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Original Article

Aerosol generation with the use of positive pressure ventilation via supraglottic airway devices: an observational study


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Summary
The amount of aerosol generation associated with the use of positive pressure ventilation via a supraglottic airway device has not been quantified. We conducted a two-group, two-centre, prospective cohort study in which we recruited 21 low-risk adult patients scheduled for elective surgery under general anaesthesia with second-generation supraglottic airway devices. An optical particle sizer and an isokinetic sampling probe were used to record particle concentrations per second at different size distributions (0.3–10 μm) during use as well as baseline levels during two common activities (conversation and coughing). There was a median (IQR [range]) peak increase of 2.8 (1.5–4.5 [1–28.1]) and 4.1 (2.0–7.1 [1–18.2]) times background concentrations during SAD insertion and removal. Most of the particles generated during supraglottic airway insertion (85.0%) and removal (85.3%) were <3 μm diameter. Median (IQR [range]) aerosol concentration generated by insertion (1.1 (0.6–5.1 [0.2–22.3]) particles.cm⁻³) and removal (2.1 (0.5–3.0 [0.1–18.9]) particles.cm⁻³) of SADs were significantly lower than those produced during continuous talking (44.5 (28.3–70.5 [2.0–134.5]) particles.cm⁻³) and coughing (141.0 (98.3–202.8 [4.0–296.5]) particles.cm⁻³) (p < 0.001). The aerosol levels produced were similar with the two devices. The proportion of easily inhaled and small particles (<1 μm) produced during insertion (57.5%) and removal (57.5%) was much lower than during talking (99.1%) and coughing (99.6%). These results suggest that the use of supraglottic airway devices in low-risk patients, even with positive pressure ventilation, generates fewer aerosols than speaking and coughing in awake patients.

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Introduction
The COVID-19 pandemic significantly impacted perioperative patient care, with millions of elective surgeries cancelled worldwide [1] and healthcare workers placed at significant risk of infection, predominately via airborne transmission. Many hospitals abandoned the use of supraglottic airway devices (SAD) because of a perceived risk of aerosol generation. Instead, modified rapid sequence induction with tracheal intubation using videolaryngoscopy became the preferred airway management technique [2], to reduce environmental contamination [3]. Current infection control guidelines are based on a precautionary rather than an evidence-based approach [4], and there is a paucity of supporting evidence.
Shrimpton et al. found that the average aerosol concentration detected during SAD insertion and removal was similar to normal tidal volume breathing and produced significantly fewer aerosols compared with a single cough [5]. The use of tracheal tubes is associated with spikes in aerosol generation during coughing episodes in the tracheal extubation sequence [5–7]. Placement and removal of a SAD is less likely to induce coughing when compared with a tracheal tube. Due to these advantages, SADs have an established role in airway management and there are important implications for not recommending their use due to the risk of aerosol generation.

A concern of using SADs in conjunction with intermittent positive pressure ventilation (IPPV) is possible aerosol exposure because of an incomplete airway seal and, therefore, spontaneous ventilation has been suggested as a preferable mode [4]. Expiration around a deflated tracheal tube cuff showed a significant plume of unfiltered exhaled gases [8] and it has been suggested that the use of second-generation SADs is preferable [9]. However, there is a lack of evidence to support this assertion. There is a gap in the evidence of the actual aerosol risk associated with the use of SADs during IPPV. This study was designed to determine the risk and extent of aerosol generation using two types of second-generation SAD.

**Methods**

This two-group, prospective cohort study was conducted in two teaching hospitals of the University of Hong Kong (Queen Mary Hospital and Gleneagles Hospital) in conjunction with the Department of Mechanical Engineering of City University of Hong Kong. Ethical approval was granted by the local Institutional Review Board.

Adult patients, who were scheduled for elective surgery under general anaesthesia using positive pressure ventilation via a SAD, were eligible for the study. Only patients assessed as low risk for SARS-CoV-2 infection on the basis of travel, occupation, contact, cluster history, being asymptomatic and with negative rapid antigen test results were considered. We did not study patients with any of the following: history of, or anticipated, difficult airway management; gastroesophageal reflux; BMI > 30 kg.m⁻²; and/or emergency surgery.

General anaesthesia and ventilation techniques were standardised. Total intravenous anaesthesia was used with target-controlled infusions of propofol (modified Marsh model) and remifentanil (Minto model) or target-controlled infusions of propofol and manual infusion of remifentanil (μg.kg⁻¹.min⁻¹). Intravenous paracetamol 15 mg.kg⁻¹ (maximum 1 g) was given, and additional analgesics added at the discretion of the anaesthetist. A single dose of cisatracurium 0.15 mg.kg⁻¹ was allowed to be given at the discretion of the anaesthetist before insertion of the SAD. All patients received intravenous 8 mg dexamethasone and 4 mg ondansetron.

In Gleneagles Hospital, an iGel® airway (Intersurgical, Wokingham, UK) and in Queen Mary Hospital an LMA® Supreme™ airway (Teleflex Medical Europe Ltd., Athlone, Ireland) was placed after induction of anaesthesia. The size of SAD was chosen according to the manufacturer’s guidelines. Pressure controlled-volume guaranteed was the chosen ventilation mode commencing with a tidal volume of 8 ml.kg⁻¹ and titrated to maintain end-tidal carbon dioxide 4.7–6.0 kPa and peak inspiratory pressure < 20 cmH₂O. In Gleneagles Hospital, a Maquet Flow-i C30 anaesthesia and monitoring machine (Getinge AB, Göteborg, Sweden) and in Queen Mary Hospital, a GE Datex-Ohmeda Aspire anaesthesia machine (GE Healthcare, Chicago, IL, USA) was used, and the operating theatre ventilation system provided 20 air changes per hour. In Queen Mary Hospital, a GE Datex-Ohmeda Aspire anaesthesia machine (GE Healthcare, Chicago, IL, USA) was used, and the operating theatre ventilation system provided 20 air changes per hour. The operating theatres maintained a positive pressure value of 21.5 Pa during the whole period of measurement and surgery for each case. The average air velocity near the operating table was 0.2 m.s⁻¹ at 1.1 m above the floor. Air temperature in the operating theatres was set to 20°C and humidity at 60% as per local practice. Both hospitals used Philips monitoring systems (Philips Medical Systems Nederland B.V., Eindhoven, The Netherlands) for continuous pulse oximetry, ECG, capnography and non-invasive blood pressure every 5 min. Philips CompuRecord™ (Philips Medical Systems Nederland B.V.) recorded all peri-operative data. Anaesthesia was delivered by specialist grade staff and samples were simultaneously and continuously collected as described below.

A light, portable and accurate optical particle sizer (Model 3330; TSI Incorporated, Shoreview, MN, USA) was used to sample air at 1 l.min⁻¹ of flowrate. The optical particle sizer recorded the particle concentrations (number of particles.cm⁻³) per second at different size distributions. To achieve a representative sample of particle size distribution and to reduce the interference caused by air flow in the operating theatres, an isokinetic sampling probe (part number 1130011; TSI Incorporated) was used to connect the optical particle sizer. The sampling probe inlet was located at a fixed cranial position 50 cm above the patient’s mouth and attached to an adjustable frame to allow variation of operating table height. The sampling
probe inlet had an internal volume of 49 ml which generated a transit time of approximately 3 s between the sampling point and optical particle sizer, and this was considered during data processing. The optical particle sizer was used to capture a range of aerosols of 0.3–10 μm in 16 channels with a time resolution of 1 s and size resolution of < 5% at 0.5 μm. All healthcare workers present in theatre during insertion and removal of the SAD wore airborne personal protective equipment, in keeping with our institutional protocol for the delivery of general anaesthesia. The sequence of insertion and removal of the SAD were treated as discrete events. In addition, continuous aerosol monitoring was performed throughout the case as well as for 2 min after removal. The timing of airway intervention was noted by the research team and included: SAD insertion; manipulation; replacement; removal; facemask ventilation and other potential aerosol-generating events (e.g. coughing). Facemask ventilation was defined as manual bag/mask ventilation of an anaesthetised patient with no airway in place.

The average background concentrations from each individual case were recorded, and background subtraction was done separately for each case. As the operating theatres were not entirely devoid of particles at any time and background concentrations were fluctuant, background samplings were recorded at the start of each case before induction of anaesthesia when the operating theatres were in use but without aerosol-generating procedures being conducted. To reduce interference, all medical staff and researchers wore N95 masks. The background concentrations \( (C_{bg}) \) were then calculated using Eqn 1. We took the time average of background concentrations and subtracted these values from the measured concentrations for each case at each particle diameter channel to account for the effect of patient generated particles as far as possible.

\[
C_{bg} = \frac{\sum_{i=0}^{1} C_i}{N_{bg}} \quad (1)
\]

\( C_i \) is the concentration at the time of sampling, \( t \) is the sampling time in seconds (we define it as 180 s before the start of each anaesthesia procedure and before facemask ventilation) and \( N_{bg} \) is the number of datasets measured before anaesthesia commenced. The \( C_{bg} \) value is individual to each patient and was therefore different for each case. In addition, for each patient, there were two background values: one before facemask ventilation before SAD insertion; and one before SAD removal. For each case, the background aerosol concentration of the first two procedures (facemask ventilation before SAD insertion and SAD insertion) was measured and calculated separately from the background aerosol concentration of the last two procedures (SAD removal and facemask ventilation after SAD removal). Since the surgical procedures involved disinfection, cutting and diathermy which interfere with the identification of bioaerosol, this was treated as background noise for SAD removal and facemask ventilation after SAD removal using Eqn 1. To avoid the effects of dissimilar background concentrations, \( C_{bg} \) was deducted from each data point. If the aerosol value after subtraction was \( < 0 \), it was regarded as 0, which means no excess aerosols were produced by the patient during the procedure.

The method to plot the particle size distribution data was applied using normalised concentration \( (dN/d\log D_p) \) (Eqn 2), where \( dN \) is the number of aerosols and \( d\log D_p \) is the difference in the log of the particle diameter channel width (calculated by subtracting the log of the lower bin boundary \( (D_{pl}) \) from the log of the upper boundary \( (D_{pu}) \) for each channel). The concentration is divided by the bin width, giving a normalised concentration value that is independent of the bin width.

\[
\frac{dN}{d\log D_p} = \frac{dN}{\log D_{pu} - \log D_{pl}} \quad (2)
\]

To assess the level of aerosols produced during SAD use, comparisons were made with other aerosol-generating events. We measured aerosols generated during talking and active coughing in the operating theatre as comparators. One healthy researcher (male, BMI 23.4 kg.m\(^{-2}\), age 26 y) was studied for each activity. For each set of measurements, both talking and coughing lasted for 110 s. During the comparator recording, the researcher was in the same position as when the patients were being measured, when the operating theatres were in use but without other aerosol-generating procedures. Thus, these records from the researcher can be compared with aerosols detected during SAD use.

Data were exported and then processed and analysed using JMP software (SAS Institute, Cary, NC, USA) and Origin software (Originlab, Northampton, MA, USA). Shapiro–Wilk test was used to evaluate the normality of data distribution. For comparisons between aerosol measurements in statistical analyses independent t-test samples or non-parametric statistical analyses were used to evaluate differences between groups. The significance level was set at \( p < 0.05 \).
Results

In total, 21 patients (18 female) were studied with a median (IQR [range]) age 52 (47–59 [27–65]) y and BMI 22.5 (20.0–25.4 [17.8–27.6]) kg·m⁻². A total of 1,734,000 data points were measured during the study, of which 93,755 data points specific to the use of SADs were analysed. The ambient background monitoring recordings show the baseline level of aerosol median (IQR [range]) was 1.9 (0.8–3.5 [0.1–5.3]) particle·cm⁻³, at the start of each case before induction of anaesthesia (operating theatre in use but without aerosol-generating procedures).

Facemask ventilation before SAD insertion, SAD insertion, SAD removal and facemask ventilation after SAD removal all produced aerosols (Table 1). Generally, facemask ventilation time was <5 min, SAD insertion was completed within 25 s and SAD removal within 15 s. Figure 1 shows a time profile illustrating the main procedures. The mean (SD) peak increase in particle concentrations during the use of SADs (including facemask ventilation, insertion and removal of the SAD) was 7.3 (8.6) times significantly greater than baseline (p < 0.001). The peak particle concentrations are summarised in Table 1.

Between SAD insertion and removal, the size distribution of the aerosols generated was very similar (Fig. 2). During SAD insertion and removal, most particles (85.0% and 85.3%, respectively) were <3 μm in diameter, forming characteristic size distribution profiles (available in online Supporting Information Figure S1).

A neuromuscular blocking drug was administered if the anaesthetist felt it was appropriate (four patients: cases 12, 15, 16 and 18). The peak values of aerosol measured during SAD insertion were 1.3, 1.6, 0 and 7.6 particle·cm⁻³, respectively, and during SAD removal were 0.9, 1.0, 1.6 and 7.8 particle·cm⁻³, which were similar to the median peak values of cases where neuromuscular blockade was not used (1.8 and 1.6 particle·cm⁻³ during SAD insertion and removal, respectively (Table 1)). In addition, the concentration distributions against particle diameter trends were similar regardless of the use of neuromuscular blocking drugs available in online supporting information (online Supporting Information Figure S1).

The distributions of aerosol concentration and particle size during SAD insertion and removal are shown in Figure 3. Most particle sizes corresponded to median particle concentrations <2 particles·cm⁻³. Median particle concentrations during SAD procedural steps are shown in Table 2. In 10 patients (cases 1–9 and case 20; available in online Supporting Information Figure S1), an iGel was used: seven patients received a size 3 and three a size 4. In 11 patients (cases 10–19 and case 21 available in online Supporting Information Figure S1), an LMA Supreme was used: eight patients received a size 3 and one a size 4. Two patients had two insertion attempts, with an initial size 3 changed to a size 4. During use of both devices, there were small amounts of aerosol generation (Fig. 4) and the particle concentration and size distribution were similar (online Supporting Information Figure S2). The median particle concentrations values and orders of magnitude were similar for the iGel and LMA Supreme (Table 2).

The aerosols produced by SAD insertion/removal were lower than those generated by talking and coughing (Fig. 5). Particle counts produced during 110 s of continuous talking (median (IQR [range]) 44.5 (28.3–70.5 [2.0–134.5]) particles·cm⁻³) and 110 s of wet coughing (median (IQR [range]) 141.0 (98.3–202.8 [4.0–296.5]) particles·cm⁻³) were 40 times and 125 times, respectively, greater than during SAD insertion (median 1.1 particles·cm⁻³, p < 0.001) and were 21 times and 66 times, respectively, greater than during SAD removal (median 2.1 particles·cm⁻³, p < 0.001). The proportion of small, easily inhaled particles (<1 μm) was 3.5% (0.1–5.3%).

### Table 1 Aerosol disturbances above background levels caused by specific procedural steps during insertion of a supraglottic airway device (SAD). Values are median (IQR [range]).

<table>
<thead>
<tr>
<th>Procedure step</th>
<th>Peak value (particle·cm⁻³)</th>
<th>Peak increase (multiples of background concentration)*</th>
<th>Particle size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facemask ventilation before SAD insertion</td>
<td>8.5 (3.6–12.4 [1.6–170.6])</td>
<td>4.8 (2.8–6.6 [1.5–26.0])</td>
<td>0.3–10</td>
</tr>
<tr>
<td>SAD insertion</td>
<td>1.8 (0.6–7.9 [0.0–89.7])</td>
<td>2.8 (1.5–4.5 [1–28.1])</td>
<td>0.3–10</td>
</tr>
<tr>
<td>SAD removal</td>
<td>1.6 (1.0–4.2 [0.0–26.5])</td>
<td>4.1 (2.0–7.1 [1–18.2])</td>
<td>0.3–10</td>
</tr>
<tr>
<td>Facemask ventilation after SAD removal</td>
<td>6.6 (4.2–11.7 [1.0–85.5])</td>
<td>10.2 (3.4–19.4 [1.9–56.6])</td>
<td>0.3–10</td>
</tr>
</tbody>
</table>

*The ambient background monitoring recordings show the baseline level of aerosol (median (IQR [range])) 1.9 (0.8–3.5 [0.1–5.3]) particle·cm⁻³. The particle concentration values have been subtracted from the background quantitative amount. If the aerosol value after subtraction was < 0, it was regarded as 0, which means no excess aerosols were produced by the patient.
produced during SAD insertion and removal was also much lower (both 57.5% of the particles) than during talking and coughing (99.1% and 99.6% of the particles, respectively) (Fig. 5b).

In all 21 patients, only two significant, but mild, coughing cases were noticed during SAD insertion or removal, and these were of short duration and infrequent (total 1–3 times). Compared with other patients with straightforward SAD insertion and removal, no significant difference in aerosol concentrations was observed when coughing occurred (peak 2.0 particle cm$^{-3}$).

**Discussion**

In our hospitals, SADs are currently used at the discretion of the anaesthetist, given that current guidance in relation to aerosol generation is not evidence based. Nevertheless, the perception that they are not as safe as tracheal intubation has resulted in a significant decline in use. However, compared with the study by Dhillon et al. on aerosol generation during tracheal intubation and extubation [6], our results indicate that mean aerosol generation value is comparable but peak aerosol generation is much lower with a SAD than that generated during tracheal intubation and extubation (mean and peak particle concentrations increase during tracheal intubation 12 and 300 times greater than background, respectively). Compared with the findings of Shrimpton et al., which measured aerosol generation with a SAD [5], our results support their assertion that SAD use generates less aerosol than speaking and coughing in an awake patient. Our results also suggest that the brand of SAD has no effect on the amount of aerosol generated by a patient during anaesthesia procedures.

Insertion of a tracheal tube is more difficult and traumatic to the pharynx and larynx than inserting a SAD [10]. Compared with tracheal intubation, the use of a SAD is associated with a lower incidence of postoperative sore throat and hoarseness, may improve patient comfort [11].
and may reduce laryngeal morbidity after surgery [12]. In infants undergoing minor elective procedures, SAD use was associated with clinically significant fewer peri-operative respiratory adverse events and a lower occurrence of major peri-operative respiratory adverse events (laryngospasm and bronchospasm) compared with tracheal intubation [13]. Supraglottic airway devices are also relatively easy to insert and, consequently, are used in approximately 56% of all general anaesthetics administered in the UK [14]. Second-generation SADs offer improved safety against gastric aspiration and regurgitation, often have integrated bite blocks and provide higher oropharyngeal leak

**Figure 3** Aerosol concentration against particle diameter during supraglottic airway device (SAD) insertion and removal (n = 21 patients): (a) during SAD insertion; (b) during SAD removal. The abscissa is the lower channel diameter. The particle concentration values have been subtracted from the background quantitative amount. Means, black rhombuses; outliers, hollow rhombuses; medians, green lines; 25th and 75th percentiles, boxes; 1.5 IQR of aerosol concentration values, whiskers.

**Table 2** Particle concentrations during specific procedural steps during insertion of a supraglottic airway device (SAD). Values are median (IQR [range]).

<table>
<thead>
<tr>
<th>Step</th>
<th>Total cases</th>
<th>iGel cases</th>
<th>LMA Supreme cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facemask ventilation before SAD insertion</td>
<td>1.4 (1.0–2.5 [0.1–10.9])</td>
<td>2.3 (1.3–3.8 [0.6–6.5])</td>
<td>1.2 (1.0–2.0 [0.1–10.9])</td>
</tr>
<tr>
<td>SAD insertion</td>
<td>1.1 (0.6–5.1 [0.2–22.3])</td>
<td>3.8 (0.9–5.2 [0.5–12.2])</td>
<td>0.7 (0.3–3.7 [0.2–22.3])</td>
</tr>
<tr>
<td>SAD removal</td>
<td>2.1 (0.5–3.0 [0.1–18.9])</td>
<td>2.2 (1.2–4.9 [0.1–18.9])</td>
<td>0.5 (0.4–2.8 [0.1–6.1])</td>
</tr>
<tr>
<td>Facemask ventilation after SAD removal</td>
<td>1.4 (0.6–3.9 [0.3–25.3])</td>
<td>3.2 (1.7–7.2 [0.5–24.6])</td>
<td>1.1 (0.6–2.7 [0.3–25.3])</td>
</tr>
</tbody>
</table>

*Particle concentration values have been subtracted from the background quantitative amount.

**Figure 4** Time profile of aerosol generation during supraglottic airway device (SAD) insertion and removal from two example cases: (a) iGel (n = 1); (b) LMA Supreme (n = 1). The particle concentration values have been subtracted from the background quantitative amount. SAD insertion, solid line; dashed line, SAD removal.
pressures. The i-Gel has a soft, gel-like, thermoplastic, non-inflatable cuff, designed to provide an anatomical impression fit over the laryngeal inlet, resulting in a lower incidence of throat and neck complaints [15]. The LMA Supreme is also a second-generation SAD with a gastric channel. It has a patented seal with the oropharynx and another with the upper oesophageal sphincter which is purported to minimise gastric insufflation and reduce the risk of pulmonary aspiration.

The above advantages should remain a consideration in airway device selection. The findings of our study are relevant to all healthcare workers involved in the provision of anaesthesia for elective surgical procedures during infectious disease outbreaks. There may also be implications for those involved in emergency airway management, although this would require further study. Our results reinforce that the use of SADs, even with positive pressure ventilation, generates little aerosol in appropriately selected patients. Implementation of a peri-operative guideline requires collaboration between all relevant stakeholders and should be continuously updated as evidence emerges. The overall risk of transmission (airborne, droplet, fomite) is distinct from the risk from aerosol-generating procedures. A confounding variable is the physiological state of the patient (our cases were apparently healthy) [16] and a shift in paradigm is required from aerosol-generating procedures to aerosol-generating patients. The return to standard anaesthetic practice should be adopted for those who are deemed to be in the lowest risk stratification [17].

Our study has some limitations. The lack of an ultraclean operating theatre environment hindered the identification of all bio-aerosols associated with airway management. Measurement deviation may have been caused by human activities in the operating theatre, such as opening and closing doors, even though we attempted to reduce the environmental interference by removing background noise. Measurements of aerosol generation by SAD use were collected from patients, whilst the measurements of talking and coughing were collected from a researcher. Thus, differences in demographics may lead to differences in the measured data, although we tried to minimise this interference through statistical calculation, averaging data collected three times from the researcher.

Although the impact of the COVID-19 pandemic on life has been diminishing in many countries, we believe this study still has important implications for airway management during other respiratory infectious disease pandemics that may occur in the future.

Acknowledgements
The study was prospectively registered on the HKU Clinical Trials Registry (www.HKUCTR.com 2987). The authors thank the operating theatre staff of Gleneagles Hospital and Queen Mary Hospital who facilitated this research project. MI is an Editor and CN is an Associate Editor of Anaesthesia.
References

Supporting Information
Additional supporting information may be found online via the journal website.

Figure S1. Size distribution of aerosols generated during supraglottic airway device insertion and removal for all 21 cases.

Figure S2. Size distribution of aerosol concentrations during supraglottic airway device insertion and removal using different devices.