaking, singing, coughing, and sneezing.[1–5] Droplets, large particles subject to gravitational forces, are rapidly deposited from air and form fomites on surfaces. Aerosols, fine solid or liquid particles which remain suspended in the air, can travel long distances (>6 m) and reach high concentrations in poorly-ventilated areas.[6–11] The relative contribution of the various modes of infection (direct contact, indirect contact via fomite, large droplet, or aerosol) for various respiratory viruses is difficult to determine, but infectious virus survival has been demonstrated in aerosols containing the epidemic and non-epidemic coronaviruses, measles, influenza virus, parainfluenza virus, human rhinovirus, human adenovirus, and respiratory syncytial virus (with survival ranging from minutes to hours, depending on environmental conditions).[2,3,12,13]

The distinction between droplets and aerosols is somewhat arbitrary since the aerodynamic fate of a given particle depends on several factors including initial particle size, chemical composition, air temperature, relative humidity, airway size, and particle velocity.[8,11] Suspended particles ≤100 μm typically deposit in the nose and large extrathoracic airways (the inhalable size fraction), while suspended particles ≤10 μm can penetrate the trachea and bronchi (the thoracic size fraction), and suspended particles ≤5 μm can reach terminal bronchioles and alveoli (the respirable size fraction).[14–16] Though the highest concentrations of many respiratory pathogens have been found in particles 5 μm or smaller,[3,17,18] even large particles between 60 and 100 μm can dynamically change their size due to evaporation, behaving as thoracic or respirable particles.[8,19] Multiple factors affect the fate of particles at any given size, including the relative humidity of the microenvironment (lower humidity associated with longer survival time of exhaled particles), initial exhaled velocity, and mouth opening size (higher velocity and larger mouth opening associated with longer distances traveled).[8]

The coronavirus disease 2019 (COVID-19) pandemic and the changing epidemiology of respiratory viral infections have highlighted the importance of respiratory infections among children.[20–22] Upper and lower respiratory infections are major contributors to disability and death worldwide and are among the most common reasons for sick visits and hospitalizations among children.[23–26] Though most children have mild COVID-19 symptoms, several studies demonstrate that children carry similar or perhaps even higher SARS-CoV-2 viral loads than adults[27–29] and can efficiently transmit SARS-CoV-2 to each other and adults.[30,31] By February 2022, about 75% of US children aged 0–11 were seropositive for SARS-CoV-2, a higher seroprevalence than among adults.[32] Non-pharmacologic interventions to reduce droplet- and aerosol-based transmission of respiratory viruses, including social distancing and face masks, have been used previously[33] and were widely implemented early in the COVID-19 pandemic. Over that same time period, significant declines were noted in several respiratory viruses.[34–36] Nonetheless, the evidence supporting the use of face masks in children is almost primarily based on studies of adults.[37–39] and there remains a lack of consensus around the effectiveness of face masks in preventing pediatric respiratory viral transmission.[40–42]

Following evolving guidance from the Centers for Disease Control and Prevention (CDC) and the American Academy of Pediatrics, most schools have relaxed masking recommendations in communities where COVID-19 transmission rates and hospital admission rates are low and hospitals have sufficient capacity.[43,44] The World Health Organization expert guidelines suggest that while mask-wearing may have potential benefits for older children, the costs of blanket mask mandates may outweigh their benefits, and the need for mask mandates among children should be assessed contextually.[45] In anticipation of future increases in cases of COVID-19 or other respiratory viral infections, research regarding the factors that affect exhaled particle production and the effectiveness of face masks in decreasing droplet and aerosol production among children is urgently needed.[46] To address these knowledge gaps, we conducted a study of healthy school-age children performing a variety of activities while wearing commonly used face masks.

METHODS

Ethical approval

The study was reviewed and approved by the MassGeneral Brigham Human Research Committee (#2020P002630) and registered at ClinicalTrials.gov (NCT04518033). Informed consent was obtained from all the children's parents or guardians.

Study design and population

We conducted a prospective crossover study to determine the effect of activity type and face mask used on the concentration and size of exhaled particles produced by children across the school-age spectrum. Children aged 3–17 years who were able to follow instructions were eligible to participate in the study. Children with chronic neuromuscular conditions that affect respiration, children with tracheostomy tubes, and children who were unable to wear a face mask for the duration of the study (approximately 2 h) were excluded. Children with symptoms of

COVID-19 (fever, rhinorrhea, nasal congestion, sore throat, cough, muscle aches, anosmia, ageusia, or dyspnea) or recent exposure to an individual with COVID-19 were also excluded.

Aerosol sampling and characterization

The study was conducted in a hospital conference room (to simulate a school classroom) with the doors closed and the HVAC system turned off. The concentration (number of particles/cm^3) and size of particles were monitored in real-time and recorded using an Aerodynamic Particle Sizer (APS) Model 3321 (TSI, Shoreview, MN), which measures aerodynamic particle number concentration (number of particles/cm^3, hereafter referred to as particle concentration) as a function of aerodynamic size in the range of 0.5–20 μm. The flow rate of the APS device was set at 5.0 L/min, and particle size and particle concentrations were measured at one-second intervals. Exhaled aerosols/particles were sampled using a funnel placed directly in front of the nose and mouth of the participant (Figure S1). Participants were reminded to keep their nose and mouth within the funnel throughout the study. Prior to each participant's aerosol characterization, the APS device was zeroed with an in-line HEPA filter and baseline room air aerosol measurements were also collected (Table S1 and Figure S2).

Activities

We divided each participant's assessment into three series (no mask, cloth mask, and surgical mask) with five activities that increased the intensity of expiratory effort (tidal breathing, speaking, singing, coughing, and sneezing). Prior studies have demonstrated that on average, sneezing (classified here as the greatest intensity activity for particle generation) is associated with the highest exhaled flow rate and particle velocity, followed in decreasing order by coughing, singing, speaking, and tidal breathing.[47–49] During the first activity, children were asked to remain silent and breathe normally (through the nose and/or mouth) while in contact with the funnel. During the second and third activities, children were asked to speak and sing continuously, respectively. For the final two activities, children were asked to imitate a natural cough and a natural sneeze approximately every 10 s, respectively. Each activity was performed for one to three minutes as tolerated or until a steady state of particle concentration was observed. Between each activity, each child was given 1–2 min to rest.

Face masks

We used hospital-supplied surgical/procedure masks with ear loop attachments (Owens & Minor Halyard, Richmond, VA) and commercially available triple-layer pleated cotton cloth masks with adjustable ear loops (Old Navy - Gap, San Francisco, CA). Both surgical and cloth masks were fitted by study staff based on the child's age and size (pediatric-size masks were provided to younger children, and adult-size masks were provided to older children).

Questionnaire

At the end of each testing session, we asked participants to rate their overall experience and how easy it was to breathe through each mask they used on a Visual Analog Scale of 0 (lowest rating) to 100 (highest rating). We also asked them to indicate their favorite mask.

Analytic approach

We calculated the average particle concentration (total number of particles/cm^3) across all one-second sampling periods for each activity/mask combination. We calculated summary statistics for baseline characteristics, as well as particle concentration as a function of aerodynamic diameter, and tested for association of these variables with particle concentration using simple linear regression. We tested for differences in particle concentration between the different masks and activities using a one-way ANOVA with repeated measures. We conducted multivariable analyses using repeated measures mixed effects models with average particle concentration or mean particle diameter as the dependent variable, fixed effect covariates including age, sex, mask, activity, and interaction terms (testing for effect modification between age × mask, age × activity, and mask × activity), and the participant as a random effect. The model predicted values (marginal effects) were plotted for interaction terms using the R package "sjPlot," holding other fixed effect covariates constant (at the reference value for categorical variables and mean for continuous variables). These plots reflect effect modification (if present), defined as the effect of the factor on the outcome of interest varying across levels of another factor.[50] All analyses were conducted in Stata 17 (College Station, TX, USA) and R Studio 6.1.1 (Boston, MA, USA).

RESULTS

A total of 23 children were enrolled in the study; 22 children completed all study procedures (one child reported being tired and was unable to complete the study). Demographic characteristics are summarized in Table 1. The mean age of participants was 10.2 ± 3.6 years (range 5.1–15.6, Figure S3), and 13 (59.1%) were female. Table 2 reports the unadjusted association between participant characteristics and average particle concentration across all activities. There was a non-significant positive association between average particle concentration and age, height, and weight.

TABLE 1 Baseline characteristics of the participants ($n = 22$)

Variables	Characteristics
Age (years)	10.2 ± 3.6
Height (cm)	139.8 ± 23.6
Weight (kg)	37.6 ± 16.3
BMI (kg/m^2)	18.3 + 3.6
Female	13 (59.1)
Race†	
White	20 (90.1)
Black	3 (13.6)
Asian	1 (4.6)
Hispanic/Latino ethnicity	3 (13.6)
History of asthma	3 (13.6)

Data were shown as mean ± SD or *n (%)*. †Participant may choose more than one.

TABLE 2 Bivariate associations with average particle concentration (cm^{-3}) across all masks and activities

Demographic variable	Parameter estimate (β)	95% confidence interval	*P*
Age (years)	0.121	−0.026, 0.269	0.102
Height (cm)	0.019	−0.003, 0.041	0.092
Weight (kg)	0.028	−0.004, 0.060	0.083
BMI (kg/m^2)	0.075	−0.076, 0.227	0.311
Sex			
Female	Ref.		
Male	0.688	−0.383, 1.758	0.195
Hispanic/Latino ethnicity			
No	Ref.		
Yes	−0.120	−1.720, 1.479	0.877
History of asthma			
No	Ref.		
Yes	−0.002	−1.602, 1.599	0.998

Associations calculated by simple linear regression. Ref, reference.

Average particle concentration increased by intensity of activity, with coughing and sneezing as the highest intensity activities (Table 3). In participants not wearing masks, sneezing was associated with an approximately four-fold greater average concentration of particles compared to quiet breathing (5.183 [95% confidence interval {CI}: 1.911, 8.455] *vs.* 1.285 [95% CI: 0.943, 1.627]). The increase observed was greatest in the respirable size fraction (≤5 μm) range (Figure 1, Figure S4, and Table S2). The mean aerodynamic particle diameter of exhaled particles significantly decreased by the intensity of activity with the largest mean particle diameter observed during quiet breathing (1.634 [95% CI: 1.527, 1.740]), and the smallest mean particle diameter observed during sneezing (1.415 [95% CI: 1.314, 1.516]) ($P < 0.0001$) (Table S3)

Both cloth and surgical masks were associated with lower total particle release compared to no mask during sneezing. However, surgical masks were associated with a greater reduction in both total and respirable size fraction particle release compared to cloth masks across all activities (Tables 3, S2, and S4). For sneezing, cloth masks reduced total exhaled particle release by 45.6% (mean absolute difference of −2.365 particles/cm^3 [95% CI: −4.360, −0.371]), while surgical masks reduced total exhaled particle release by 54.1% (mean absolute difference of −2.802 [95% CI: −4.796, −0.807]), and release of respirable particles ≤ 5 μm by 54.1% (mean absolute difference of −2.802 particles/cm^3 [95% CI: −5.457, −0.146]). Cloth masks were not associated with significantly reduced particle introduction to the indoor air compared to no mask for any of the lower intensity activities (breathing, speaking, or singing); in fact, for several activities cloth mask use was actually associated with an increase in observed particle concentration.

Finally, we developed multivariable regression models with interaction terms to estimate the effect of activity by age, the effect of the mask by activity, and the effect of the mask by age. Significant effect modification was observed between activity and age, and between mask and activity, but not between mask and age. In particular, we observed: (1) a greater increase in average particle concentration with high-intensity activities among older children compared to younger children ($P_{\text{interaction}}$ age×activity = 0.003, Figure 2A); (2) a greater reduction in average particle concentration among high-intensity activities by surgical mask compared to cloth mask ($P_{\text{interaction}}$ mask×activity = 0.010, Figure 2B); (3) no change in the efficacy of masks by age ($P_{\text{interaction}}$ mask×age = 0.839, Figure 2C).

At the end of the study procedures, we asked participants to rate their experience wearing each of the mask types. The majority of children indicated they would prefer to wear cloth masks (64% ± 14%) over surgical masks (36% ± 8%) in a school setting, and most (16/22, 72.7%) indicated that their favorite mask was cloth. On a scale of 0 (worst score) to 100 (best score), participants reported an overall better experience wearing the cloth compared to surgical masks (72.1 ± 20.0 *vs.* 64.4 ± 18.0) but rated the breathability (how easy it is to breathe through a mask) of surgical masks better than cloth masks (83.8 ± 20.0 *vs.* 75.0 ± 21.0).

DISCUSSION

In this study of school-age children wearing commonly used face masks across a wide range of activities, we found that activities with greater intensity (coughing and sneezing) were associated with a higher production of exhaled

TABLE 3 Average particle concentration (95% confidence interval) (cm^{-3}) by mask type and activity

Activity	None	Cloth mask	Surgical mask	*P*
Breathing	1.285 (0.943, 1.627)	1.298 (1.046, 1.550)	1.160 (0.913, 1.407)	0.025
Speaking	1.329 (0.991, 1.668)	1.473 (1.175, 1.771)	1.247 (0.992, 1.501)	0.002
Singing	1.392 (1.055, 1.728)	1.409 (1.115, 1.702)	1.222 (0.984, 1.460)	0.042
Coughing	1.739 (1.276, 2.202)	1.674 (1.365, 1.983)	1.336 (1.087, 1.585)	0.027
Sneezing	5.183 (1.911, 8.455)	2.818 (1.866, 3.769)	2.381 (1.125, 3.637)	0.026
P	0.0002	<0.0001	0.009	−

P-value calculated by one-way repeated measures ANOVA across rows and columns. $F = 2.323$; overall $P = 0.0198$. −, not applicable.

particles. Higher production was particularly observed in the respirable size fraction, reflecting the formation of smaller exhaled particles during activities with a greater expiratory flow. Both surgical and cloth masks reduced the production of exhaled particles during high-intensity activities, though surgical masks were associated with reduced particle emissions compared to cloth masks across all activities.

Additional study findings included the observation of a significant effect modification of activity by age (a greater increase in average particle concentration with high-intensity activities among older children compared to younger children) and of activity by mask type (a greater reduction in average particle concentration among high-intensity activities by surgical mask compared to cloth mask), as seen in Figure 2. We did not find any evidence of effect modification of mask efficacy by age, indicating that face masks work equally well at reducing exhaled particles across the age spectrum.

Our study provides direct evidence that face masks are effective in reducing the release of exhaled particles when used by school-aged children. While our study enrolled healthy children and did not measure the effectiveness of face masks in reducing viral transmission, our findings are consistent with several epidemiologic studies that provide indirect evidence of face mask effectiveness among children. Prior to the COVID-19 pandemic, a large observational study measured the effectiveness of various interventions to reduce the spread of seasonal influenza among elementary schoolchildren in Japan; the authors found that face mask wearing was similar to that of vaccination, and even greater among older schoolchildren.[56] A study of South Korean schoolchildren found that children who reported continuous use of face masks had a lower rate of influenza infection during the H1N1 epidemic.[57] More recently, a study of children and adults with viral respiratory infections found a significant reduction in respiratory viral shedding of seasonal coronavirus and influenza but not rhinovirus.[58] In the setting of the COVID-19 pandemic, a study in Arizona found that COVID-19 outbreaks were 3.5 times as likely in schools without mask requirements compared to schools with mask mandates,[59] and a national study found that US counties without school mask requirements had higher increases in pediatric COVID-19 rates as schools reopened in fall 2021 compared to counties with mask requirements.[60] Similarly, a CDC study in Arkansas found the incidence of COVID-19 in schools to be 23% lower in schools requiring masks compared to those in which masks were optional,[61] and an analysis of the staggered lifting of mask mandates in Massachusetts schools found that the lifting of universal mask requirements was associated with an additional 44.9 COVID-19 cases per 1000 students and staff.[62] Other studies have used computational fate, transport modeling, and mannequin computational fluid dynamic simulations to evaluate the efficacy of mask-wearing in classroom settings,[63,64] and highlighted the importance of other environmental interventions (e.g., ventilation and barriers) in reducing the spread of respiratory viruses.

Two large randomized trials of face masks have been conducted among adults during the COVID-19 pandemic. The first randomized 6024 adults in Denmark to a recommendation to wear surgical masks versus none. The study found a non-significant reduction in COVID-19 infection among those who wore face masks (1.8% intervention *vs.* 2.1% control) over a 1-month period.[65] The second trial tested a multi-pronged face mask promotion technique together with free mask distribution in 300 villages in Bangladesh, resulting in an increase in face mask use from 13% in control villages to 42% in intervention villages. Both cloth and surgical face mask interventions were associated with reduced symptomatic COVID-19 seroprevalence compared to controls (9.3% for cloth masks, 11.2% for surgical masks).[66] A case-control study matching cases who had received a positive SARS-CoV-2 test result to controls who had received a negative result found lower adjusted odds of a positive test result among those who always wore a face mask or respirator in indoor public settings, with a significantly lower adjusted odds for those who noted that

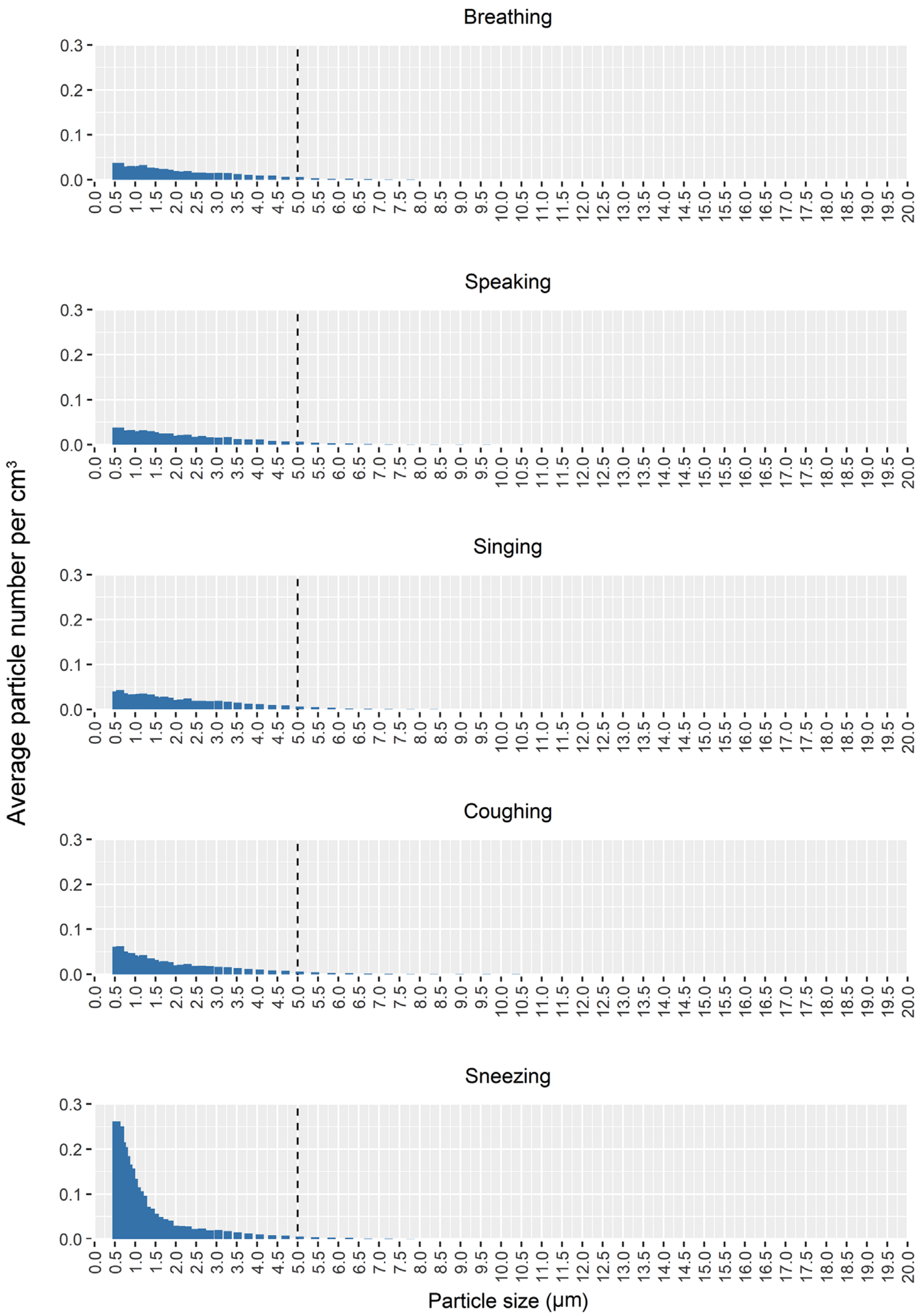

FIGURE 1 Particle size distribution across activities while unmasked.

they typically used N95/KN95 respirators.[67] These studies suggest that while the widespread use of face masks among adults may decrease community spread, wearing a surgical mask to protect oneself may provide only a modest benefit.

The paradoxical observation of increased particle emissions associated with cloth masks in our study compared to no mask is consistent with prior research.[51] Several studies have found that mechanical manipulation of cloth can aerosolize particles in the absence of respiratory emissions.[52–54] Asadi et al.[51] found that manual mask rubbing and jaw movement against cloth masks released high concentrations of particles, and they noted that the shedding of particles by cloth masks is a significant confounding factor in determining their efficacy to reduce the release of exhaled particles. However, a cluster randomized

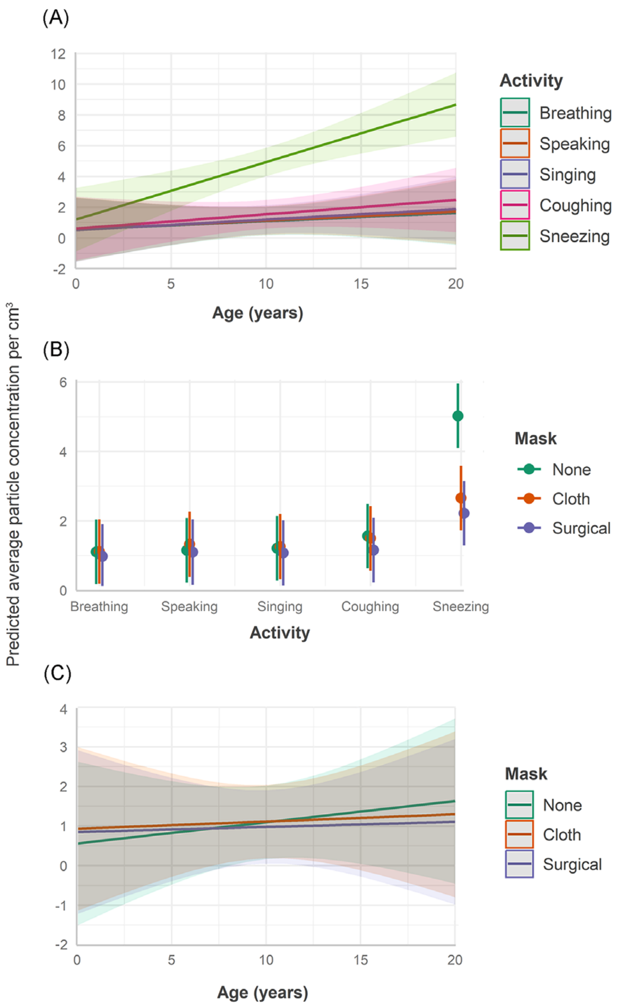

FIGURE 2 Effect modification plots of (A) age by activity, (B) mask by activity, and (C) mask by age using multivariable regression models.

controlled trial of 1607 hospital ward staff in Vietnam found that the use of cloth masks was associated with decreased incidence of influenza-like illness compared to surgical masks,[55] suggesting that surgical masks in fact provide superior protection against the spread of respiratory viruses in a healthcare setting.

The findings of our study are consistent with prior research regarding the efficacy and acceptability of various face masks. Both laboratory-based simulations and clinical studies have demonstrated statistically significant superior filtration efficiency for surgical compared to cloth masks (with the caveats regarding particle release by cloth masks noted above), and even greater filtration efficiency for KN95 and N95 respirators.[68–72] For example, in a laboratory-based simulation study using a model bacteriophage virus, viral filtration efficiency for a typical three-ply cloth mask was 54.4%–64.8%, compared to 98.5%–99.9% for surgical masks and 99.5%–99.9% for N95 respirators.[69]

While high-filtration masks or respirators may provide superior filtration efficiency compared to cloth and surgical masks, fit and leak around the mask are the major determinants of real-world protection.[73,74] At present, there are no internationally accepted criteria for review and standardization of pediatric masks or respirators, but any mask or respirator would need to be fit to the facial features and size of a child to be effective.

Children in our study commented on the superior breathability of surgical masks and the superior comfort of cloth masks. Prior studies have found that type and number of layers of filter material determine breathability and comfort; in most cases, additional layers of filter material provide higher filtration efficiency but greater pressure differential and lower breathability.[71] Ultimately, the choice of face mask must balance efficacy and willingness to wear a mask correctly in daily use.

Beyond adding to the growing evidence regarding the effectiveness of face masks, our findings also contribute to our understanding of exhaled particle production among children. A recent study among older children and adults found that children aged 12–14 years and adults aged 19–72 years generate similar amounts of aerosol in breathing, speaking, and singing.[49] In our study, we found that coughing and sneezing are associated with an increase primarily among particles in the respirable aerosol range. Though a further study of the physiology and mechanisms of respiratory particle formation among younger children is warranted,[46] our study highlights factors that affect the concentration and size of exhaled particles, which has implications for understanding and preventing airborne transmission of respiratory viruses. Knowledge of these factors would directly inform preventive measures, including the selection of appropriate personal protective equipment and hospital infection control guidelines for cohorting patients with respiratory viral infections.[6,7,75]

Our study has several limitations. First, the relatively small sample size does not provide sufficient power for subgroup analyses. In the future, the larger study could provide additional insight regarding the variability of exhaled particle transmission in a population and help identify factors associated with increased particle transmission. Second, our methods are limited to the detection of exhaled particles, and therefore we are unable to draw conclusions regarding the degree of protection provided by a mask to the wearer. Third, unlike some prior laboratory-based studies,[76–78] our measurements were not conducted in a clean chamber with zero ambient particles. Similar to other studies measuring the effect of particular activities on the relative production of particles,[51,79–83] our study design allows relative comparisons (e.g., breathing *vs.* sneezing, surgical *vs.* no mask), but limits our ability to compare absolute particle concentrations to the findings of other studies. Finally, our study was limited to volunteer participants in a clinical research study, who may be more adherent to appropriate mask-wearing than other children in real-world settings. The real-world effectiveness of face masks in reducing exhaled particles depends on the amount of time the mask is worn and whether the mask is worn correctly. Reported rates of adherence to face mask mandates in school settings ranging from 50% to 80%,[84–86] and a study reported that higher grade level and greater parental education were associated with greater mask adherence.[85] Future studies should address these limitations and ultimately must determine the benefit of face masks in reducing the transmission of respiratory viral infections among children.[58]

In summary, this study demonstrates that higher-intensity activities are associated with greater production of aerosol-size particles among children and that face masks effectively reduce the release of exhaled particles from high-intensity activities such as sneezing in indoor room microenvironments. Further research is urgently needed to determine the real-world effectiveness of face masks in preventing the transmission of respiratory viruses among children, providing data to inform infection control measures and public health guidance.

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CONFLICT OF INTEREST

Dr. T. Bernard Kinane is a member of the *Pediatric Investigation* editorial board.

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Additional Supporting Information may be found online in the supporting information tab for this article.

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