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Airflow dispersion during common neonatal resuscitation procedures: A simulation study

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Abstract

Background: Aerosol generating medical procedures (AGMPs) are common during newborn resuscitation. Neonates with respiratory viruses such as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection may pose a risk to healthcare workers. International guidelines differ on methods to minimize the risk due to limited data.

Objective: We examined the expiratory airflow dispersion during common neonatal resuscitation AGMPs using infant simulators.

Methods: Expiratory airflow dispersion in term and preterm manikins was simulated ($n = 288$) using fine particle smoke at tidal volumes of 5 ml/kg. Using ImageJ, we quantified dispersion during common airway procedures including endotracheal tube (ETT) and T-piece ventilation.

Results: Maximal expiratory dispersion distances for the unsupported airway and disconnected uncuffed ETT scenarios were 30.2 and 22.7 cm (term); 22.1 and 17.2 cm (preterm), respectively. Applying T-piece positive end expiratory pressure (PEEP) via an ETT (ETT^{PEEP}) generated no expiratory dispersion but increased tube leak during term simulation, while ventilation breaths (ETT^{VENT}) caused significant expiratory dispersion and leak. There was no measurable dispersion during face mask ventilation. For term uncuffed ETT ventilation, the particle filter eliminated expiratory dispersion but increased leak. No expiratory dispersion and negligible leak were observed when combining a cuffed ETT and filter. Angulated T-pieces generated the greatest median dispersion distances of 35.8 cm (ETT^{PEEP}) and 23.3 cm (ETT^{VENT}).

Conclusions: Airflow dispersion during neonatal AGMPs is greater than previously postulated and potentially could contaminate healthcare providers during resuscitation of infants infected with contagious viruses such as SARS-CoV-2. It is possible to mitigate this risk using particle filters and cuffed ETTs. Applicability in the clinical setting requires further evaluation.

KEYWORDS

aerosol biology, COVID-19, critical care, neonatal pulmonary medicine, resuscitation

1 | INTRODUCTION

Highly infectious respiratory viruses are associated with significant morbidity and mortality including severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) coronavirus disease 2019 (COVID-19).[1] Healthcare workers (HCWs) exposed to aerosol generating medical procedures (AGMPs) are vulnerable to respiratory virus contamination,[2] particularly if appropriate personal protection equipment (PPE) is unavailable, such as in low-resource settings, or is incorrectly used. Furthermore, respiratory bioaerosols from infected patients can contaminate the environment posing additional risk to other patients, visitors, and HCWs not immediately caring for the patient.[3]

Neonatal airway maneuvers are AGMPs and common during resuscitation in delivery rooms.[4] Although full PPE is recommended when resuscitating newborn infants where maternal COVID-19 is suspected or confirmed, international guidelines assessed the SARS-CoV-2 contamination risk to HCWs to be low[5,6] as the vertical transmission is unlikely.[7,8] However, the UK Obstetric Surveillance System (UKOSS) study[9] found that 5% of babies born to SARS-CoV-2 positive mothers had positive SARS-CoV-2 tests. As only symptomatic patients were tested, many more could have asymptomatic SARS-CoV-2 infection.[10] More recent U.K. data[11] found the incidence of SARS-CoV-2 positive infants ≤28 days old requiring hospital treatment during the first pandemic wave was 5.6 per 10 000 births, with a quarter born to positive mothers, a quarter born preterm, and many in neonatal and pediatric intensive care units. Furthermore, 42% of positive neonates were classified as having severe neonatal SARS-CoV-2 infection and 33% required respiratory support including invasive ventilation.

The effects of maternal COVID-19 around the time of birth and the associated higher preterm birth rate[9] could increase the need for HCWs to attend deliveries and provide resuscitation or stabilization and on-going care. Furthermore, infants may need readmission to hospital with community-acquired infection and require airway support in emergency departments, pediatric wards, and intensive care units. Providing care in these settings could expose HCWs to SARS-CoV-2, especially during AGMPs. There is insufficient evidence behind the airflow dispersion pattern and transmission risk to HCWs when performing AGMPs during neonatal resuscitation or stabilization.[12,13]

It is postulated that aerosolization during AGMPs in neonatal resuscitation is much lower than that of an adult due to the lower tidal volumes with dispersion distances of <2 cm estimated.[6,12] However, there are no neonatal data to support this and it is difficult to extrapolate the limited adult data[14] into neonatal settings. This has resulted in uncertainty and differences within international recommendations to minimize the contamination risk during neonatal AGMPs.[5,6,15–17] We aimed to examine the expiratory air dispersion during common neonatal AGMPs using term and preterm infant simulators and methods to reduce dispersion.

2 | MATERIALS AND METHODS

This simulation study used both term and preterm scenarios. All experiments were conducted in the Trent Simulation and Skills Centre (Nottingham University Hospitals NHS Trust, Nottingham, UK). The room used was identical to a typical obstetric theater used for surgical delivery of newborn infants with a resuscitaire (Hill-Rom Air-Shields RW82 VHA-1C) placed against the wall >2 m from the mother. This facility does not use negative pressure ventilation. Ethical approval is not required as this is a simulation study using manikins.

2.1 | Simulation model

Neonates create relatively small volumes during respiration. We used tidal volumes of 5 ml/kg for each simulation as this fell within the typical 4–6 ml/kg domains recommended by Keszler.[18] Simulations were re-created with term (Laerdal, Norway) and preterm infant manikins (Laerdal Premature), using a tidal volume of 15 and 5 ml per breath, respectively, based on a 3 kg term and 1 kg preterm newborn. The right bronchus of the manikin was clamped off to re-create a full expiration. A three-way tap with sealed tubing was attached to the left bronchus to instill smoke to visualize expiratory airflow pathways.

For each experiment, the same investigator (T.C.K.) injected the desired tidal volume over 0.5 s. The first breath was used to prime the dead space and was not included in the analysis, with subsequent breaths used for quantification. Four breaths were instilled on three different occasions giving nine quantifiable dispersion measures for each scenario.

2.2 | Airflow dispersion visualization

Previous studies have used fluid-based smoke generators to recreate aerosol dispersion data producing small particles <1 μm diameter, which poses the greatest bioaerosol risk as they linger longer in the air and penetrate deeper into the respiratory system.[3,19,20] A 500 W smoke machine (HA0196R; AGPtEK) was used to create nontoxic smoke with a mixture of mineral oil and glycol high-grade medium density fluid (160.587 UN; AVSL). To visualize the smoke, the room was fully darkened, and a black polyester background was used to negate any visual interference. Particle illumination was achieved using a 10 000 Lux LED light panel (Nature Bright). Video images were captured on a GoPro Hero high definition camera (12 megapixels 1080 at 25 frames/s; GoPro) fixed to a stand and placed 75 cm away from the manikin's mouth (E-video 1a-n).

2.3 | Experimental procedures

Common AGMPs occurring during newborn airway maneuvers in neonatal resuscitation in the delivery room or intensive care[4] were

TABLE 1 Table depicting the median (interquartile range) expiratory dispersion and leak, as well as maximum dispersion distance for the common aerosol generating medical procedures occurring during newborn airway maneuvers

Scenario	Model	Expiratory dispersion (cm)	Leak (cm)	Maximum dispersion (cm)
Unsupported airway	Term Preterm	21.4 (8.6–26.9) 11.3 (9.3–15.0)	0 0	30.2 22.1
Face mask^{PEEP}	Term Preterm	0 0	0 0	8.3 0
Face mask^{VENT}	Term Preterm	0 0	0 0	0 0
Face mask^{SIB}	Term Preterm	0 2.2 (0–2.6)	0 0	0 2.9
ETT	Term Preterm	11.3 (10.6–16.1) 12.0 (10.4–13.9)	2.9 (0.8–4.2) 0	22.7 17.2
ETT + Filter	Term Preterm	0 –	5.9 (4.2–8.1) –	12.5 –
ETT^{PEEP}	Term Preterm	0 16.5 (15.9–17.2)	10.3 (9.3–12.3) 0	20.2 17.5
ETT^{PEEP} + Filter	Term Preterm	– 0	– 0	– 0
ETT^{VENT}	Term Preterm	19.0 (16.4–24.0) 13.4 (12.5–14.2)	11.8 (4.6–13.7) 0	26.1 17.0
ETT^{VENT} + Filter	Term Preterm	0 0	8.6 (7.5–16.3) 0.9 (0–2.8)	22.4 3.6
ETT^{SIB}	Term Preterm	19.5 (14.0–25.0) 4.8 (4.0–6.0)	0 0	26.6 6.8
ETT^{SIB} + Filter	Term	0	11.7 (10.4–22.6)	27.0
Cuffed ETT	Term	19.0 (16.2–19.8)	0	22.3
Cuffed ETT^{PEEP}	Term	22.7 (20.8–23.3)	0 (0–0.9)	23.9
Cuffed ETT^{PEEP} + Filter	Term	0	3.3 (0–4.3)	4.6
Cuffed ETT^{PEEP} + Angled	Term	35.8 (31.1–36.7)	0	37.5
Cuffed ETT^{PEEP} + Angled + Filter	Term	0	3.0 (0–3.7)	3.8
Cuffed ETT^{VENT}	Term	19.2 (17.9–20.3)	0 (0–3.0)	21.0
Cuffed ETT^{VENT} + Filter	Term	0	5.1 (3.1–6.6)	8.5
Cuffed ETT^{VENT} + Angled	Term	23.3 (22.1–27.4)	0	30.0
Cuffed ETT^{VENT} + Angled + Filter	Term	0	4.0 (1.0–5.8)	11.1
Cuffed ETT^{SIB}	Term	6.7 (5.7–9.7)	0	10.8
Cuffed ETT^{SIB} + Filter	Term	0	0 (0–4.3)	4.3

Note: $N = 9$ exhalations per method.

Abbreviations: angled, angulated T-piece; ETT, endotracheal tube; PEEP, standard T-piece positive end expiratory pressure; SIB, self-inflating bag ventilation breath; VENT, standard T-piece ventilation breath.

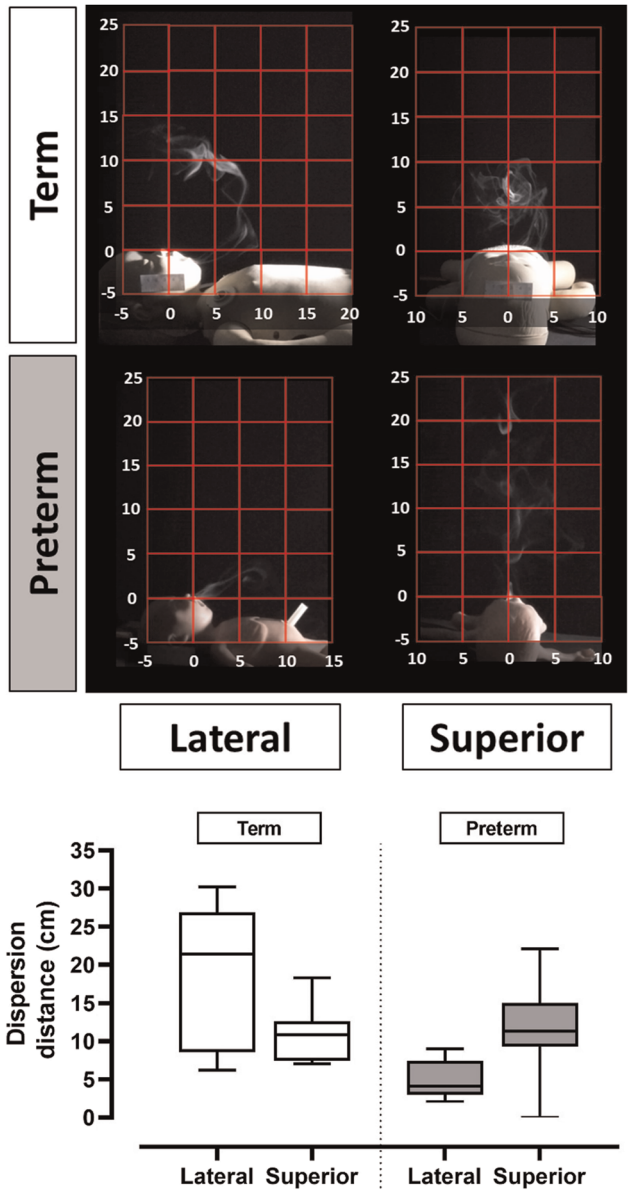


FIGURE 1 Representative images of airway dispersion pattern from term and preterm manikins in the unsupported airway scenario with bar chart representing dispersion distances. Grids represent 5 cm × 5 cm area. *N* = 9 per simulation [Color figure can be viewed at wileyonlinelibrary.com]

assessed. Airway procedures included: (1) unsupported airway; (2) standard uncuffed endotracheal tube (ETT) (3.0 mm diameter preterm, 3.5 mm diameter term; Portex Blue Line; Smiths Medical); (3) 3.5 mm cuffed ETT (Parker Medical; P3 Medical); (4) self-inflating bag (SIB; Laerdal Silicone Resuscitator); (5) silicone face mask (term and preterm; NeoFlow resuscitation masks; Armstrong Medical); (6) standard and angulated T-piece (Fisher & Paykel Healthcare); and (7) a particle filter (dead space approximately 35 ml; Ultipor 25). The airway procedures were carried out by D.S., an experienced neonatal consultant.

The study aims were to explore ways to minimize the aerosol dispersion around infants, thereby limiting the potential exposure risk of HCWs to highly infectious respiratory viruses including SARS-CoV-2. Therefore, we assessed three approaches to minimize aerosol dispersion: (1) particle filter; (2) cuffed ETT; and (3) angulated T-piece (allowing airflow to be directed toward the feet rather than vertically).

2.4 | Airflow dispersion quantification

For each quantifiable breath, we identified the maximal dispersion point and captured the freeze-frame image. These images were loaded into ImageJ analysis software.[21] Two researchers (T.C.K. and R.S.) independently measured the dispersion distances using ImageJ. A 5 cm marker placed at the manikin's head was used by ImageJ to scale each experiment when calculating dispersion distance. For the dispersion and leak measurement in the unsupported airway scenarios, the measurement point was from the tip of the manikin's nose. Airway leak was measured from the manikin's nose/mouth when using airway adjuncts. For ETT, T-piece, and SIB the measurement point was from the airflow outlet of each device (E-image 1). Experiments with an ETT were conducted using a T-piece at 8 L/min flow rate with 5 cm H_2O positive end expiratory pressure (PEEP) (ETT^{PEEP}), T-piece with ventilation breaths (ETT^{VENT}) of 30 cm H_2O (term), and 25 cm H_2O (preterm),[4] or a SIB with manual ventilation breaths (ETT^{SIB}). Data for each experiment were averaged and any significant outliers (>10% difference between two researchers) were adjudicated by a third researcher (D.S.).

2.5 | Statistical analysis

Data were not normally distributed, so dispersion distance was presented as median and inter-quartile range (IQR) along with maximum range to highlight the potential dispersion range. Measures of dispersion, and approaches to minimize these, were compared using Mann–Whitney *U* test with $p < .05$ considered significant. Data were analyzed using GraphPad Prism (Prism v8).

3 | RESULTS

A total of 23 scenarios were performed with nine dispersion measurements quantified per scenario giving 288 measurements in total.

3.1 | Unsupported airway and face mask ventilation

In the unsupported airway scenario, the median expiratory dispersion distances were 21.4 cm (term) and 11.3 cm (preterm) with maximal distances of 30.2 cm (term) and 22.1 cm (preterm). There was no measurable expiratory dispersion or leak during face mask ventilation using a standard T-piece. A median expiratory dispersion

distance of 2.2 cm was generated with face mask ventilation for the preterm manikin using a SIB (Table 1 and Figure 1).

3.2 | ETT

Using a disconnected, uncuffed, and uncut ETT, the median dispersion distances were 11.3 cm (term) and 12.0 cm (preterm). Ventilation using an ETT^{SIB} produced median dispersion distances of 19.5 cm (term) and 4.8 cm (preterm) (Table 1 and Figure 2).

Applying PEEP via a T-piece (ETT^{PEEP}) resulted in no visible expiratory dispersion but increased leak during term simulation with median leak distance of 10.3 cm, while ventilation breaths (ETT^{VENT}) caused significant expiratory dispersion (median of 19.0 cm) and leak (median of 11.8 cm). In the preterm simulation, the median dispersion distance during ETT^{PEEP} and ETT^{VENT} were 16.5 and 13.4 cm, respectively. No leak was visible across all preterm simulations using a 3.0 mm diameter ETT (Table 1 and Figure 2).

3.3 | Methods to minimize expiratory dispersion from neonatal AGMPs

3.3.1 | Particle filter

For term uncuffed ETT, the particle filter reduced expiratory dispersion distances to zero although at the expense of increased leak. The median leak distances when particle filter was added onto term uncuffed ETT were 5.9 cm (ETT disconnected), 8.6 cm (ETT^{VENT}), and 11.7 cm (ETT^{SIB}), respectively (Table 1 and Figure 3).

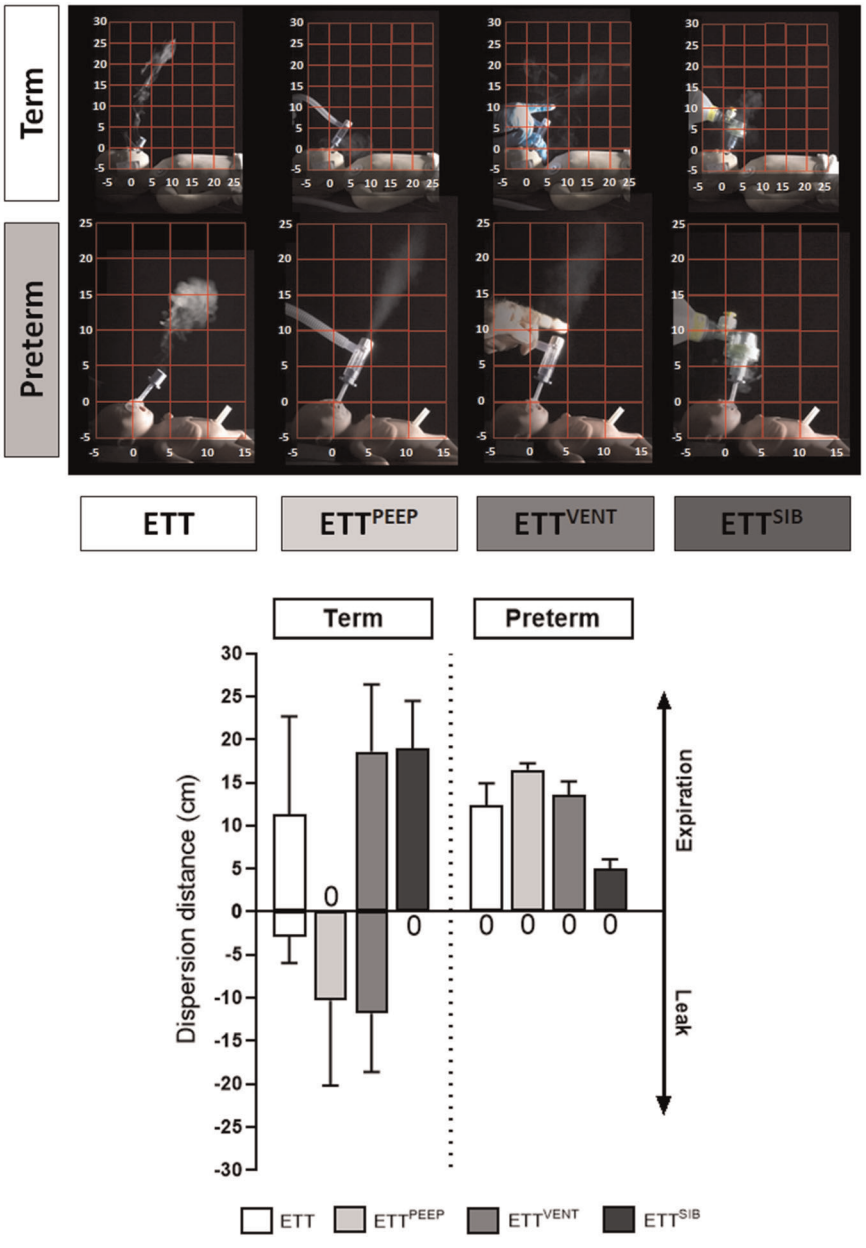


FIGURE 2 Representative images from term and preterm manikin airflow dispersion in the uncuffed endotracheal tube (ETT) scenarios (ETT disconnected, standard T-piece peak end expiratory pressure (ETT^{PEEP}), standard T-piece ventilation breaths (ETT^{VENT}), and self-inflating bag ventilation breaths (ETT^{SIB})) with bar chart representing dispersion distances and any measurable leak. Grids represent 5 cm × 5 cm area. $N = 9$ per simulation [Color figure can be viewed at wileyonlinelibrary.com]

3.3.2 | Cuffed ETT

Combining the cuffed ETT and particle filter reduced expiratory dispersion across all scenarios to a negligible amount. However, this was associated with a significant increase in the leak although this was less than that of the uncuffed ETT. The median leak was 3.3 cm (ETT^{PEEP}), 5.1 cm (ETT^{VENT}), and 0 cm (ETT^{SIB}), respectively (Table 1 and Figure 4).

3.3.3 | Angulated T-piece

Using a cuffed ETT with an angulated T-piece, the expiratory airflow dispersion was directed away from the operator. However, this resulted in a significant increase in dispersion distance for both ETT^{PEEP} (median 35.8 cm vs. 22.7 cm, $p < 0.01$) and ETT^{VENT} (median 23.3 cm vs. 19.2 cm, $p < 0.01$) compared to the standard T-piece. Inclusion of the filter eliminated all measurable expiratory dispersion with a small increase in the leak (Table 1 and Figure 5).

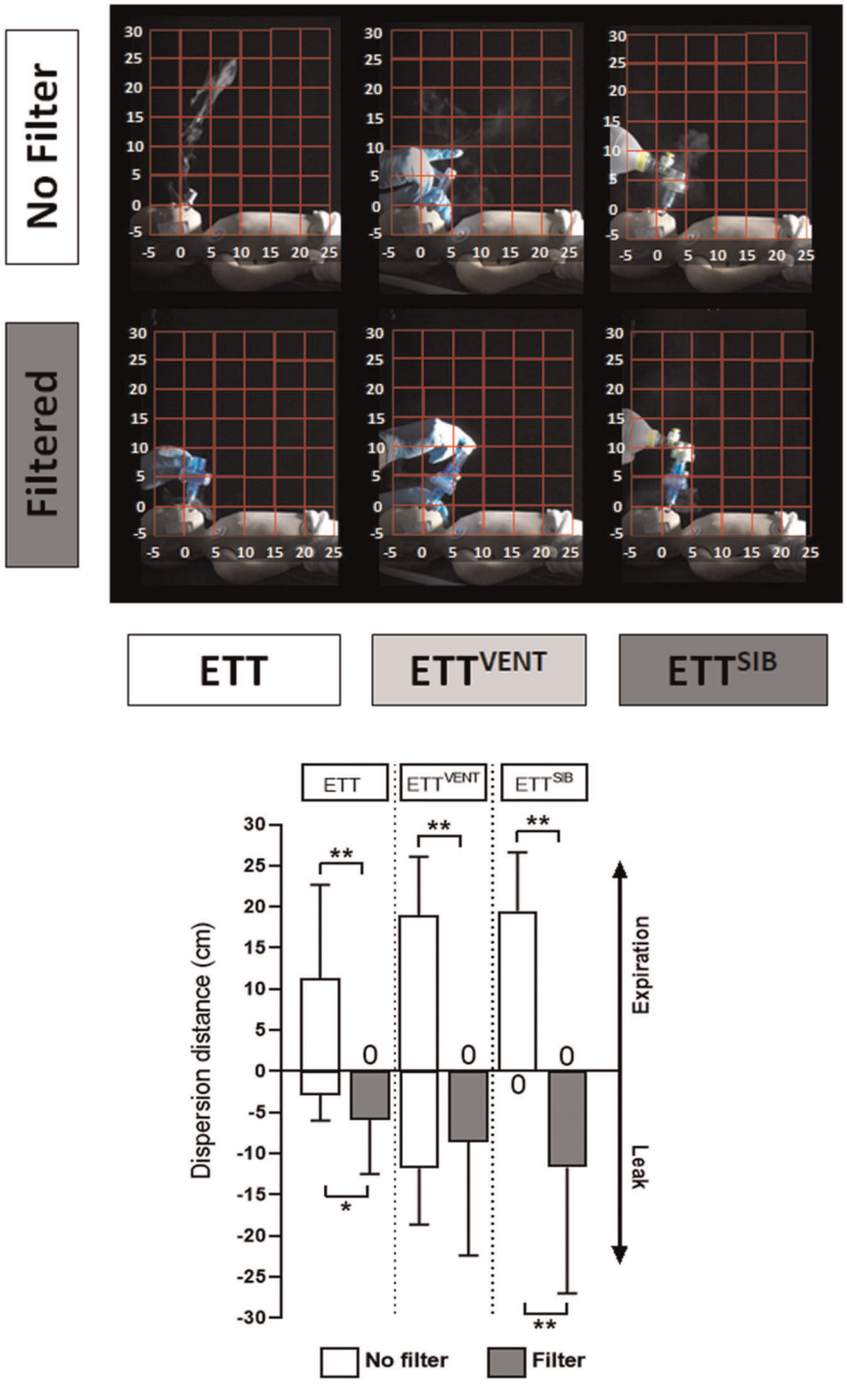
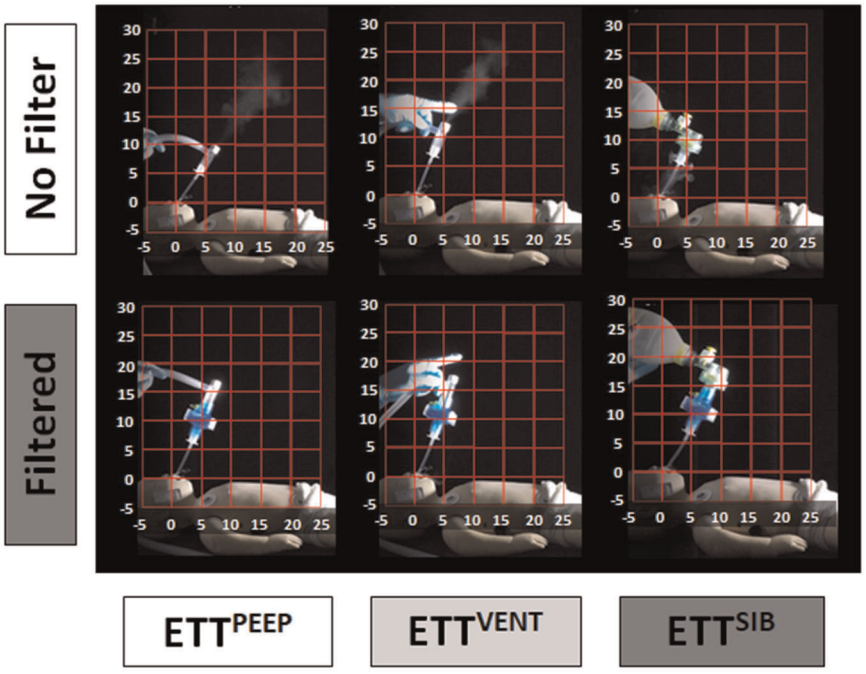


FIGURE 3 Representative images from term manikin airflow dispersion with the addition of a particle filter in the uncuffed endotracheal tube (ETT) scenarios (ETT disconnected, standard T-piece ventilation breaths (ETT^{VENT}) and self-inflating bag ventilation breaths (ETT^{SIB})), with bar chart representing dispersion distances and any measurable leak. Grids represent 5 cm × 5 cm area. $N = 9$ per simulation, $^{*}p < .05$, and $^{**}p < .01$ [Color figure can be viewed at wileyonlinelibrary.com]



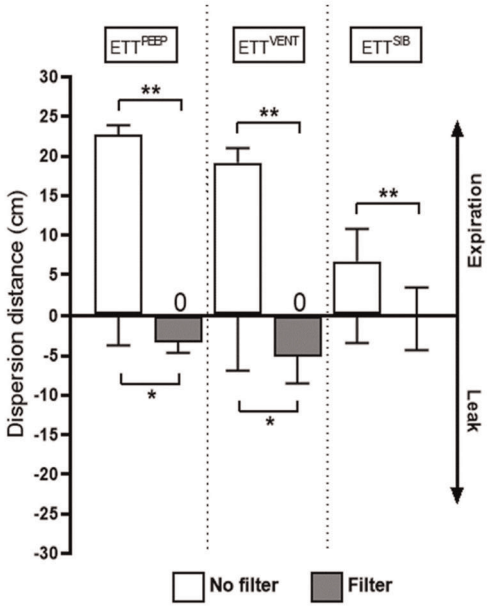


FIGURE 4 Representative images from term manikin airflow dispersion using a cuffed ETT in addition to the particle filter across various scenarios (standard T-piece peak end expiratory pressure (ETT^{PEEP}), standard T-piece ventilation breaths (ETT^{VENT}), and self-inflating bag ventilation breaths (ETT^{SIB})), with bar chart representing dispersion distances and any measurable leak. Grids represent 5 cm × 5 cm area. $N = 9$ per simulation, $^{*}p < .05$, and $^{**}p < .01$ [Color figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

Airflow dispersion during AGMPs in neonates has not previously been reported but is of significant importance to HCWs caring for infants infected with highly contagious respiratory viruses such as SARS-CoV-2. We demonstrate that even at small tidal volumes, significant airflow dispersion occurs during common neonatal AGMPs in newborn resuscitation. The expiratory dispersion for some of the common neonatal AGMPs may be over 10 times the distance previously postulated,[12] exceeding many incubator or resuscitaire platform footprints. This poses a contamination risk to those undertaking newborn AGMPs in infants with SARS-CoV-2, albeit a low risk. HCWs need to carry out newborn resuscitation in close proximity to the airway due to the small size of the infant and the intricacies of the procedures, making contamination more likely. Furthermore, resuscitation of newborn infants in intensive care settings often occurs in an incubator or on a resuscitaire whereby a negative pressure environment is not standard or possible, potentially increasing the exposure risk to airborne particles.[22–24]

4.1 | Face mask ventilation

Face mask ventilation is one of the most common methods used to support newborn breathing. We found no measurable

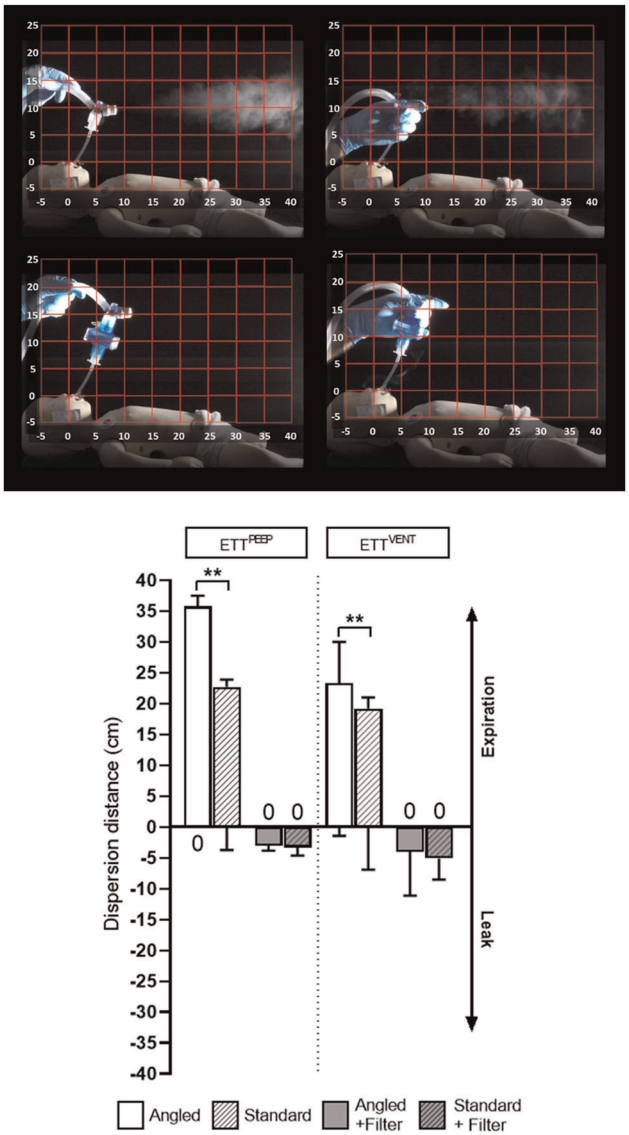


FIGURE 5 Representative images of airway dispersion pattern from term manikins using a cuffed endotracheal tube (ETT) in addition to (a) angulated T-piece; (b) standard T-piece; (c) angulated T-piece with filter; and (d) standard T-piece with filter, with bar chart representing dispersion distances and any measurable leak. Grids represent 5 cm × 5 cm area. $N = 9$ per simulation and $^{**}p < .01$. ETT^{PEEP}, endotracheal tube with T-piece peak end expiratory pressure, ETT^{VENT}, endotracheal tube with T-piece ventilation breath [Color figure can be viewed at wileyonlinelibrary.com]

dispersion or leak during face mask ventilation. This is potentially due to the greater dead space within the oropharynx[25] and the face mask itself (preterm 25 ml and term 35 ml). Although we did not explore the impact of practitioner's experience on airflow dispersion, good mask technique is crucial during face mask ventilation to minimize dispersion of expired air. The use of a particle filter during face mask ventilation may increase the leak due to the extra weight of the filter, especially in the hands of practitioners with limited neonatal resuscitation experience.

4.2 | Particle filter

Particle filters, as used in this study, are reported to remove almost 100% of airborne and liquid-borne pathogens including viruses.[26] In our study, the particle filter almost eliminated the expiratory airflow dispersion, potentially reducing the risk of viral dispersion. This is consistent with findings in adult practice.[19,27] However, the neonatal simulation models revealed that the elimination of expiratory dispersion with particle filters occurs at the expense of increased leak from an uncuffed ETT. Furthermore, the filter may add dead space and increase system resistance to the ventilatory circuit. Hence, it is advisable to use the appropriate size filter for newborn infants and avoid prolonged ventilation using this approach, especially in the smaller, extremely preterm infants.[12,13] It is also unclear if the addition of a filter could affect ventilatory technique especially during mask ventilation. The extra weight of the filter may impair effective mask ventilation technique leading to increased leak. We did not observe any visible leak although this requires further evaluation using respiratory monitors, which are able to measure leak.

4.3 | Cuffed or tight-fitting endotracheal tube

The combination of a particle filter with cuffed or tightly fitting ETT eliminated expiratory dispersion and reduced the leak compared to an uncuffed ETT. However, in neonates, the use of cuffed or tight-fitting ETTs can increase the risk of airway trauma and edema, although newer tubes may be safer for short-term ventilation.[28] Hence, cuffed or tight-fitting ETTs should be used with caution, especially for a prolonged period and in extremely preterm infants. If cuffed ETTs are used, a one-half to one size internal diameter smaller than that of uncuffed ETTs should be used.

4.4 | Angulated T-piece

The angulated T-piece resulted in the greatest expiratory dispersion when compared to the standard T-piece. This is likely due to the direction of gas flow and reduced airflow resistance in the angulated structure. Although the expired dispersion is directed away from the healthcare professional performing the airway maneuver, the greater expiratory dispersion distance increases the contamination risk of other healthcare providers who are within close proximity to the infant.

4.5 | Strengths

To the best of our knowledge, our study provides the first neonatal expiratory airflow dispersion data during common neonatal resuscitation AGMPs using term and preterm infant simulators. This provides new data to guide recommendations during newborn resuscitation and support mitigation strategies for HCWs resuscitating

infants with, or at risk of, contagious respiratory viral infections such as SARS-CoV-2.

4.6 | Limitations

As this is a simulation study, applicability in the clinical setting, environmental factors such as room airflow and filter dead space need further evaluation. Negative pressure rooms are often used for caring for patients with infectious respiratory disease, but these are often not available in the neonatal setting. Hence, additional examination in these settings would be desirable. There are no suitable neonatal manikins able to recreate different lung pathologies. Hence, we focused on the expiratory phase of respiration when AGMPs are most likely to create the greatest aerosol and risk of contamination. Airflow dispersion will vary depending on underlying clinical characteristics and pathology.

The airflow dispersion visualized in our study may be different from the actual dispersion of infectious droplets with the expired breath of newborn infants. There are no neonatal data on aerosol or droplet size, and the potential viral content of these, making the importance of dispersion distance unclear. However, aerosolization studies from adult patients with respiratory infections found a predominance of pathogens in small particles of <5 μm.[29] This is consistent with the size of particles generated by our smoke generator. With highly infectious agents such as SARS-CoV-2, precautions need to be taken and mitigation strategies adopted until this is better understood and more data becomes available as we learn more about aerosol transmission in other settings.[3]

5 | CONCLUSIONS

In summary, our study demonstrates that during common neonatal AGMPs, the risk of significant airflow dispersion is greater than previously postulated but that it can be reduced with good mask technique and the use of particle filters. Short-term cuffed or tightly fitting uncuffed ETTs should be considered on an individual basis depending on the clinical circumstances of the infant and risk of airway trauma, along with the risk of infectious respiratory viral transmission. These measures, alongside correct use of appropriate PPE, could minimize the risk of staff contamination from AGMPs when caring for infants potentially infected with SARS-CoV-2 or other respiratory viruses.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

T'ng Chang Kwok and Don Sharkey conceptualized the study, designed it, and ran the experiments. All authors analyzed/interpreted the data and drafted/approved the final manuscript.

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SUPPORTING INFORMATION

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

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