Computer Simulation Approach to Assessing Anesthetic Gas Leak Exposure to Theater Staff

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Anesthetic gas scavenging systems (AGSS) have been standard in UK operating theaters (OTs) since the 1980s, introduced to protect staff from exposure to volatile anesthetic agents such as nitrous oxide and isoflurane.[1] Early regulations were based on older anesthetic techniques that used high fresh gas flows and linear breathing circuits, combined with theaters that lacked modern ventilation design. Today, however, anesthetic practice has changed significantly. Low-flow circle systems, reduced use of nitrous oxide, and highly engineered ventilation systems raise the question of whether AGSS remains essential for staff safety.[2,3] To explore this, airflow and anesthetic gas dispersion were modeled using computational fluid dynamics (CFD) in a UK hospital environment.

This study focused on two spaces: the anesthetic room (AR) and the OT. The AR uses a clean airflow path (CAP) system delivering 15 air changes per hour (ACH), while the OT uses an ultra-clean ventilation (UCV) canopy capable of either 39 or 110 effective air changes per hour (eACH). CFD modeling was used to identify where anesthetic gases accumulate, which staff members are most exposed, and how different clinical scenarios influence exposure. Because real-world leak rates are difficult to quantify—influenced by fit of mask/airway, fresh gas flow, lung compliance, and APL valve setting, this computer model assumes a deliberately extreme "worst-case" scenario of 100% anesthetic gas leak at either the patient's head or the AGSS entrainment grill.

METHODS

The CFD model was first validated against real-world conditions using carbon dioxide (CO_2) as an inert tracer gas.[4] The physical rooms were digitally scanned and converted into a computational mesh of 3.8M discrete cells. After confirming that the model's predictions for CO_2 concentration showed excellent agreement with on-site measurements, the simulation phase for anesthetic gases began.

The gas properties in the validated model were then substituted for those of sevoflurane. While sevoflurane is heavier than CO_2, both behave as passive tracers in the turbulent, convection-dominated airflow of a ventilated room, making CO_2 a robust surrogate for validating the transport model. For the sevoflurane simulations, virtual monitoring points were placed in the breathing zones of personnel to record concentrations over time. These data were then used to calculate the eight-hour time-weighted average (TWA8) exposure levels presented in the results.

RESULTS

Airflow Patterns and Exposure in the AR

The AR's ceiling-mounted supply diffusers create a distinctive airflow pattern: air spreads along the ceiling, descends the walls, converges along the floor, and then rises toward the patient (Figure A). This updraft means that any gas leaking from the patient's mask or airway is carried directly into the anesthetic team members' breathing zones (Figure B). During induction—especially pediatric inhalational induction using open circuits such as the Ayre's T-piece—short-term sevoflurane concentrations exceeded 200 ppm for the anesthetic team.

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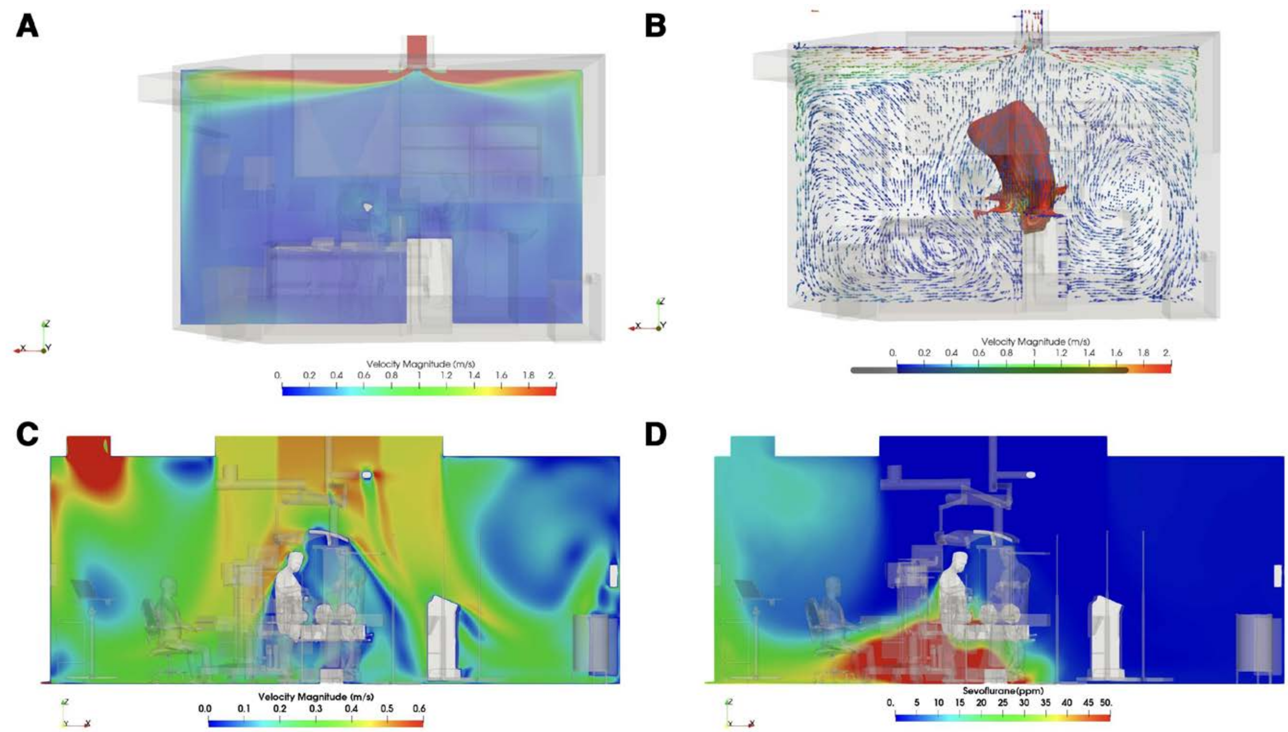

Figure. Visual representation of airflow and sevoflurane plume in both spaces. A, Anesthetic room airflow velocity. B, Anesthetic room airflow and sevoflurane plume. C, Operating theater airflow velocity. D, Operating theater sevoflurane concentration.

As expected, AGSS had little effect in this phase because it is not designed to remove gases released into the general room air. The study confirms that the AR is the location of the highest staff exposure, particularly during induction.

Airflow Patterns and Exposure in the OT

In contrast, the OT's UCV canopy delivers a strong downward flow of filtered air over the patient and surgical team (Figure C). This pushes leaked gases toward the floor and into low-level extraction grills. CFD visualizations showed that most of the theater space maintained low concentrations of sevoflurane and nitrous oxide, with the highest levels again near the anesthetist (Figure D). Equipment such as surgical lamps and robotic arms disrupted the airflow, creating small recirculation zones that could trap gases, but overall exposure remained far lower than in the AR.

Even with AGSS switched off, UCV significantly reduced gas accumulation. Increasing eACH from 39 to 110 further lowered exposure, demonstrating a clear relationship between ventilation rate and staff safety. However, the anesthetist—positioned near a ceiling-level recirculation extract—experienced the highest OT exposure, with maintenance-phase concentrations reaching 23 ppm in some scenarios (Table: clinical scenarios with both AR and OT inductions).

Impact of AGSS

AGSS scavenges excess gas from the circuit effectively, but when leaks occur at the patient's head, AGSS had minimal effect. Recent findings that only 25% to 50% of vaporized agent reaches AGSS in clinical practice mean that a substantial proportion of waste anesthetic gas escapes into the theater environment regardless of scavenging.[5–7]

Eight-Hour Time-Weighted Averages

To estimate daily exposure, the study combined steady-state CFD results (Supplemental Digital Content, Tables S1 and S2, https://links.lww.com/AA/F841) into typical clinical rotas (Table). Under the 100% leak assumption, anesthetists experienced TWA8 exposures of: (a) 13 to 37 ppm when inductions occurred in the AR; (b) 2 to 28 ppm when inductions occurred in the OT; (c) up to 40 ppm for nitrous oxide when used, for instance, during pediatric lists.

These values exceed recommended exposure limits for sevoflurane in some jurisdictions, but with an emphasis that the model represents an extreme and unrealistic leak scenario, with no staff movement or active equipment modeled. Real-world exposures are expected to be substantially lower.

DISCUSSION

The AR poses the greatest risk due to its airflow pattern and the high-leak nature of induction, contrasting

Table. Anesthetist's 8-h Average Exposure on Typical Clinical Days, Showing Highest Exposure During Pediatric High Turnover Lists and Using AR for Induction

	Procedure(s)	Reps	TMA8 (ppm)	TMA1 (ppm)
Day 1	One long case, eg, oesophagectomy • Induction in AR: 10 min @ 8 L/min [AR1/*OT5*] • Maintenance for 480 min @ 0.5 L/min in OT [OT4 and OT8] • Total 490 min	1	Sevo: 26 (39eACH) 13 (110eACH) *24 (39eACH)* *11 (110eACH)*	Sevo: 41 (39eACH) 30 (110eACH) *30 (39eACH)* *19 (110eACH)*
Day 2	Elective list, eg, four laparoscopic cholecystectomies • Induction in AR: 5 min @ 8 L/min [AR1/*OT5*] • Maintenance for 90 min @ 0.5 L/min in OT [OT4 and OT8] • 10-min breaks between cases with no sevoflurane input • 20-min lunch break • Total 440 min	4	Sevo: 23 (39eACH) 13 (110eACH) *20 (39eACH)* *10 (110eACH)*	Sevo: 32 (39eACH) 20 (110eACH) *26 (39eACH)* *14 (110eACH)*
Day 3	Pediatric fast turnover list: 13 cases • Induction in AR: 5 min @ 6 L/min including N2O [AR3/*OT3* and *OT7*] • Maintenance for 20 min @ 0.5 L/min in OT [OT4 and OT8] • 10-min breaks between cases with no sevoflurane/N_2O input • 20-min lunch break • Total 475 min	13	Sevo: 37 (39eACH) 30 (110eACH) *28 (39eACH)* *7 (110eACH)* N_2O: 40 *4 (39eACH)* *2 (110eACH)*	Sevo: 49 (39eACH) 38 (110eACH) *45 (39eACH)* *10 (110eACH)* N_2O: 75 *53 (39eACH)* *4 (110eACH)*
Day 4	Mixed case list adult: 3 cases • Induction in AR: 10 min @ 8 L/min [AR1/*OT5*] • Maintenance for 180 min with 10-min break [OT4 and OT8] • 20-min lunch break • Induction in AR: 5 min @ 8 L/min [AR1/*OT5*] • Maintenance for 90 min @ 0.5 L/min in OT [OT4 and OT8] with 10-min breaks • Total 430 min	1 2	Sevo: 26 (39eACH) 14 (110eACH) *23 (39eACH)* *11 (110eACH)*	Sevo: 41 (39eACH) 30 (110eACH) *36 (39eACH)* *19 (110eACH)*

TWA8 values noted as AR induction/*OT induction*. AR/OT codes refer to Supplementary Digital Content S1 and S2, https://links.lww.com/AA/F841.
Abbreviations: AR, anesthetic room; eACH, effective air changes per hour; N_2O, nitrous oxide; OT, operating theater; ppm, parts per million.

with UCV in the OT, which is highly effective at reducing exposure, especially at higher eACH settings. AGSS does not reduce exposure from head leaks, which are the dominant source during induction, and may represent 50% to 75% of volatile leak into the clinical space in real conditions.

While the modeled TWA8 values exceed recommended limits, they do so only under the unrealistic assumption of total gas leakage, and no staff movement, heat generation, or equipment use. Modern low-flow anesthesia and reduced nitrous oxide use may already keep real-world exposures within safe limits, and these findings support conducting clinical trials to measure actual staff exposure with AGSS on and off.

Current regulations do not reflect contemporary anesthetic practice or modern ventilation systems and further studies are warranted.

DISCLOSURES

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