Carbon dioxide insufflation deflects airborne particles from an open surgical wound model

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SUMMARY
Background: Surgical site infections remain a significant burden on healthcare systems and may benefit from new countermeasures.

Aim: To assess the merits of open surgical wound CO2 insufflation via a gas diffuser to reduce airborne contamination, and to determine the distribution of CO2 in and over a wound.

Methods: An experimental approach with engineers and clinical researchers was employed to measure the gas flow pattern and motion of airborne particles in a model of an open surgical wound in a simulated theatre setting. Laser-illuminated flow visualizations were performed and the degree of protection was quantified by collecting and characterizing particles deposited in and outside the wound cavity.

Findings: The average number of particles entering the wound with a diameter of <5 μm was reduced 1000-fold with 10 L/min CO2 insufflation. Larger and heavier particles had a greater penetration potential and were reduced by a factor of 20. The degree of protection was found to be unaffected by exaggerated movements of hands in and out of the wound cavity. The steady-state CO2 concentration within the majority of the wound cavity was >95% and diminished rapidly above the wound to an atmospheric level (~0%) at a height of 25 mm.

Conclusion: Airborne particles were deflected from entering the wound by the CO2 in the cavity akin to a protective barrier. Insufflation of CO2 may be an effective means of reducing intraoperative infection rates in open surgeries.

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Introduction
Surgical site infection (SSI) remains a significant cause of morbidity, prolonged hospitalization, increased cost of treatment, and mortality. SSIs range in severity from relatively...
trivial superficial wound exudate to causing, at least in part, one-third of postoperative deaths.1

There is much debate over sources of SSIs; however, a large proportion of SSIs from low-infection-risk operations are thought to be caused by contaminated airborne particles.2–4 Whyte et al. suggested that 98% of bacteria in orthopaedic wounds came directly or indirectly from the air.4 Particles may settle directly in the wound or be transferred to the wound after settling on instruments or the surgeon’s hands. Infectious airborne particles may be (i) single bacterial cells or spores, fungal spores, or viruses; (ii) aggregates of several cells, spores, or viruses; or (iii) pathogen-laden carrier particles such as skin scales, lint, and respiratory droplets. These micro-organisms and particles range in size from 0.02–0.3 μm viruses to 0.3–10 μm bacteria and bacterial clumps, and skin scales from <5 μm to 500 μm in diameter, with a thickness of about 2–5 μm.2,7–9

Airborne particles are ubiquitous and may carry viable micro-organisms.10 Seal and Clark measured as many as 5.6 million particles/m³ in a ventilated operating theatre during surgery.11 Gosden et al. found that operating theatre airborne contamination was dependent almost exclusively on the number of people present and their activity within the room.12 Skin scales are shed from the human body at a rate of about 7000 particles/min and may carry *Staphylococcus aureus*, which forms part of typical skin flora and is frequently responsible for SSIs.13 Skin scales spread into the operating room from both patient and staff passing freely through the pores of tightly woven fabrics.6–10,14,15

Attempts to reduce dispersion of airborne particles and wound contamination include the use of low-turbulence flow (LTF) ventilation. Conventional ventilation systems create a high-efficiency particulate air (HEPA)-filtered unidirectional downward flow over the sterile field at a flow rate achieving ≥20 air changes per hour.1 Persson and van der Linden introduced a gas diffuser for CO₂ insufflation of cardiothoracic wounds to prevent arterial air embolism in open heart surgery.1,6 The authors proposed that the heavier-than-air CO₂ remained inside and covered the wound cavity like a protective barrier reducing airborne contamination. They showed a 7.1-fold reduction in contamination rate with a CO₂ flow of 10 L/min, although they did not confirm the cushion mechanism or show the spatial distribution of CO₂ and whether elevated levels of CO₂ posed a risk to theatre staff.

This study visualizes the effect of CO₂ insufflation on the motion of airborne particles over an open wound and quantifies any influence on particle deposition rates. Flow visualization experiments were performed with and without CO₂ insufflation using aerosolized glycol and a laser sheet in a simulated theatre environment and wound model. The effect of the motion of surgeons’ hands was also assessed. A quantitative evaluation of the degree of protection provided by CO₂ insufflation against the entry of particles into the wound was performed at different locations in the wound cavity. The presence and concentration of CO₂ was also measured directly to confirm the role of CO₂ in the protection mechanism and to elucidate the extent of the CO₂ coverage.

Methods

A theatre environment with LTF ventilation was simulated with a positive-pressure clean room enclosure (bioBUBBLE, Fort Collins, CO, USA). The ventilation flow rate was controlled to achieve a mean vertical velocity of 0.25 m/s at a height of 1.2 m above fixed floor level in accordance with operating theatre design standard DIN 1946-4:2008-12. Aerosolized glycol from a QTFX-1500 fog generator was introduced to the down flow with particle diameters ranging from 0.4 to 15 μm (89% <5 μm, 10% 5–10 μm, 1% >10 μm).

A simplified abdominal surgical incision was modelled as an optically transparent elliptical cavity (Figure 1) with a length, width, and depth of 180, 100, and 50 mm, respectively.17 A Vita-diffuser™ (Cardia Innovation AB, Stockholm, Sweden) was used for insufflation of 10 L/min CO₂ and positioned at the narrow end of the wound at a depth of 25 mm below the wound edge. For flow patterns over and in the wound, with and without CO₂, insufflation was visualized by observing aerosolized particles in a 2-mm-thick vertical laser (1 W, 532 nm, LT-301). Video recordings (1280×720 pixels) of 60 s duration were taken for each experimental set-up. The distribution and motion of particles over each minute-long recording were visualized in time-lapse-like images created by selecting the maximum pixel intensity over all video frames.

Time-averaged CO₂ concentrations within the CO₂-filled wound cavity were measured with a gas analyser (CheckMate II, PBI Dansensor, Ringsted, Denmark) and probe traversed vertically from the wound floor (−50 mm) to a height of 50 mm above the wound edge. A 5 mL/min sample flow rate was considered to be small enough (0.05% of the insufflation flow rate) to have negligible effect on the overall concentrations.

The degree of protection offered by CO₂ insufflation at different locations in the cavity was quantified as a protection factor given by (ISO 14644-1):

\[
P_{F_x} = \log \left( \frac{C_x}{C_{ref}} \right),
\]

(Eq. 1)

where \(P_{F_x}\) is the degree of protection at position \(x\), \(C_x\) is the concentration of particles at position \(x\), and \(C_{ref}\) is the reference concentration of particles measured in the background. A 100-fold reduction of particles in the ‘protected’ area compared with the background therefore corresponded with a protection factor of two, and 1000 times a factor of three, and so on. Particle concentrations were measured by collecting and counting deposited particles on glass slides held

![Digital Camera](Image 328x69 to 527x253)

**Figure 1.** Schematic of modelled wound geometry.

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horizontally at the centre of the wound at depths of 0, −10, −30, and −50 mm (wound floor), and on the wound edge. Experiments were also performed simulating the motion of a surgeon’s hands within the wound in a worst-case scenario by intentionally attempting to disrupt CO₂. Repeated movements with two hands were made in and out and sideways within the wound cavity for the respective tests’ full 60 s durations. The background particle concentration was simultaneously sampled 200 mm above the top of the wound. Repeats were performed to provide \( N = 3 \) for each experimental set-up. A programme to detect and count the particles was written using Matlab™ (MathWorks, Natick, MA, USA) and validated manually with <1% variation.

Results

Particle trace images with and without CO₂ insufflation are shown in Figure 2. The border of the wound and location of the diffuser are highlighted with white dotted lines. Time-averaged CO₂ concentrations in and over the wound cavity during insufflation are plotted and overlaid in Figure 3. Error bars show the range over which the CO₂ concentrations fluctuated in steady-state conditions. Average protection factors calculated for each measurement condition and location investigated are given in Table I.

Discussion

Aerosolized glycol was selected for simulating airborne particles for two reasons. First, the size range roughly matched the most frequent particle sizes found in theatres. Two studies found that >99% of particles sampled in ventilated operating theatre were <5 μm.¹⁵,¹⁸ Second, the particles were calculated to be small enough to follow the motion of the gas flows faithfully and to give an accurate picture of the flow pattern. The Stokes number (Stk) is a dimensionless number in fluid
mechanics that indicates whether a particle will continue in a straight line under its own inertia as a fluid turns (Stk \(>1\)) or if viscous forces dominate and the particle will follow the fluid flow faithfully (Stk \(\ll 1\)). The Stokes number for the largest particles generated (15 \(\mu m\)) was 0.001 in air and 0.002 in CO\(_2\). Experiments therefore not only traced the motion of airborne particles directly but also accurately modelled the gas flows.

The trace images in Figure 2 illustrate a distinct reduction of airborne particles entering the wound cavity with insufflation of CO\(_2\). In the control case without insufflation (Figure 2a) streamlines of particles can be seen entering and in some cases exiting the wound. With insufflation (Figure 2b) the airflow and particles are deflected from entering the cavity at the top of the wound and interface between air and CO\(_2\). Figure 3 shows the cavity is filled with CO\(_2\) and for the majority is above a concentration of 95%. Above the wound a covering of CO\(_2\) \(\approx 5\) mm thick forms as the CO\(_2\) spills over the wound edge — akin to continuing to overfill a cup with water and a protective barrier.\(^{16}\) In this region the CO\(_2\) concentration varied by up to \(\pm 10\%\) due to mixing, whereas elsewhere in the domain the concentration was stable to within \(\pm 1\%\). The CO\(_2\) concentration rapidly diminished to 0%, 25 mm above the wound, demonstrating negligible risk to theatre staff breathing in elevated levels of CO\(_2\).

The protection factors (PFs) in Table I confirm the deflection mechanism shown qualitatively in Figure 2. The case without insufflation served as the experimental control and was necessary to assess any protection offered by the cavity geometry itself. The negative PFs showed that the cavity geometry assisted particle deposition likely due to reduced flow velocities within the cavity and shorter relaxation times. The PF for particles \(<5\ \mu m\) was on average 3.0 (\(P < 0.001\)) across the wound, which corresponds to a 1000-fold reduction in particle deposition rate. PFs were higher for particles \(<5\ \mu m\) than larger particles (\(P < 0.001\)), which was expected due to the higher Stokes number of the larger particles. The average PF for particles \(>5\ \mu m\) was 1.3 (\(P < 0.001\)). We surmised that the movement of a surgeon’s hands would disrupt the cushion of CO\(_2\). However, there was no significant difference (\(P > 0.2\)) in PFs with exaggerated hand movements.

Persson and van der Linden in an operating room with ultraclean airflow showed that CO\(_2\) insufflation reduced the number of particles \(<5\ \mu m\) and \(>5\ \mu m\) diameter entering an experimental open surgical wound by 18- and 15.5-fold, respectively, when the surgeons leaned forward over the wound during sham surgery. No airborne particles were detected in the cavity when the surgeons were inactive, standing upright next to the open wound cavity.\(^{19}\) Debate over the benefit or perhaps harm of different ventilation systems with different performance characteristics is ongoing.\(^{20,21}\) As early as 1976, Clark et al. found a reduction in both the concentration of airborne particles and SSI rates after installing a high-flow HEPA-filtered vertical ventilation system.\(^{22}\) Later, however, Taylor and Bannister found a 27-fold increase in wound contamination when the surgeon leaned over the wound and into vertically directed ‘laminar’ downflow.\(^{21}\)

Table I

<table>
<thead>
<tr>
<th>Depth</th>
<th>No insufflation (control)</th>
<th>CO(_2) Insufflation</th>
<th>CO(_2) Insufflation with hand movement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(&lt;5\ \mu m)</td>
<td>(&gt;5\ \mu m)</td>
<td>(&lt;5\ \mu m)</td>
</tr>
<tr>
<td>Wound edge</td>
<td>–</td>
<td>–</td>
<td>3.4 (0.4)</td>
</tr>
<tr>
<td>0 mm centre (top)</td>
<td>–</td>
<td>–</td>
<td>2.9 (1.0)</td>
</tr>
<tr>
<td>–10 mm centre</td>
<td>–</td>
<td>–</td>
<td>3.4 (1.7)</td>
</tr>
<tr>
<td>–30 mm centre</td>
<td>–</td>
<td>–</td>
<td>2.4 (0.3)</td>
</tr>
<tr>
<td>–50 mm centre (floor)</td>
<td>–0.2 (0.1)</td>
<td>–0.1 (0.0)</td>
<td>2.9 (0.3)</td>
</tr>
</tbody>
</table>

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It is not clear in the literature whether airborne particle concentrations correlate with surgical site infection rates. Attempts to show correlations appear to be confounded by a number of other factors that influence SSI rates such as the type of operation, surgical technique, antibiotic prophylaxis, patient risk factors, and the degree of wound contamination. Whyte et al. demonstrated an effect of airborne contamination and estimated that a 13-fold reduction in airborne bacteria would reduce wound contamination by ~50% during biliary surgery where there was little contamination from non-airborne routes. Reduction of infection rates with reduced airborne contamination have also been shown for orthopaedic, spinal, and shan operations. If the regression model of Lidwell et al. of orthopaedic joint sepsis rates (Eq. 2) is applied to the lowest CO₂ insufflation PF factor on a wound surface of 1.3 from the present study, with an air contamination of 177 bacteria/m³ averaged across 15 hospitals, then a reduction of joint sepsis rate from 3.2% to 1.4% could be expected.

Joint sepsis rate (%) = 0.84 + 0.18(Air contamination)² (Eq 2)

The ability to visualize the motion of small or individual particles was limited both by a magnification of 0.2 mm/pixel and the intensity of light scattered. It was therefore not possible to detect isolated particles and it was necessary to collect and count deposited particles on a microscope to quantify the qualitatively observed deflection mechanism. In four experiments the maximum number of particles was collected on the background slide before any particles were observed at the location of interest. For these cases the PFs are reported in Table 1 as ‘greater than’ based on an assumed particle count of unity since an infinite PF is not verifiable.

Other studies have counted the number of bacterial colonies in agar plates to assess airborne contamination; however, they have included the added variable of the viability of infecting material. In the present study we counted all particles deposited, whether they contained viable bacteria or not. This may account for the larger PFs measured in the present study compared with those of Persson and van der Linden. Whyte et al. noted that when bacteria from bile were present, they were so numerous in the wound that they masked the presence of airborne bacteria. For contaminated surgeries where endogenous infection sources may dominate airborne sources and neglect any benefits of reduced airborne deposition, CO₂ insufflation may still have bacteriostatic benefits against aerobic bacteria, and improve oxygenation. Also, a CO₂-covered wound surface is insulated from sub-body-temperature theatre ventilation, so if CO₂ insufflation is warmed and humidified, it may assist with wound temperature maintenance and reduce the incidence of hypothermia.

We have demonstrated the essential physics that insufflation of an open wound cavity with CO₂ affords protection from airborne contamination even when disturbed. CO₂ insufflation may be an effective supplementary means of reducing intraoperative infection rates in open surgeries.

Conflict of interest statement
C.J.T Spence, K. Kokhanenko and G. Papotti are employees of Fisher & Paykel Healthcare Ltd (Auckland, New Zealand) which markets and sells the Vita-diffuser. J.A. van der Linden is a shareholder of Cardia Innovation AB (Stockholm, Sweden) which manufactures the Vita-diffuser.

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