

# The Effect of Heated CO<sub>2</sub> Insufflation in Minimising Surgical Wound Contamination During Open Surgery

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**Abstract**—The primary source of infections in open surgeries has been found to be bacteria and viruses carried into the surgical wound on the surfaces of skin particles shed by patients and surgical staff. In open cardiac surgeries, insufflation of the wound with carbon dioxide is used to limit the quantity of air able to enter into the heart, avoiding air embolisms when the heart is restarted. This surgical technique has been evaluated as a method of limiting the number of skin particles able to enter into the wound, using computational fluid dynamics (CFD) simulations and experimental testing. Spherical particles of 5.0 and 13.5 μm in diameter were used to simulate skin particles falling above a wound, travelling in air ventilation velocities of either 0.2 or 0.4 m/s, and with or without CO<sub>2</sub> insufflation. The CFD simulations with CO<sub>2</sub> included a diffuser placed in the wound and supplied with CO<sub>2</sub> at a rate of 10 L/min. Experimental testing was completed under similar conditions. The results of CFD simulations and experimental testing showed CO<sub>2</sub> insufflation can significantly limit the number of particles able to enter into the wound.

**Keywords**—Carbon dioxide, Surgical insufflation, Infection, Skin particles.

## INTRODUCTION

Hospital-acquired infections have been estimated to have cost the UK a minimum of 1 billion pounds per a year with 15,000 treatable infections and 5000 deaths occurring.<sup>9</sup> A proportion of those infections and deaths were a result of infections acquired during surgery, with literature suggesting surgical site infection rates range from 0.8 to 16% in cardiac surgeries, to as high as 30% in abdominal surgeries.<sup>22,24</sup>

Antibiotic resistant strains of bacteria began to be found in the early 1960s and their prevalence in recent years has only increased, as has the need to develop new methods of stopping these infections from occurring.<sup>1,11</sup> The primary source of infection in surgeries is commonly agreed to be bacteria and viruses such as staphylococcus epidermidis<sup>22</sup> and staphylococcus aureus,<sup>23</sup> carried on skin scales which once shed, have the possibility of entering into the surgical wound. Skin particles naturally flake off at an estimated rate of between 10<sup>6</sup> and 10<sup>7</sup> particles per a day.<sup>9</sup> These particles are then dispersed into the air through natural and forced convection.

The main method used to reduce the probability of airborne particles from entering into the wound, (aside from sterilising equipment and using sterile gloves and gowns), is to place downward ventilation above the operating table, forcing particles away from the operating area towards the outer edges of the room. While surgeons' and staff bodies are mostly covered and typically hairnets (or equivalent) are used, skin is still exposed. For example, surgeon's necks are often exposed, and the nature of surgery requires surgeons to lean over the wound. The presence of the surgeon intermittently leaning over the wound has been found to potentially increase wound contamination by a factor of 27 when compared to the surgeon placed away from the wound.<sup>25</sup>

Carbon dioxide has been used in cardiothoracic surgery to de-air the surgical cavity for the past 50 years, lowering the chance of air embolisms when the heart is restarted.<sup>16,21</sup> More recently heated and humidified CO<sub>2</sub> insufflation of an open wound has been utilised as a method of helping to reduce surgical site infections,<sup>18</sup> maintain core temperature<sup>10</sup> and improve tissue oxygenation.<sup>12</sup>

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The aim of this study was to investigate the difference in wound contamination of skin particles with and without the use of warmed carbon dioxide to fill the wound during surgery through computational and experimental methods; (humidity has been excluded from the carbon dioxide to simplify the computational models). The source of the skin cells was not considered to be of interest. As such, a micro-environment around the surgical wound and ventilation above the wound were considered rather than the operating theatre as a whole.

## MATERIALS AND METHODS

To evaluate the effectiveness of CO<sub>2</sub> insufflation, ANSYS CFX 17.0<sup>TM2</sup> was used to simulate a model of a standard wound (without carbon dioxide) and a wound with carbon dioxide insufflation. Ventilation above the operating table was included and the skin particles were introduced at the same location.

### Computational Fluid Dynamics

#### Wound Model and Diffuser

Creo Parametric<sup>TM19</sup> was used to create the standard and the CO<sub>2</sub> insufflated wound models. The wound geometry chosen was based on that used by Persson *et al.*,<sup>17</sup> resulting in an elliptical wound shape of 180 mm in length, 90 mm in width and a wound depth of 50 mm as shown in Fig. 1. The wound edge was rounded with a 10 mm radius and the edge within the wound cavity was rounded with a 5 mm radius. The section of the body surrounding the wound was extended to equal 400 mm in both length and width.

The CO<sub>2</sub> insufflated wound model utilised the Vita-Diffuser<sup>4</sup> manufactured by Cardia Innovation AB

(Stockholm, Sweden). Persson *et al.*<sup>16</sup> found that this diffuser provided better wound protection compared to CO<sub>2</sub> provided through an open-ended tube. The diffuser included a flexible tube with an internal diameter of 5 mm which terminates in the wound cavity with a cylindrical foam tip of 20 mm in diameter and 12 mm in length. The lower face of the foam tip was placed at a height of 20 mm above the surface of the wound. The volume of air surrounding the wound and the ventilation source modelled had a vertical extent of 1.3 m, estimated to be representative of the height of a ventilation outlet above surgical tables and similar to the system used in experimental testing. The plane parallel to the wound had dimensions of 500 mm in length and width.

To evaluate the effectiveness of CO<sub>2</sub> insufflation, ANSYS CFX 17.0<sup>TM2</sup> was used to simulate the flow and transport of particles.

#### Skin Cell Modelling

The size of skin particles have been found to range from 10 to 25  $\mu\text{m}$  in diameter and 1 to 5  $\mu\text{m}$  in thickness,<sup>8,13</sup> and having settling rates of approximately 0.005 to 0.006 m/s.<sup>9,15</sup> Nobel *et al.*<sup>15</sup> found a Stokes equivalent diameter of 14.2  $\mu\text{m}$  for a settling rate of 0.006 m/s. The volume equivalent spherical diameter of the particle sizes gave minimum and maximum diameters of 5.3 and 16.7  $\mu\text{m}$ , respectively. While the volume equivalent diameter calculation does not take into account the difference in drag forces, the Stokes equivalent diameter considers the settling rate of the particles and therefore accounts for the difference in size. A particle size of 13.5  $\mu\text{m}$ , similar to that found by Nobel *et al.*, was chosen for the simulations as well as a smaller particle size of 5  $\mu\text{m}$ . This enabled the consideration of whether there would be a difference of deflection of particles based on size.

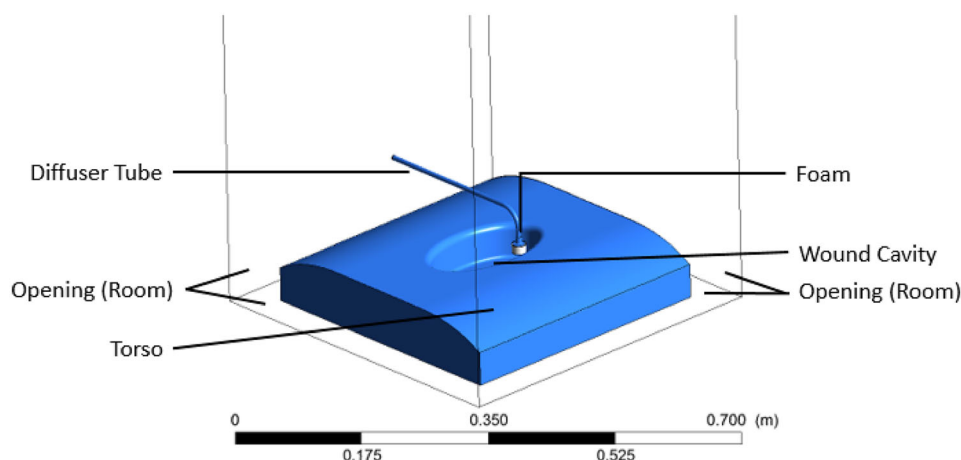


FIGURE 1. CAD model of standard wound with CO<sub>2</sub> diffuser.

**TABLE 1. Material properties used for air and carbon dioxide.**

	Molar mass (kg kmol <sup>-1</sup> )	Density (kg/m <sup>3</sup> )	Viscosity (kg/m s)	Reference temperature (°C)	Reference pressure (atm)
CO <sub>2</sub> (ideal gas)	44.01	1.74	1.553 × 10 <sup>-5</sup>	37.5	1
Air	28.96	1.185	1.835 × 10 <sup>-5</sup>	20.0	1
Water	18.02	997.0	N/A	20.0	1

The skin particles were modelled as spheres of water due to insufficient data on skin particle material properties. As the location of the source and the trajectory of the particles to reach the wound were of little interest, the skin particles were introduced at the same location as the air ventilation with uniform distribution across the location. A rate of 750 particles per minute entered at the ventilation location based on a person shedding 150 particles per minute and assuming there to be five staff in the operating theatre. One hundred and fifty particles or CFU (Colony Forming Units) is a conservative number,<sup>6,20</sup> however it is expected that not all particles reach the patient.

#### *Air Ventilation Rates*

Studies have shown that ventilation velocities of 0.2 and 0.4 m/s represent the medium and higher velocities expected in operating theatres.<sup>6,7,13,20</sup> Laminar flow over the operating table has typically been shown to be more successful at transporting particles away than more turbulent flows. Information on the level of turbulence however has not been measured or reported.

#### *Mesh Generation*

The computational meshes for the models were developed using the inbuilt meshing program in ANSYS Workbench 17.0<sup>2</sup> using the unstructured tetrahedron method. Given the large space between the ventilation outlet and the wound, the geometry was sectioned into three regions to allow larger sized elements further away from the wound where higher mesh refinement was not needed. The maximum global face sizes for the three sections were 7.5, 5 and 1.5 mm each with growth rates of 1.2. Five inflation layers were added to the wound cavity surfaces, the torso faces and the walls of the operating room air with a growth rate of 1.2 and a transition ratio of 0.77. These settings gave a minimum edge length of 0.25 mm.

A mesh independence study was completed. Five meshes were used with each having approximately double the number of elements of the previous mesh. The pressure on the bottom face of the wound was used as the variable of interest. A steady-state model of the wound filling with CO<sub>2</sub> was used with a RMS

residual target of 10<sup>-4</sup>. The results were then plotted and the mesh with the lowest number of elements for which the result did not change was selected. This resulted in a final mesh for the simulations of approximately 2,700,000 nodes and 12,600,000 elements.

#### *Initial and Boundary Conditions*

Multiphase models were used which included a buoyancy model with a reference density of 1.2 kg/m<sup>3</sup>. The properties of air, CO<sub>2</sub> and water were taken from included material libraries within ANSYS<sup>2</sup> and are shown in Table 1. In the CO<sub>2</sub> insufflated wound model, the computational domain was split into three regions consisting of two fluid domains and a porous domain: the operating room air (including the walls of the wound and torso), the diffuser tube, and the diffuser foam tip respectively, as shown in Fig. 1. The standard wound model did not have the diffuser present and was modelled as a single fluid domain.

The operating theatre volume was filled with air (ideal gas, continuous fluid) at a temperature of 20 °C and atmospheric pressure (101.325 kPa). The top face of the model was defined as an inlet and would model the outlet of the ventilation system (air source). The air velocity was then set at 0.2 and 0.4 m/s downwards in two separate simulations both using the Shear Stress Transport turbulence models with a medium intensity of 5%. The sides of the model and bottom face surrounding the torso of the wound were set to have a static pressure value boundary condition (fluids and particles could flow in or out) with a relative pressure of 0 Pa at a temperature of 20 °C. The solid surfaces of the wound and torso were defined to be hydraulically smooth with a no-slip velocity condition.

In an operating theatre, it is expected that the carbon dioxide would cool, increasing the density and providing a better barrier against the skin particles. However, even at 37.5 °C, Carbon Dioxide has a higher density (1.74 kg/m<sup>3</sup>) than air at 20 °C (1.20 kg/m<sup>3</sup>). An isothermal model was used, providing a worst case scenario while simplifying the CFD model. There are a number of unknowns which would make the inclusion of heat transfer difficult to quantify, such as room opening boundary conditions and heat transfer

of the patient to the room and from the carbon dioxide.

The diffuser tube's inlet provided 0.288 g/s (10 L/min) of carbon dioxide (ideal gas, continuous fluid) at 37.5 °C. The Shear Stress Transport turbulence model was used and set to a low turbulence intensity of 1%. The walls of the diffuser were defined as non-slip, adiabatic walls. The porosity (96.6%) and permeability ( $3.9 \times 10^{-9} \text{ m}^2$ ) of VITA-diffusers were determined empirically and the foam was modelled using a generalised form of the Navier Stokes equations with Darcy's Law. A turbulence intensity of 5% was used in the foam. The air and CO<sub>2</sub> were coupled with a mixture model which treats the fluids symmetrically based on their surface area per unit volume.

The skin particles were introduced into the environment from the ventilation unit outlet with the same velocity and temperature as the surrounding air. Skin particles leaving operating theatre staff would be warmer than the surrounding air, though it is expected that the particles would cool to the ambient air temperature before reaching the wound and once the skin particles were within the ventilation flow, the temperature of the particles would have little effect on their trajectories. The volume fraction of particles entering the flow domain was set to  $1.61 \times 10^{-13}$ . This was based on 750 particles per minute, with a diameter of 13.5  $\mu\text{m}$ , with a downward flow velocity of 0.4 m/s through the ventilation outlet cross-sectional area of 0.25 m<sup>2</sup>. The same volume fraction of particles was used for all simulations leading to a particle injection rate of 14,759/min for 5.0  $\mu\text{m}$  sized particles at a ventilation rate of 0.4 m/s, and rates of 375/min and 7379.5/min for 13.5 and 5.0  $\mu\text{m}$  sized particles respectively, in a ventilation rate of 0.2 m/s.

An Eulerian–Eulerian multiphase model of dispersed solid particles with the properties of water was used to simulate the skin particles. Solid particles were used rather than a dispersed fluid to simplify the model and allow the particles to act more similarly to the solid skin particles found in operating theatres rather than water droplets which would deform and be affected by surface tension. A Full Buoyancy Model was included and uses the density differences of the fluids and particles. The Schiller–Naumann drag model was included to model the drag between the skin particles and air or CO<sub>2</sub>. This model is appropriate for sparsely distributed solid particles.<sup>2</sup>

#### Simulation Sequence

The CO<sub>2</sub> insufflated wound model first required a transient model to fill the wound with carbon dioxide and reach a steady state before modelling the addition of skin particles. The transient model was initialised

with air only. The wound was filled with CO<sub>2</sub> for 10 s at 10 L/min as Cater *et al.*<sup>5</sup> found that these settings were sufficient to fill the wound and reach a quasi-steady state when using the same diffuser. Given the wound volume of 0.661 L, the wound would fill within approximately 4.0 s with a residence time of 0.25 s. A time step sensitivity analysis was completed and found a time step of 0.05 s was sufficient to accurately model the CO<sub>2</sub> insufflation. A minimum of 3 coefficient loops and a maximum of 5 were used and an RMS residual target of  $10^{-5}$  was set.

Steady-state models were then used to model both the CO<sub>2</sub> insufflated and standard wounds when exposed to the air ventilation and skin particles. The transient model results were used as the initialisation point for the CO<sub>2</sub> steady state models. Identical settings to the transient models were used in the steady state models with the addition of the simulation of skin particles. The simulations were completed on a computer with an Intel(R) Core(TM) i7-4770 CPU at 3.40 GHz and 16 GB of RAM. A maximum of 350 iterations and an RMS residual target of  $10^{-5}$  were set.

#### Experimental Methodology

A 'BioBUBBLE<sup>TM</sup>•3' was used to physically model the restricted domain used in the computational simulations. BioBUBBLE<sup>TM</sup>s are enclosures which can be used as clean rooms and include HEPA filters as well as the ability to produce either positive or negative pressure environments provided through the ceiling of the enclosure, mimicking the air ventilation of an operating theatre. The air velocity was adjusted to give a rate of 0.21 m/s which was deemed to be sufficiently close to the CFD simulation velocity of 0.2 m/s.

To simulate the surgical wound cavity a plastic wound with the same dimensions as those used in the CFD simulations was used and heated to  $37 \pm 2$  °C.

A Vita-Diffuser<sup>TM</sup> manufactured by Cardia Innovation<sup>4</sup> was used to diffuse the heated carbon dioxide into the wound cavity. The tube supplying the diffuser with carbon dioxide contained a heating wire and control system which heated the carbon dioxide as it travelled along the length of tube ensuring that the temperature of the carbon dioxide at the foam was equal to  $37 \pm 2$  °C. The carbon dioxide was supplied from a gas bottle. A flow rate of 10 L/min of carbon dioxide was used in testing which was equal to the mass flow rate used in the CFD models.

Talcum powder was used to act as the skin particles. Talcum powder is made up of hydrated magnesium silicate with the chemical formula of  $\text{H}_2\text{Mg}_3(\text{SiO}_3)_4$ . These particles were not spherical like the water droplets used in the CFD simulations but are small particles in a flake-like form matching more similarly the

shape of skin particles. The particle sizes ranged in diameter from approximately 2 to 40  $\mu\text{m}$ . A table was placed in the BioBubble<sup>TM</sup> at a height of 1.2 m from the ventilation outlet.

The talcum powder was dropped vertically at the same location as the air ventilation to spread an even layer of talcum powder across the centre of the enclosure. A PVC pipe with a number of holes along its length was used. One end was sealed while other was connected to the talcum powder source and compressed air to aerate the powder. The velocity of talcum powder was checked to ensure it matched the ventilation flow.

For each test, two microscope slides were used. One slide was placed in the centre of the wound cavity while the other was placed 40 cm laterally away from the wound at a height of 15 cm above the table. The samples were compared to account for differences in the distribution of particles for each test. The microscope slides were cleaned, and images of the slides at the set location were recorded before each experiment. The wound was also cleaned between each test. Any particles which remained on the slides after cleaning were excluded from those counted after testing. If the insufflated wound model was to be tested, the carbon dioxide flow was switched on for a minimum of 10 s before the slide was placed within the wound. Images were then taken of the microscope slides at the same locations as taken after being cleaned. The talcum powder was introduced over the wound cavity for 120 s, as this was empirically determined to permit counting of the particles on the slides. Approximately 3 g of talcum powder was used per test. The interval between each test was a minimum of 15 min to allow particles in the air from the previous test to settle.

The testing for the insufflated wound model and the standard wound model were repeated six times each, alternating between each. The number of particles on each slide were counted three times and averaged. The particles were segmented into two groups of particles either smaller than 10  $\mu\text{m}$  or larger than 10  $\mu\text{m}$ . The pictures were taken at  $\times 100$  magnification, and each image has an area of  $1.2 \times 10^6 \mu\text{m}^2$ .

## RESULTS

### Computational Results

#### Standard Wound Simulation Results

Figure 2 shows the volume fraction of 5.0  $\mu\text{m}$  sized particles in a cross section through the centre of the model at air ventilation velocities of 0.2 and 0.4 m/s respectively. It can be seen that the volume fraction of skin particles in the supplied ventilation is

$1.61 \times 10^{-13}$  as specified and this remains relatively constant until the particles near the wound. In both models, skin particles enter the wound but do not appear to accumulate on the wound surface significantly. The 0.4 m/s air ventilation model image shows a greater volume fraction of skin particles reaching further within the wound than for 0.2 m/s. This suggests that high flow rates may increase the quantity of the skin particles entering the wound, rather than moving the particles away toward the ventilation outlets and agrees with the findings of Memarzadeh *et al.*<sup>13</sup> and Rui *et al.*<sup>20</sup>

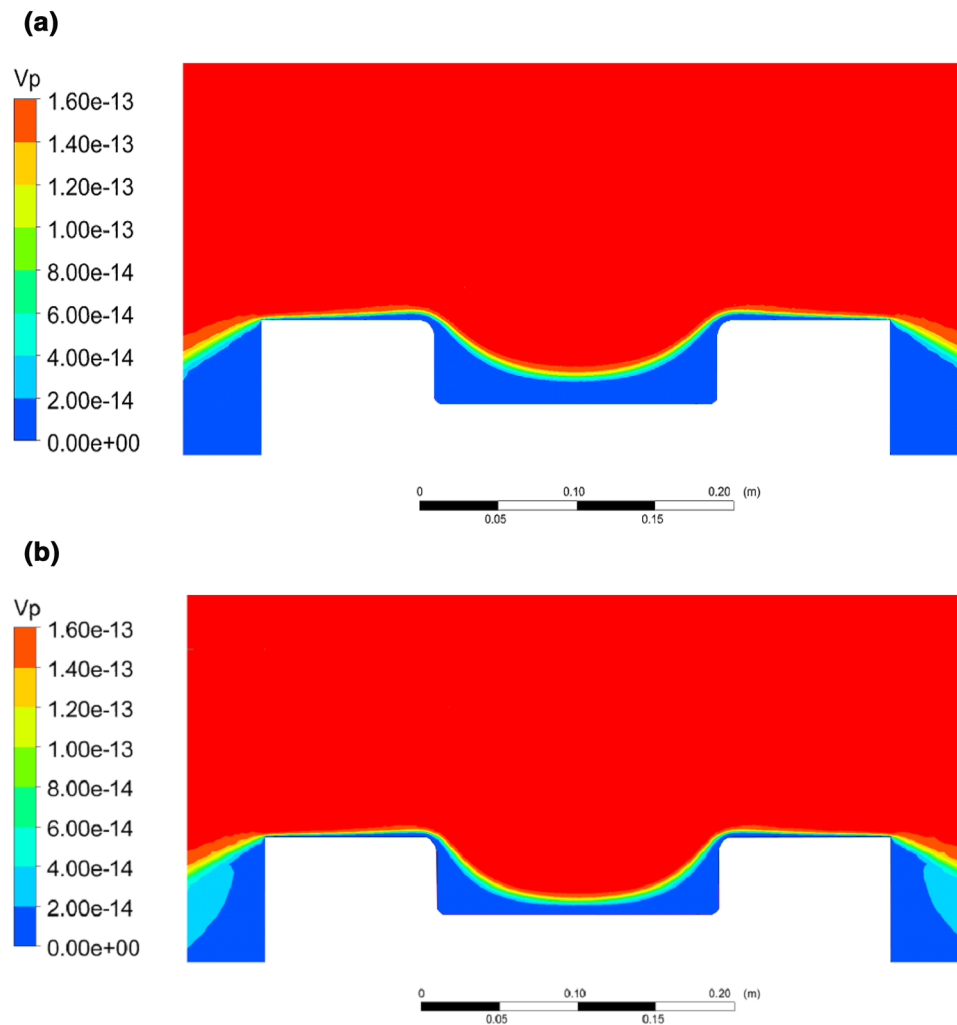
The standard wound models with 13.5  $\mu\text{m}$  sized particles, shown in Fig. 3, shows a marked difference in the volume fraction of particles in comparison to the 5  $\mu\text{m}$  sized particles. While the 5  $\mu\text{m}$  sized particles did not noticeably reach the wound surfaces, the 13.5  $\mu\text{m}$  sized particles accumulated on the lowermost surface and sides of the wound. An increase in diameter from 5.0 to 13.5  $\mu\text{m}$  would increase the Stokes number from 0.000168 to 0.00122 for flow at 0.4 m/s in air with a characteristic length of the wound length, however both particle sizes have Stokes numbers significantly smaller than 1, and can be considered to behave as flow tracers.

### CO<sub>2</sub> Insufflated Wound

The transient simulations to fill the wound with carbon dioxide were completed, and the wound filled within the 10 s as also found by Cater *et al.*<sup>5</sup> The steady state results for the 5.0 and 13.5  $\mu\text{m}$  sized particles are shown in Figs. 4 and 5. Unlike the standard wound models, there is a volume fraction less than  $2.00 \times 10^{-14}$  within the wounds of all four CO<sub>2</sub> insufflated wounds. There is a layer at the location of mixing between the carbon dioxide and air at the top of the wound where the volume fraction of skin particles decreases. At this location, the volume fraction of particles is not a smooth transition showing that there is some mixing of the particles with the carbon dioxide and air before they are carried away. The carbon dioxide, therefore, does not act as a complete “barrier” but transports some particles which mix with the carbon dioxide, as it leaves the wound.

### Comparison of Standard and CO<sub>2</sub> Insufflated Wounds

The number of particles within the wound was used to quantify the differences between the standard and CO<sub>2</sub> insufflated wounds. The particles which entered the wound but were not in contact with the wound surface are also of interest as in reality, surgical instruments and surgeon’s hands are located within the wound during surgical procedures. Any particles that enter the wound may become attached the surgeon’s



**FIGURE 2.** Skin particle volume for  $5\ \mu\text{m}$  sized particles at air ventilation velocities of (a) 0.2 m/s and (b) 0.4 m/s.

hands or medical equipment and could then be transferred to the wound surface potentially leading to an infection.

The volume of particles within the wound were found using the simulation post-processor CFD-Post.<sup>2</sup> The number of particles within the wound were then found by evaluating the volume fraction of particles within the defined wound volume and the volume of the given size of particle.

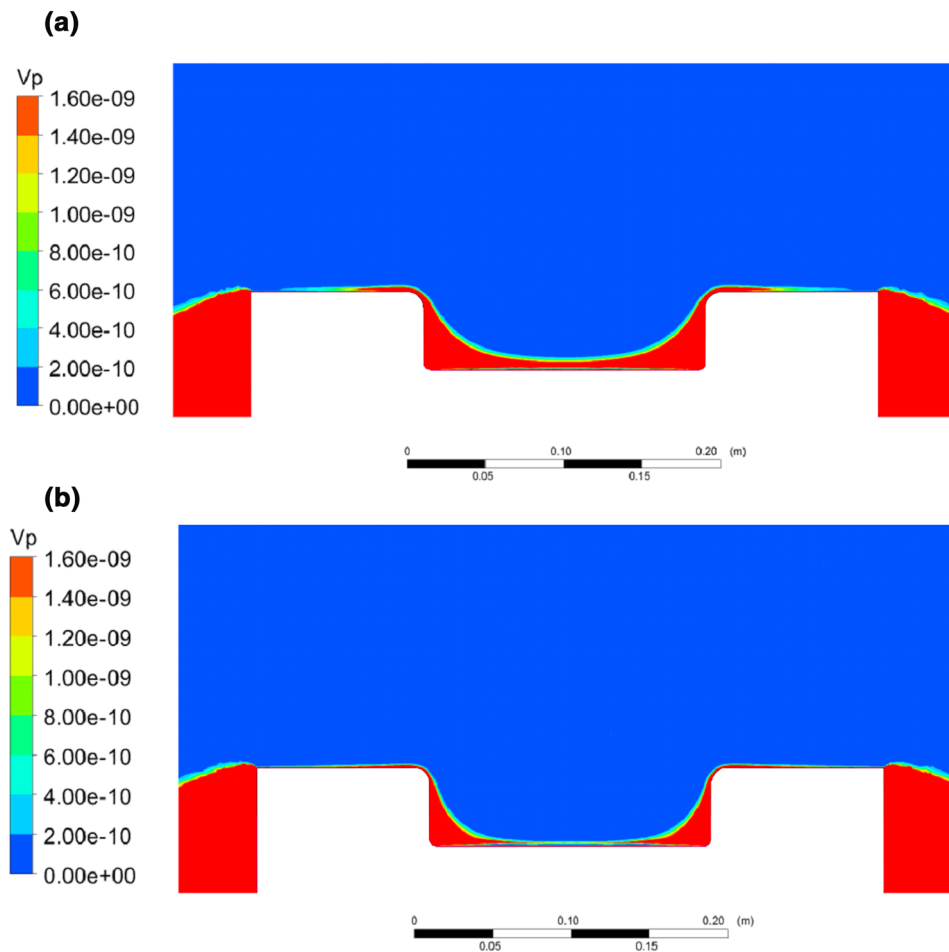
Only one  $5.0\ \mu\text{m}$  sized particle was found in the standard wounds in both the 0.2 and 0.4 m/s models, while no particles were found in the  $\text{CO}_2$  insufflated wound. This demonstrated that the flow of the air ventilation above the operating theatre may be effective in limiting the number of small particles able to enter into the wound.

In contrast, approximately 31,000 and 16,000  $13.5\ \mu\text{m}$  sized particles were found in the standard wound with ventilation velocities of 0.2 and 0.4 m/s respectively. Again no particles were found in the  $\text{CO}_2$

insufflated wound model. This shows that while smaller particles may have a smaller chance of entering into the wound,  $\text{CO}_2$  insufflation of an open wound could eliminate any particles, both large and small from being able to enter into wound irrespective of the ventilation flow rate.

### *Experimental Results*

Example microscope slide images for both the standard wound and the  $\text{CO}_2$  insufflated wound are shown in Fig. 6. In the standard wound, a similar number of particles accumulated in the wound as were found on the microscope slide outside of the wound. In contrast, the  $\text{CO}_2$  insufflation was able to significantly reduce the number of particles which adhered to the wound slides. In each of the six tests for the standard wound and the  $\text{CO}_2$  insufflated wound, similar results were found.



**FIGURE 3.** Skin particle volume fractions for 13.5  $\mu\text{m}$  sized particles at air ventilations of (a) 0.2 m/s and (b) 0.4 m/s.

Table 2 displays the average number of particles found on the slide located away from the wound in the air and the average number of particles on the slide within the wound for each test. The ratio of particles on the slide in the wound to those outside are also presented.

The results show a difference in the number of particles on the wound surface for the CO<sub>2</sub> insufflated wound and the standard wound. For particles less than 10  $\mu\text{m}$ , CO<sub>2</sub> insufflation reduced the number of particles able to land on the lowermost wound surface by a factor of 54 for particles smaller than 10  $\mu\text{m}$ , by a factor of 39.5 for particles larger than 10  $\mu\text{m}$ , or overall by a factor of 49.

A statistical analysis was completed using MiniTab 17.1.0<sup>®</sup> Statistical Software.<sup>14</sup> Anderson–Darling normality tests showed that the number of particles counted on the slides away from the wound for the CO<sub>2</sub> insufflated wound and the standard wound were normally distributed ( $p = 0.511$  and  $p = 0.237$  for particles < 10  $\mu\text{m}$  and,  $p = 0.703$  and  $p = 0.436$  for particles > 10  $\mu\text{m}$  respectively). The Levene Test

found equal variances ( $p > 0.1$ ) between the standard and CO<sub>2</sub> insufflated wound for both < 10 and > 10  $\mu\text{m}$  sized groupings with  $p$  values of 0.448 and 0.127 respectively.

A two-sample  $T$  test was then completed to evaluate the null hypothesis that there would be no statistically significant difference between the number of particles which landed on the microscope slides away from the wound during the CO<sub>2</sub> insufflated wound tests and the standard wound tests. For particles less than 10  $\mu\text{m}$  in size and greater than 10  $\mu\text{m}$  in size, the tests showed that there was no evidence to suggest there was any difference between the two groups ( $p > 0.1$ ), with the  $p$  values equal to 0.621 and 0.436 respectively.

Two-sample  $T$  tests were then conducted comparing the number of particles which fell on the wound slides in the standard wound and on the CO<sub>2</sub> insufflated wound with groupings made up of particles less than 10  $\mu\text{m}$  and greater than 10  $\mu\text{m}$  in size. The null hypothesis was that there would not be a statistically significant difference between the two groups. Tests for normality were completed for the numbers of particles

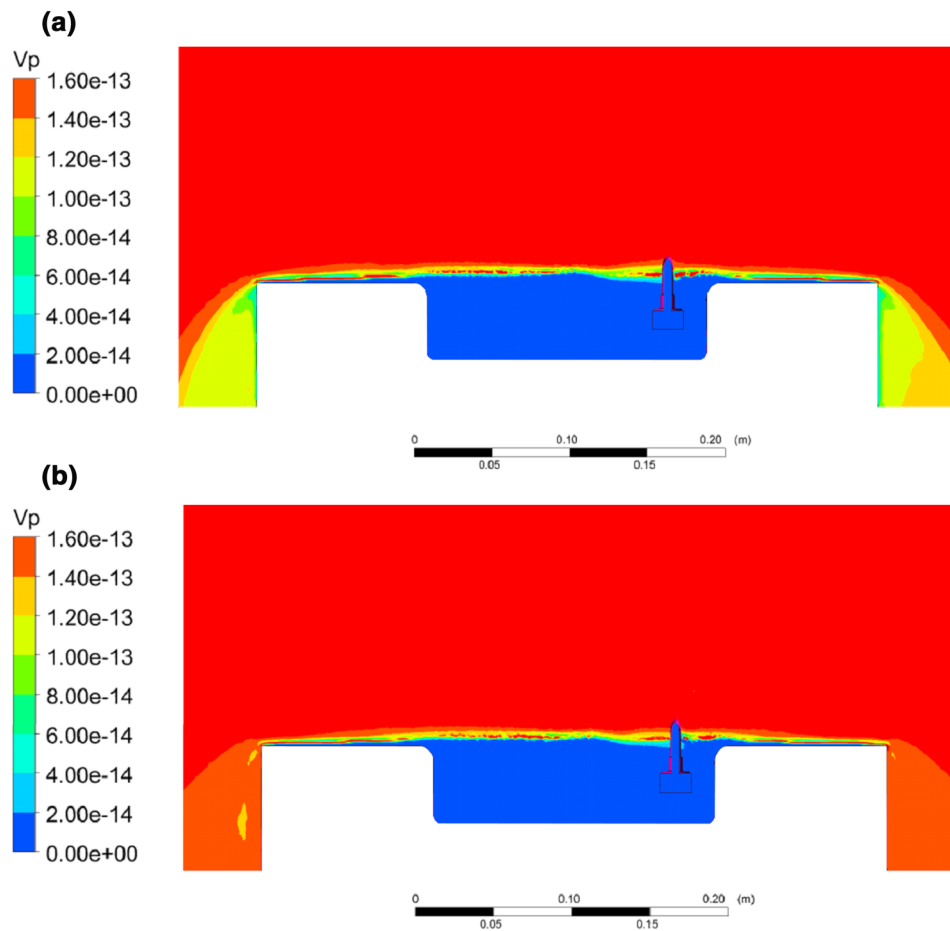


FIGURE 4. Skin particles volume fractions for  $5 \mu\text{m}$  sized particles at air ventilation velocities of (a)  $0.2 \text{ m/s}$  and (b)  $0.4 \text{ m/s}$ .

which fell on to the wound slides and there was no evidence ( $p > 0.1$ ) to suggest the particles found on the wound slides for each test were not normally distributed ( $\text{CO}_2$  insufflated wound  $< 10 \mu\text{m}$ :  $p = 0.394$ , Standard wound  $< 10 \mu\text{m}$ :  $p = 0.449$ ,  $\text{CO}_2$  insufflated wound  $> 10 \mu\text{m}$ :  $p = 0.708$ , Standard wound  $> 10 \mu\text{m}$ :  $p = 0.548$ ). Equal variance between the standard and  $\text{CO}_2$  insufflated wounds was not found and therefore Welch  $t$  test without assumed equal variance was performed for the number of particles on the wound slides.

The Welch  $T$  test without assumed equal variance for the particles less than  $10 \mu\text{m}$  in size showed a strong statistical difference ( $p < 0.01$ ) between the two groups, with a mean of 4 particles on the  $\text{CO}_2$  insufflated wound slides and 279 particles on the standard wound slides, resulting in  $p$  value equal to 0.001. For particles greater than  $10 \mu\text{m}$  in size, the  $T$  test gave a  $p$  value of 0.000, giving very strong evidence ( $p < 0.001$ ) that there is a statistically significant difference between the standard wound and the insufflated wound.

## DISCUSSION

Computational fluid dynamics (CFD) simulations and experimental testing both showed insufflating a surgical cavity with warmed carbon dioxide was able to substantially decrease the number of airborne particles that remained in a wound model. There was a general overall agreement, though the methods used only permit qualitative comparison. The results also agree with testing carried out by Persson *et al.*<sup>16</sup>

The greatest discrepancy between simulations and experimental results were between the  $5.0 \mu\text{m}$  sized particles in the standard wound simulations and the grouping of particles of less than  $10.0 \mu\text{m}$  in the standard wound of the experimental testing. The simulations found only one particle entered into the wound for both ventilation outlet velocities of  $0.2$  and  $0.4 \text{ m/s}$ . In contrast, an average of 279 particles were found on the lowermost surface of the wound in an area of approximately  $2.34 \times 10^6 \mu\text{m}^2$  in the experimental testing. Despite the differences between simulations and experiments, a greater number than one of  $5 \mu\text{m}$



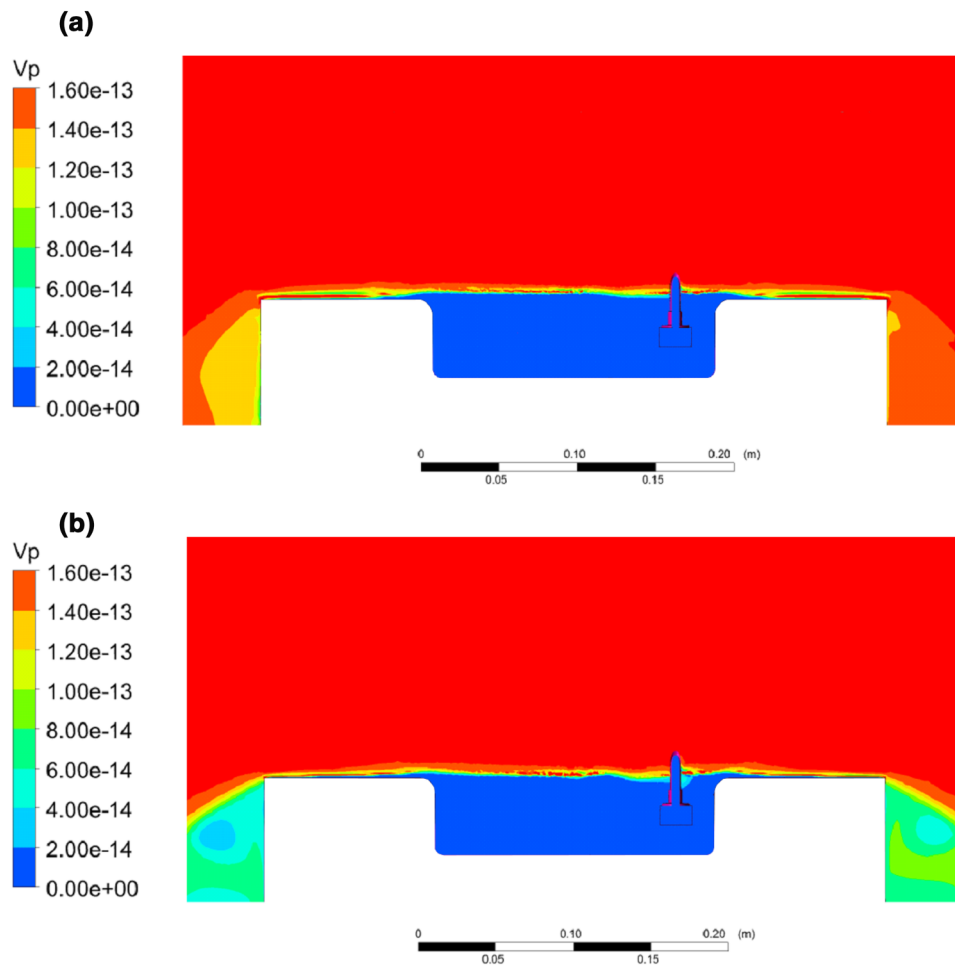


FIGURE 5. Skin particle volume fractions for 13.5  $\mu\text{m}$  sized particles at air ventilation velocities of (a) 0.2 m/s and (b) 0.4 m/s.

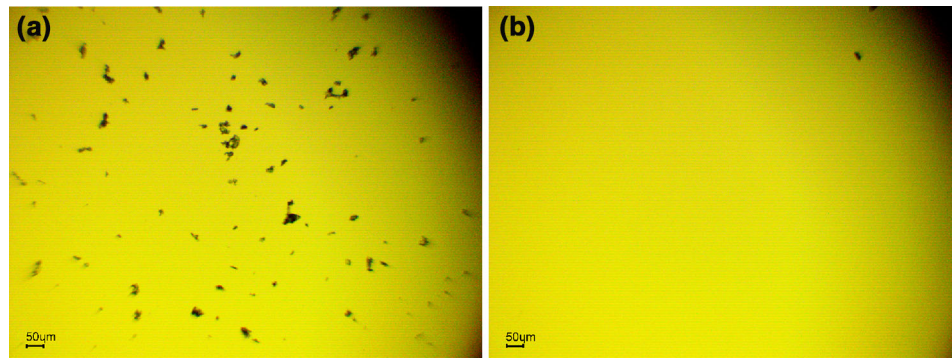


FIGURE 6. Talcum powder particles (a) in the standard wound and (b) in the CO<sub>2</sub> insufflated wound from Test 1.

sized particles were expected to be found in the standard wound simulations, particularly given the large number present in the 13.5  $\mu\text{m}$  sized particle simulations. Particles as small as 2.0  $\mu\text{m}$  were found within the standard wound in experimental testing. This difference suggests that spherical particles of 5.0  $\mu\text{m}$  in

diameter are too small to simulate the behaviour of disk-shaped skin particles.

While one 5.0  $\mu\text{m}$  sized particle was observed in the standard wound simulations, no particles were found in the CO<sub>2</sub> insufflated wound simulations. The results of the simulations alone do not indicate that the CO<sub>2</sub>

**TABLE 2. Experimental particle counts.**

	Particles < 10 micron			Particles > 10 micron			All particles Ratio on wound to air slide
	No. on wound slide	No. on air slide	Ratio	No. on wound slide	No. on air slide	Ratio	
Standard Wound	279	243	1.08	92	120	0.79	0.98
CO <sub>2</sub> insufflated wound	4	288	0.02	3	140	0.02	0.02

insufflation can significantly affect the number of particles within the wound based on the difference of one particle. However, the experimental results provide convincing evidence.

In contrast to the smaller particle results, the results of the 13.5  $\mu\text{m}$  sized particle simulations and experimental testing for particles greater than 10.0  $\mu\text{m}$  were in agreement. Both the simulations and experimental testing showed a large number of large particles were able to remain in the standard wound. When the same simulations and testing were completed with CO<sub>2</sub> insufflation, the number of particles reduced significantly. Based on the lower number of particles present in the simulations than in experimental testing, if the number of particles in the simulations were increased, it is expected that a few particles may be found in the CO<sub>2</sub> insufflated wound. These results would then directly match the experimental testing. Given these differences, the standard wound and CO<sub>2</sub> insufflated wound simulations of the 13.5  $\mu\text{m}$  sized particles successfully simulated what was found experimentally. Future studies may therefore use CFD to simulate more complex wound geometries or varying types of surgery with confidence.

The simulations of the CO<sub>2</sub> insufflated wound showed it is equally able to deflect skin particles under both 0.2 and 0.4 m/s air ventilation rates. This should give confidence to surgeons utilising CO<sub>2</sub> insufflation that it is effective irrespective of the design or type of operating theatre ventilation being used.

## CONCLUSION

Warmed carbon dioxide insufflation of an open surgical wound was found to significantly reduce the number of particles able to enter into the wound compared to a standard wound without carbon dioxide in both simulations and experiments. Computational fluid dynamics (CFD) simulations showed no particles, of either 5.0 or 13.5  $\mu\text{m}$  in diameter, were able to enter into the wound when the wound was filled with carbon dioxide. In the experimental results, an average ratio of 0.98 of the particles exposed to the wound without carbon dioxide insufflation landed in

the wound when exposed to particles ranging in size from 2.0 to 40.0  $\mu\text{m}$ . Under the same conditions, when the wound was insufflated with warmed CO<sub>2</sub> insufflation, the ratio of particles on the wound dropped to 0.02.

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## COMPETING INTERESTS

Monika Baumann is an employee of Fisher & Paykel Healthcare Ltd. (NZ) which sells CO<sub>2</sub> surgical humidifiers and distributes VITA-diffusers supplied by Cardia Innovation AB (Stockholm, Sweden). John Cater has previously been employed as a consultant for Fisher & Paykel Healthcare Ltd. (NZ).

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