ABSTRACT

Outcomes are reported from an antimicrobial-resistance research initiative into the infection control offered by downward laminar-flow ventilation in hospital operating theatres. Pre-cooled air is forced down onto the patient with the intention of diverting airborne pathogens from the surgical wound. The concept was commercialised in the early 1970s as the Ultra Clean Ventilation (UCV) system, a commonly applied contemporary solution. Data collected by the authors in unoccupied UCV theatres in a recently completed acute hospital indicate that as the warming air descends into the occupied zone, it may be subject to recirculation within the suite of spaces. This phenomenon is confirmed by the authors’ experimental modelling. Increasing the residence time of microorganisms will increase the probability of surgical site infection (SSI). An alternative is proposed: an upflow displacement ventilation scheme in combination with a localised source of filtered air to ventilate the wound as required. Likely ventilation flows are modelled experimentally and compared with those of the downdraught-ventilated UCV type. The alternative arrangement appears to provide comparable risk of SSI, while requiring less energy to drive the ventilation system. The concept is developed into a novel surgical theatre proposal in which background airflows are driven by natural buoyancy.

POLICY RELEVANCE

It is doubtful that the UCV configuration for surgical theatres fulfils its original design intent. New evidence contributes to an evolving concern that the system may not eliminate the risk of SSIs of airborne origin. If airborne transmission of infection in surgery is, in practice, a very minor concern, as some surgeons believe the resource-intensive UCV configuration is unnecessary. At a global scale, surgical equity is not served by the complexity, capital and operating costs of this model with its high maintenance burden. The alternative upflow-ventilated surgical theatre described, being a configuration rather than a product, could be created by using locally available construction.
1. INTRODUCTION

The UK National Health Service (NHS) is statutorily required to deliver healthcare environments in which infection is eliminated, while reducing carbon emissions to net zero by 2040, as outlined in the Greener NHS policy statement Delivering a ‘Net Zero’ National Health Service (NHS England & NHS Improvement 2020).

The effectiveness of pre-cooled laminar downward-flow (LDF) ventilation in surgical theatres in delivering infection control is investigated. Pre-cooled air is forced down though a fixed hood onto the patient to divert airborne pathogens from entering the open surgical wound. Waste air is extracted at high level. The concept was commercialised in the early 1970s as the Ultra Clean Ventilation (UCV) system and is a commonly applied solution. UCV using LDF was intended to create a ‘sterile’ zone within an open theatre containing non-sterile space.

There is no clear evidence that this system reduces surgical site infections (SSIs) or infection arising within a surgical wound space (Humphreys et al. 2002). If airborne transmission is significant, evidence is presented here that this ventilation strategy does not eliminate the risk of airborne SSIs, and the LDF-based UCV configuration for surgical theatres will not reliably fulfil its original design intent. If airborne transmission of infection in surgery is, in practice, a minor concern, then the carbon-intensive UCV configuration is unnecessary and other approaches merit review (Lidwell 1981).

New data are presented from recently opened, unoccupied UCV theatres together with outcomes of experimental modelling. This will demonstrate that microorganisms have a range of residence times in the operating theatre with associated risks of infection. SSIs remain a significant issue in contemporary surgery. Currently over 5% of patients undergoing surgery in the UK will develop an SSI (NICE 2019), and 60% of these are deemed preventable (Meeks et al. 2011).

Spaces for surgery in a modern acute hospital are highly carbon intensive. The healthcare sector contributes approximately 4.4% of total global net emissions (Arup 2019). Surgical theatres typically consume three to six times more energy than other areas in hospitals (Rizan et al. 2020). The Royal College of Surgeons (RCS) reports that the carbon footprint of spaces dedicated to surgery contributes some 200 kt CO₂e, 21.86% of total NHS retained estate-related carbon emissions (Whiting et al. 2020). The RCS further reports that 58% of all carbon emissions associated with surgical theatres derive from the energy directly consumed, averaged at 14 kg CO₂ for every 60 min of operating time. Extrapolated across the 4.54 million procedures recorded in the period 2013–14, this yields 109 kt CO₂e from the direct use of energy in surgical theatres and 473 kt CO₂e total annual emissions associated directly with surgery, including consumables and staff travel.

2. THE HYPOTHESIS FOR PRE-COOLED LAMINAR DOWNFLOW VENTILATION IN SURGICAL THEATRES

Modern operating theatres can be grouped into two main types: conventional plenum ventilation or UCV (Stacey & Humphreys 2002). The core UCV strategy is to generate LDF. The LDF system has been demonstrated to be effective at reducing bacterial air contamination, but whether LDF systems directly prevent SSIs is disputed (Hansen et al. 2005; Humphreys & Hoffman 2020). LDF has variously been reported to be either protective against or no different than other types of ventilation, or resulting in an increase in SSI (Lidwell et al. 1982; Bischoff et al. 2017; McHugh et al. 2015; Brandt et al. 2008). Reviews of observational studies of different types of ventilation in operating theatres conclude that there is no difference in protection between LDF and conventional turbulent ventilation, and increased risk of SSI with LDF has even been reported (Bischoff et al. 2017, Gastmeier et al. 2012; Sadrizadeh et al. 2021). In fact, the World Health Organization (WHO) (Humphreys & Hoffman 2020) does not recommend the use of laminar airflow ventilation systems as a measure to reduce SSIs in total arthroplasty surgical procedures due to low to very low quality of evidence of efficacy.
One explanation for increased risk of SSI with LDF is the creation of turbulent airflow over the operating field caused by plumes of warm air colliding with the cold downdraught adjacent to people and instruments, increasing the chance of airborne particles depositing themselves into the open surgical wound (Taylor & Bannister 1993). These unintended effects are demonstrated in the present paper. Mobile ventilation and local wound ventilation devices have been trialled to supplement existing operating theatre ventilation systems (Sossai et al. 2011; Loomans et al. 2016). In summary, it is unclear if high velocity ventilation is essential to reduce the risk of SSI transmission (Ayliffe 1991).

Airborne pathogens are not proven to be a significant source of SSI, but there is a suspicion that they have driven operating theatre design for more than 120 years (Charnley & Eftekhar 1969; Bourdillon & Colebrook 1946; Blowers et al. 1955, 1963). This historical belief led the orthopaedic surgeon John Charnley to reinvent the surgical theatre as a pre-cooled, forced, downward, laminar air flow LDF chamber, the UCV proposition, first published in 1964 (Stacey & Humphreys 2002). UCV was driven by the belief that the mechanical forcing of pre-cooled air down over the patient, surgical team and instruments would eliminate SSIs (Kinmonth et al. 1958; Charnley & Eftekhar 1969). Airborne-related infections were believed to derive from the presence of pathogens within the surgical space, predominantly bacteria or fungi, depositing into surgical wounds (Operating Theatre Hygiene Subcommittee 1962; Chow & Yang 2003; Korol et al. 2013; Lydon et al. 2014).

LDF embodied in UCV is one of the most energy-intensive ventilation systems (MacNeill et al. 2017), but Stacey & Humphreys (2002) reported that:

Few have convincingly demonstrated a direct relationship between the microbiological quality of operating theatre air and postoperative wound infection.

Difficulties are reported in supporting modern surgical techniques as effectively in UCV spaces (Siddaiah-Subramanya et al. 2017; Humphreys 2009) as theatres with other ventilation systems.

The present authors revisited the original argument for the LDF UCV strategy (Charnley 1964a, 1964b) and contemporary assumptions about the sources of infection acquired during surgery (Lidwell et al. 1982).

Figure 1 shows Charnley's proposed solution to the reduction of SSIs from hip replacement procedures. Orthopaedic surgery tends to make large incisions exposing the wound to ambient air, increasing infection risk. His innovative clean-air room enclosure, first built in Wrightington Hospital, was the prototype for the Charnley Howorth DF10 clean air operating enclosure developed commercially by Messrs James Howorth of Bolton, and now ubiquitous. According to Charnley's
notes, this prototype had been in use ‘very satisfactorily for 34 months’, dating its introduction to mid-April 1965. Charnley explained the purpose of the whole assembly: ‘to protect an open surgical wound from bacteria-laden particles of dust’. He was sceptical that even a high-quality ‘plenum’ ventilation system with two or three times the ventilation rate with catch-all air filters would maintain bacteriologically clean air and prevent contamination of an open wound. He stated that this approach ‘merely raises costs’. He reported that his enclosure could generate a positive movement of air in a predetermined direction, whereas in an open plenum ventilated theatre, i.e. pressurised, the same rate of flow would not suppress the normal turbulence from thermal convection (Charnley & Eftekhar 1969). Charnley observed that at air speeds above 80 feet/min, turbulence is inevitable and likely to entrain dust particles and ‘forcibly inject’ them into the wound, which may overcool and desiccate. Charnley’s surgical team wore sealed protective suits under negative pressure, connected by half-inch-diameter plastic piping to a vacuum pump (Figure 1, no. 15). He explained that the enclosure really operates by turbulent dilution of the air, only feasible because of the forced extraction of all particles shed by the surgical team members at source within the sealed suits. The airflow was 10°F cooler than customary in plenum systems to cool the team wrapped in the evacuated suits.

The enclosure comprised half-inch armour-plate glass, plan area 7 × 7 ft, lifted off the floor by 1/8th inch to allow the laminar flow air to escape. The air was supplied via a two-speed fan discharging through a custom-made, stainless steel, water-spray-type humidifier, over a steam-heated coil through a final filter to 1–2 µm. Ultraviolet strip lights were installed above the point of entry into the enclosure to sterilise the internal sides of the supply chamber. The surgeons came to run the airflow at maximum volume, 4000 ft³/min and the enclosure was left running continuously at 2000 ft³/min when idle. Charnley believed this solution was far superior to the conventional plenum theatres in which the attempted elimination of SSIs required no movement of nurses at all during an operation. The commencement of surgery was delayed for 5 min to allow the air to settle and the sealing of doors throughout the procedure.

Charnley anticipated the key difficulties arising from the pre-cooled laminar downflow LDF, principally the turbulent flows arising that could direct pathogens into the open wound, but his formula included the elimination of a significant risk factor: airborne particles arising from the surgical team members themselves in the enclosed operating zone of theatre, by encasing them in evacuated suits. His full formula was commercialised in later practice into a powerful LDF system, UCV, not exactly as Charnley’s sketch shows (Figure 1).

3. INFECTION CONCERNS WITH FORCED VENTILATION IN SURGICAL THEATRES

Surgical procedures that aerosolise droplets containing microorganisms from the patient’s own body or on skin squames may release these into the air. Droplets may sediment into wound sites or onto instruments. SSIs affect 5% or more of NHS patients. Research suggests that SSIs are under-recorded and that the resulting costs in lengthy readmissions may reach £700 million/year in the UK (Leaper et al. 2004). A recent meta-analysis on ‘all surgical wounds, anywhere in the body’ (Hyldig et al. 2016) showed an infection rate of 9%. A single SSI can cost provider and patient £10,000, with significant morbidity and mortality for patients (Tanner et al. 2009; Surgical Site Infection Programme 2019; Astagneau et al. 2001).

SSIs are predominantly bacterial in origin and most are caused by the bacterium Staphylococcus aureus, which is part of the natural skin microbiome. Fungal pathogens can also pose a significant risk; a small number of cases of invasive fungal infections of surgical wounds linked to contamination of operating theatre equipment (Vandecasteele et al. 2002) or air-handling units (Adogwa et al. 2014; Lutz et al. 2003) have been reported. Human fungal infections are most often caused by Aspergillus spp., an ubiquitous environmental fungi, or Candida spp., which is also part of the skin microbiome. Four primary sources of entry of microorganisms into a surgical site are considered in contemporary studies: from (1) the patient; (2) skin shedding or the contaminated hands of operating theatre or post-surgical care staff; (3) the air; or (4) contaminated equipment (Ibrahimi et al. 2011). Theoretically the first two sources of entry can also become airborne.
It is still widely accepted that airborne sources of SSI are significant, but this is still yet to be proven (Ibrahimi et al. 2011; Alfonso-Sanchez et al. 2017). The number of viable bacterial particles in respiratory aerosols is likely to be too low to pose a meaningful risk of SSI. S. aureus and other common bacterial causes for SSI are not prominent in oral nasopharyngeal flora (Ibrahimi et al. 2011). While many more bacteria are shed with skin scales, it is not clear what role this plays in airborne transmission of microorganisms from surgical staff into the patient’s surgical openings. Findings also suggest that SSIs are more likely to occur by direct contact with fomites and/or a contaminated environment. There is still a lack of strong evidence showing an association between airborne bacterial counts and SSIs (Pada & Perl 2015). Indeed, several studies indicate that SSIs tend to derive from microorganisms on the patient’s skin, rather than from external sources (Cheadle 2006). Contemporary suspicion appears to reside less on the air volume within the theatre, which supports a review of the effectiveness and value of LDF installations.

4. RECORDED AIRFLOWS IN AND ADJACENT TO A CONTEMPORARY SURGICAL THEATRE

In order to test the air flow pattern and mixing in an LDF ventilation system, data from a recently commissioned operating theatre in the East of England were collected. Here the background ventilation rate is 25 air changes per hour (ach), a customary rate (Humphreys et al. 2002). Air is supplied from four downflow vents arranged in the centre of the theatre above the patient/clinician zone following the UCV format. In order to study the air flow pathways, a pulse of CO₂ was released just below the inflow vents. The authors investigated how this pulse spread and mixed through the surgical theatre and adjacent spaces. The dilute CO₂ acts as a passive tracer, following the air flow, and so measurements of CO₂ concentration provide a proxy for the motion of the air in the theatre. Small airborne aerosols and particles, which may be host to infection, will also be carried by the air flow on the relatively short time scales of the air flow in the theatre, and so the data about the evolving pulse of CO₂ provides information about the residence time distribution of small airborne particles within the theatre.

Figure 2 shows the measurements from a series of CO₂ sensors, distributed over the operating theatre, following the release of the CO₂. The CO₂ becomes diluted and vents from the space within 300–400 s, but in the meantime, all the sensors record evidence of the CO₂ release, showing how the air is also dispersed through the space. The concentration of CO₂ at all sensors in the theatre is at least a factor 0.1 of the maximum concentration recorded, and illustrates how in the mixing regime a localised source becomes dispersed as it is diluted and vented from the space.

5. EXPERIMENTAL MODELLING OF AIRFLOW IN AN LDF-VENTILATED SPACE

In order to explore the air flow and mixing in different designs of surgical theatres, it is helpful to run small-scale analogue experiments in water bath models; these models can replicate the air flow patterns in an operating theatre provided they are dynamically similar. This requires that the Reynolds number of the flow is in excess of about 5000 to ensure the flows are fully turbulent and that the timescale of the turbulent mixing by convective flows compared with the timescale of the ventilation also scales in a similar way to the theatre (cf. Linden 1999; Gladstone & Woods 2001). The convective flows from local sources of heat scale as \( B^{1/3}H^{-1/3} \), where \( B \) is the buoyancy flux associated with the heat supply \( Q_H \), where \( B = gQ_H/TC \), where \( g \) is gravitational acceleration, \( T \) is ambient temperature (about 300 K), \( C \) is the specific heat of the air (about 1000 kg/m³), and \( H \) is the height of the theatre (cf. Morton et al. 1956), while the ventilation flow scales as \( Q/A \), where \( Q \) is the ventilation volume flow rate and \( A \) the cross-sectional area of the theatre. It is then possible to visualise the flow in the water bath model using dye in either the inflowing fluid or the emissions from a point source of infection in the theatre in order to track how the flow circulates and mixes before ventilation. Figure 3 shows a physical water bath model of a pre-cooled laminar downflow of air (pink), the UCV configuration, encountering the plumes of heat rising from surgical staff, the patient and medical machinery (yellow). The clean downflow mixes with the plumes in the operating zone.
Figure 4 shows an experiment the authors carried out to illustrate the brief release of warmed contaminants in the upflowing plume of hot air from the heat sources near the patient, in the environment of a pre-cooled downflow, with the air being exhausted at high level. Infectious
waste is being cast aside alongside surgery in progress beneath pre-cooled forced laminar flow of the UCV system. The warmed contaminants are entrained in the pre-cooled downflow and forced down into the operating zone. A variant of this phenomenon was observed in Zurich in 2015, a mechanical airflow into the downdraught generated by medical equipment. It was reported by Public Health England (PHE) (2017) as:

*Mycobacterium chimaera*: infections link to heater cooler units. Guidance for healthcare professionals on infection control and clinical aspects of *M. chimaera* infection associated with cardiopulmonary bypass.

PHE further reported:

*Mycobacterium chimaera* [...] is an environmental non-tuberculous mycobacteria [that] has been recognised as a cause of endocarditis, severe disseminated infection and chronic sternal wound infection in patients who have undergone cardiothoracic surgery. [...] Investigations in multiple countries shows [sic] this is likely to be transmitted from heater cooler units, which are part of the cardiopulmonary bypass equipment.

(UK Government 2021: n.p.)

By 30 September 2021, 49 cases of *M. chimaera* infection had been recorded following surgery on cardiopulmonary bypass, 33 proving fatal.

### 6. A COMPARISON OF VENTILATION, MIXING AND RESIDENCE TIME IN THE LDF AND NOVEL SURGICAL THEATRE CONFIGURATIONS

Typically, contemporary surgical theatres generate 25–50 ach to give a level of confidence in achieving infection control objectives. In a theatre of dimension 8 × 8 × 3 m, this implies an air flow rate of about \( V = 1.5–3.0 \text{ m}^3/\text{s} \). In a theatre with a heat load of \( Q_H \), if a reasonably well-mixed space is assumed, the ventilation air will have a temperature increase \( DT \) on passing through the space of about:

\[
DT = \frac{Q_H}{C_p} \cdot V
\]
where $C_p$ is the specific heat of the air, of order 1000 J/kg/K. With heat loads in the range of 10 kW, this implies a temperature uplift of 3–6°C for flow rates of 1.5–3.0 m$^3$/s. Given the significant thermal load in the operating theatre due to lighting, people and equipment, the use of upward displacement ventilation could be very effective since it ensures that the hot air collects in the upper part of the theatre and then vents away.

With appropriate design, the inflowing cooler air can fill the lower part of the theatre, leading to thermal stratification, with the occupants remaining below the higher temperature layer of air, as suggested in Figure 5a. Some modelling of this regime is also provided.

In contrast, with vigorous mixing through the theatre, the occupants will experience the temperature of the thermally equilibrated hot air. For example, LDF systems that supply preconditioned air from the ceiling vents lead to a hybrid regime: in the centre of the region below the ceiling inflow vents the air properties may be similar to the inflow, but as one moves out and beyond the downflowing plume, the air will be significantly heated by entrainment and mixing of the air, leading to temperatures similar to the outflow temperature (Figure 5b).

In order to explore the air flow and mixing in different designs of operating theatres, it is helpful to run small-scale analogue experiments in water bath models; these models can help to visualise the three-dimensional air flow patterns in an operating theatre provided the flow regime is dynamically similar. To complement the experiments, some simplified quantitative physical models of the flow and mixing were also developed to enable a comparison of ventilation times and the potential dose of contaminant or airborne infection.

As shown in Figure 6, the upflow displacement mode flushes the air and heat upwards and into an upper layer of hot air, as has been reported in numerous earlier studies (Linden 1999; Gladstone & Woods 2001), but with a large outflow stack, the interface between this hot mixed air and the inflowing ventilation air may be in the stack, out of harm's way and taking any contaminants with it. In contrast, the mixing ventilation produced by the downflow of ventilation air from the top of the space leads to mixing, and hence a possible longer residence time of airborne infection produced at lower levels in the space, and this is explored below.

The series of images in Figure 6a illustrate the mixing of incoming ventilation air, dyed orange, over time as it mixes across the lower part of the space and is then entrained and carried upwards to upper layer and eventually the outflow vent. The evolution of the air in the buoyancy-driven plume produced from the heat loads in the space may be seen in the lower row of figures; the plume air rises through the lower layer of inflowing air, entraining some of this lower layer and carrying it up to the top of the space where it mixes and eventually vents from the outflow stack.

In the experiment shown in Figure 6b, the ventilation is supplied through the top of the space as in a laminar air supply (blue fluid). This mixes down into the space and leads to a well-mixed interior. The source of buoyancy (red) is mixed by the downflowing ventilation air and becomes dispersed through the space before ventilation.
For the conventional downflow mixing ventilation one can expect that a finite release of contaminant will eventually become well mixed; although at this point, some contaminant may have been ventilated, the remaining contaminant concentration will decay exponentially with time, according to the relation:

\[ V \frac{dC}{dt} = -C \frac{Q}{V} \rightarrow C(t) = C(0) \exp\left(-\frac{Q}{V} t\right) \]

The use of a calibrated light attenuation technique (Cenedese & Dalziel 1998) provides the ability to measure the decay of the concentration of the blue dye injected into the system from the top ventilation inflow, and also the red dye released from a source of contaminant near the base of the operating theatre. In both cases, the intensity of the average dye concentration decays with time according to this model (Figure 6c), and the spatial variance of the concentration in dye intensity.
within the space has decayed after a time of order \((0.05–0.10) V/Q\). This corresponds to the mixing time, which in this example is a fraction of about 10% of the ventilation time, illustrating that much of the mixing occurs before the ventilation and replacement of the air in the space.

In terms of infection control, the main objective of the ventilation system is to limit the residence time of the microorganisms in the space. With a design air change rate of 25 ach, or approximately one air change every 2 min, the well-mixed model leads to a decay of the concentration of microorganisms within the space by a factor of about 10 in a time of about 270 s. With a release of contaminants with a quanta of infection, \(C(0)\), one can estimate the dose received by someone in the surgical theatre in terms of the volume of air breathed in per unit time, \(q\), the time in the operating theatre, \(t\), and the concentration of infection quanta in this air, \(C(t)\), as a function of time after release, assuming for simplicity that the space is well mixed, leading to the expression:

\[
Dose = \int_0^t C(t) q dt = C(0) q V/Q \times (1 - \exp(-Qt/V))
\]

This dose may then carry a risk of infection given by the Well–Riley relation (Noakes & Sleigh 2009; Loomans et al. 2020):

\[
P(t) = 1 - \exp(-Dose)
\]

showing that the higher the forced ventilation rate, the smaller the dose and hence the lower the risk of infection.

7. FLOWS IN THE NOVEL UPFLOW DISPLACEMENT SURGICAL THEATRE

Some aspects of the ventilation in a simplified theoretical model of the novel theatre design are now considered, focusing on the size of the vents to achieve satisfactory interior conditions through a natural or hybrid ventilation solution, and on the impact of this ventilation system for the dose of contaminant which may be experienced in the surgical theatre.

In the novel theatre design, the ventilation air enters through a series of vents around the perimeter of the theatre, which are fed by downflow stacks from the exterior. The air entering the space will then move into the theatre, across the floor, filling the lower part of the theatre. Here the air will be heated by the various sources in the theatres, including much of the surgical machinery and equipment and the medical team, leading to a series of plumes of warm air rising to the upper parts of the theatre. A heat source of strength \(Q\) leads to a plume with volume flux:

\[
Vp = 0.1 \left( Q g / \rho C_p T \right)^{1/3} h^{5/3}
\]

where \(h\) is the height above the source; \(g\) is the acceleration of gravity; and \(T\) is the ambient temperature (kelvin). Figure 7 illustrates the magnitude of the flow at a height of 2 m and 4 m, as a function of the strength of the heat load.

Figure 7: Volume flux in a plume produced by a source of heating as a function of heating rate.

Note: Flux at heights of 2 m (blue line) and 4 m (orange line) above the heat source.
Given the anticipated flow rate for the ventilation of 1.5–3.0 m³/s, the thermal plumes typically have a smaller volume flux than the background flow at height 2 m (blue line) and 4 m (orange line) above the heat source (Figure 7). As a result, the thermal plumes will rise to the top of the space, while the remainder of the air in the space will rise from the inflow supply (Figure 8). In order to vent the air from the space with this net upflow mode, these air streams will mix at the top of the space and in the outflow stacks, producing a buoyancy force, which complements the wind forcing in a purely natural mode. In order to ensure a comfortable interior condition, the incoming air should be pre-conditioned to a temperature of $T_1 = 18$–$19^\circ$C, and on rising through the theatre to the rising stacks, the air will be heated to temperatures of $T_2 = 24$–$25^\circ$C. If the external temperature is $T_a$, then the total buoyancy force driving the flow, per unit mass will be:

$$F_b = g \left[ (T_1 - T_a) h_i + (T_2 - T_a) h_o \right] / T_a.$$

If there is also a wind pressure $F_p$ per unit mass between the inflow and outflow vents, then the natural ventilation flow will be:

$$V_n = cA \left( F_b + F_p \right)^{1/2}$$

where $cA$ is the product of the loss coefficient and effective area for the system, which includes the pressure loss along the stacks and through the openings:

$$cA = 1 / \left( f_i L_i / A_i^3 + f_o L_o / A_o^3 + 1/c_i A_i^2 + 1/c_o A_o^2 \right)^{1/2}$$

where $A_i$, $L_i$, $r_i$, and $f_i$ are, respectively, the area, length, radius and friction factor of each of the stacks for the inflow ($i = 1$) and outflow ($i = 2$); and $c_i$ is the loss coefficient across the opening.

In the design for the operating theatre ventilation, then as an example, with $f = 0.1$, $r = 1$ m, $L = 10$ m and $A = 3$ m², and assuming $c_i$ is of order 0.2, it is found that $cA = 0.2$, and so the natural flow depends on the temperature according to Figure 5.

In conditions with little wind, in order to increase the flow rate to the value of 1.5 m³/s, it is proposed that some additional pressure draw be added to the stack system using a low wattage large area fan in the outflow stacks. As an alternative, different total areas of the vents can be deployed, with Figure 9 illustrating the typical sensitivity to the total duct and vent area, with the curves ranging from 1 to 5 m² of duct area assuming a wind draw of 10 Pa, for comparison with Figure 8.

In the above model, it is assumed that the cold external air is pre-heated before entering the theatre in order to temper the air relative to the exterior. This heating can be achieved through a series of heat-exchange panels in the inflow stacks, through which pre-heated air or water is circulated.
In hotter ambient conditions, some precooling of the supply air would be of benefit, and this may be achieved by using either the same heat exchange pipework, with some cooling water in circulation, or a plenum with thermal mass designed to provide heat exchange. The calculations illustrate the potential for the system to operate effectively in different climate zones, where the exterior temperatures differ. One shortcoming of the design relates to the lack of control of humidity, and in very hot and humid locations the approach may require some additional pre-conditioning of the air, but in less humid climates the approach can in principle operate effectively.

For this low energy air supply system, there will also need to be some acoustic damping in the inflow duct in order to reduce the transmission of sound from the exterior and into the space through the duct system.

With upward displacement ventilation, any airborne infection produced in a hot plume will be carried up in a plume to the upper layer area where the plume forms and rises in the background flow. However, any airborne infection present in the lower part of the space outside these plumes will be carried upwards through the lower layer within the upward displacement flow, until it is entrained into a plume. Assuming very small particles with negligible fall speed, the upflow speed is given by:

$$ w = \left[ Q(\text{vent}) - Q(\text{plume}) \right] / A $$

where $A$ is the cross-sectional area of the space. Any airborne infection in the upflowing lower layer would be diluted with background turbulent stirring of the air (e.g., Mingotti et al. 2020). The maximum residence time of this contaminant is given by the ventilation time of the air in the lower layer. Eventually the air is entrained into the upflowing plumes that rise into the upper layer above the occupied zone and it is then ventilated. The maximum time for this to occur is given by $1.7 \, Vh/HQ$, where $h/H$ is the fractional depth of the lower layer of the space. It follows that the maximum dose of contaminant would be $1.7 \, h/H$ of the dose received in the mixing ventilation case, and this would require that person to be in the path of the contaminant. This illustrates that the risks of infection in such an upflow displacement system are comparable to the risks in the downflow LDF clean air mixing regime.

8. AN ALTERNATIVE DESIGN FOR AN OPERATING THEATRE

The research project concluded by exploring the potential for a safer, simpler, naturally ventilated environment for surgery. One prospective avenue emerged from investigation of the aseptic...
movement’s operating room designs of the late 19th and early 20th centuries (Hofmokl 1910; Murken 1979). A great deal of attention was given at the time to the design of the largely natural ventilation scheme. The authors reconstructed the surgical theatre in the 1897 Operationshaus at St. Georg, Hamburg, digitally (Figure 10) and modelled the space to determine the efficiency of its upflow displacement ventilation scheme to exhaust airborne pathogens. The findings are reported in Woods et al. (2021). Records show that air was introduced at low level into the theatre at 18°C at approximately 1 ach and exhausted naturally at a high level, exploiting the natural stack effect. Contemporary reports explained (Wallraff 1898) that surgeons engaged the full effect of the stack ventilation between operations to flush the space, but reduced airflow during surgery. The model outcomes are promising but affected adversely in cold conditions by the heat losses through the prodigious perimeter glazing.

The research project developed a hybrid ventilation system coupling elements of natural ventilation with some mechanical component for the more challenging seasonal conditions. The ventilation system has three functions: (1) the thermal management of the space; (2) infection control ensuring that any microorganisms have a short residence time within the space; and (3) provision of sufficient ventilation air to dilute any anaesthetic gases escaping in the theatre.

The design (Figure 11) is developed using the dimensions of the Department of Health’s guidance for surgical theatre design, a 10 × 10 m square floorplate, but developed vertically to give increased ≥5 m ceiling height and to allow full-width clerestory glazing to north, east and west, heavily protected from direct solar gain. Air supply ducts at the perimeter draw air down from the roof level to low-level intakes into the surgical space discharging at waist height. Incoming air can be heated at entry to the space. Airflows are induced by the substantial stack located at the centre of the ceiling above the surgical zone. The multicellular stack enables four peripheral ducts to drain the general space and a central stack to vent the volume defined by a glazed hood above the surgical zone. The stack has a complex termination designed to discourage wind-induced reversed flows, the result of earlier extensive experimentation in other low energy ventilation projects, some built and monitored. High-efficiency particle arrester (HEPA)-filtered air is supplied as required to the surgical zone through flexible hoses that can be positioned at will by the surgical team. In the version depicted in the animation stills, in consultation with the focus group of surgeons, the sidewalls are faced in seamless glass sheets with photochromatic properties, enabling a continuous slow flux of colour, intended to make the space more empathetic for the surgical team and for patients as the practice of anaesthetising in theatre becomes more frequent. An animation of the design depicts a colon resection procedure observed by the researcher team (Figure 12). The animation became the primary vehicle for consultation across the group of 50 surgeons, anaesthetists and surgical theatre staff whose responses to the design and attitudes to and behaviours within the surgical space will be published in a subsequent paper (Schlich 2007).
9. CONCLUSIONS

This paper considered strategies to eliminate airborne surgical site infections (SSIs) in surgical theatres. The Ultra Clean Ventilation (UCV) system devised in the mid-1960s, the laminar downflow of pre-cooled air (laminar downward-flow—LDF) onto the surgical zone, was intended to eliminate SSI. The authors’ physical and computational modelling supported by the measurement of actual flows in unoccupied exemplary new surgical theatres show that a risk of airborne infection remains as the laminar flows mix the air in the space.

Calculations show that the dose received by occupants of the novel upward flow theatre is dispersed by the upflow displacement regime proposed in the novel theatre design. The authors note that the rapid removal of leaking anaesthetic gases requires a minimum ventilation rate. Other more sustainable approaches to anaesthesia are being developed.

Based on this analysis, it is suggested that an upflow displacement system will provide a safe and well-ventilated interior space in which the air flow can be driven by buoyancy and wind forces. Some guides for the openings and ducts needed for the effective operation of the theatre ventilation are outlined. In more temperate conditions it is proposed to use some fan assist for the flow.
The design exploits natural buoyancy and wind-assisted ventilation, but can deliver high-efficiency particle arrestor (HEPA)-filtered air directly onto the wound site and instruments as directed by the surgical team, rather than saturating the whole theatre with HEPA-filtered air. Surgical spaces are prodigious users of energy and policy requires the NHS to be net carbon neutral by 2040. Reductions in infection risk must be accompanied by reductions in associated carbon emissions.

The proposal for a novel theatre contributes to surgical equity: it is less complex requiring fewer scarce components, lower maintenance commitments, lower energy requirements and operating costs. The design can be realised in various regional construction modes to accommodate various climate types. It is a configuration, not an assembly of components manufactured by one of a small number of Western corporations protected by intellectual property rights.

The various novel characteristics are being assessed by focus groups of surgeons, to be reported in a later paper.

AUTHOR AFFILIATIONS

C. Alan Short orcid.org/0000-0001-5699-0259
Department of Architecture, University of Cambridge, Cambridge, UK;
Clare Hall, University of Cambridge, Cambridge, UK

Andrew W. Woods orcid.org/0000-0002-5098-9940
BP Institute for Multiphase Flow, University of Cambridge, Cambridge, UK

Lydia Drumright orcid.org/0000-0002-3361-8080
Department of Medicine, University of Washington, Seattle, WA, US;
Department of Medicine, University of Cambridge, Cambridge, UK

Rabiya Zia orcid.org/0000-0003-2407-3936
The Healthcare Improvement Studies (THIS) Institute, School of Clinical Medicine, University of Cambridge, Cambridge, UK

Nicola Mingotti orcid.org/0000-0001-9579-0145
BP Institute for Multiphase Flow, University of Cambridge, Cambridge, UK;
Department of Chemical Engineering and Biotechnology, University of Cambridge, Cambridge, UK

AUTHOR CONTRIBUTIONS

C.A.S: principal investigator of the ExISE project, architect, historical and contemporary design analysis and solutions.

A.W.: fluid flow specialist recording, analysing and modelling airflows, co-designer of solutions.

L.D.: Medical School head of informatics, specialist in mechanisms of cross-infection and their control, history of infection control.

R.Z.: post-doctoral researcher for ExISE, Wellcome-THIS Research Fellow, infection specialist.

N.M.: post-doctoral researcher in fluid mechanics low carbon ventilation strategies.

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SUPPLEMENTAL DATA

A short video on the ExISE project can be viewed on: https://vimeo.com/667338881
REFERENCES

Adogwa, O., Fatemi, P., Perez, E., Moreno, J., Gazcon, G. C., Gokaslan, Z. L., Cheng, J., Gottfried, O., & Bagley, C. A. (2014). Negative pressure wound therapy reduces incidence of postoperative wound infection and dehiscence after long-segment thoracolumbar spinal fusion: A single institutional experience. Spine Journal, 14, 2911–2917. DOI: https://doi.org/10.1016/j.spinee.2014.04.011

Alfonso-Sánchez, J. L., Martínez, I. M., Martín-Moreno, J. M., González, R. S., & Botía, F. (2017). Analyzing the risk factors influencing surgical site infections: The site of environmental factors. Canadian Journal of Surgery/Journal canadien de chirurgie, 60, 155–161. DOI: https://doi.org/10.1503/cjs.017916

Arup. (2019). Health care’s climate footprint: How the health sector contributes to the global climate crisis and opportunities for action. https://www.arup.com/perspectives/publications/research/section/healthcares-climate-footprint

Astagneau, P., Rioux, C., Golliot, F., Brücker, G., & INCISO Network Study Group. (2001). Morbidity and mortality associated with surgical site infections: Results from the 1997–1999 INCISO surveillance. Journal of Hospital Infection, 48(4), 267–274. DOI: https://doi.org/10.1053/jhin.2001.1003

Ayliffe, G. A. (1991). Role of the environment of the operating suite in surgical wound infection. Reviews of Infectious Diseases, 13(Suppl. 10), S800–S804. DOI: https://doi.org/10.1093/clinids/13.Supplement_10.S800

Bischoff, P., Kubilay, N. Z., Allegrenzi, B., Egger, M., & Gastmeier, P. (2017). Effect of laminar airflow ventilation on surgical site infections: A systematic review and meta-analysis. The Lancet Infectious Diseases, 17, 553–561. DOI: https://doi.org/10.1016/S1473-3099(17)30059-2

Blowers, R., Lidwell, O. M., & Williams, R. E. (1963). Design and ventilation of operating-room suites for control of infection and for comfort. Lancet, 1, 165. DOI: https://doi.org/10.1016/S0140-6736(63)91044-4

Blowers, R., Mason, G. A., Wallace, K. R., & Walton, M. (1955). Control of wound infection in a thoracic surgery unit. Lancet, 266, 786–794. DOI: https://doi.org/10.1016/S0140-6736(55)92385-0

Bouddillon, R. B., & Colebrook, L. (1946). Air hygiene in dressing-rooms for burns or major wounds. Lancet, 1, 601. DOI: https://doi.org/10.1016/S0140-6736(46)90447-3

Brandt, C., Hott, U., Sohr, D., Daschner, F., Gastmeier, P., & Ruden, H. (2008). Operating room ventilation with laminar airflow shows no protective effect on the surgical site infection rate in orthopedic and abdominal surgery. Annals of Surgery, 248, 695–700. DOI: https://doi.org/10.1097/SLA.0b013e31818b757d

Cenedese, C., & Dolzi, S. B. (1998). Concentration and depth fields determined by the light transmitted through a dyed solution. In Proceedings of the 8th International Symposium on Flow Visualization (ed. G. M. Carlomango & I. Grant), paper 061.

Charnley, J. (1964a). A clean-air operating enclosure. British Journal of Surgery, 51, 202–205. DOI: https://doi.org/10.1002/bjs.1800510309

Charnley, J. (1964b). A sterile-air operating theatre enclosure. British Journal of Surgery, 51, 195–202. DOI: https://doi.org/10.1002/bjs.1800510308

Charnley J. (1968). Clean-air operating room enclosure (Unpublished Internal Publication No. 13. February). Centre for Hip Surgery, Wrightington Hospital.

Charnley, J., & Eftekhar, N. (1969). Postoperative infection in total prosthetic replacement arthroplasty of the hip-joint. With special reference to the bacterial content of the air of the operating room. British Journal of Surgery, 56, 641–649. DOI: https://doi.org/10.1002/bjs.1800560902

Cheadle, W. G. (2006). Risk factors for surgical site infection. Surgical Infections, 7(Suppl. 1), S7–S11. DOI: https://doi.org/10.1089/sur.2006.7.s1-7

Chow, T., & Yang, X. (2003). Performance of ventilation system in a non-standard operating room. Building and Environment, 38, 1401–1411. DOI: https://doi.org/10.1016/S0360-1323(03)00155-0

Gastmeier, P., Breier, A. C., & Brandt, C. (2012). Influence of laminar airflow on prosthetic joint infections: A systematic review. Journal of Hospital Infection, 81, 73–78. DOI: https://doi.org/10.1016/j.jhin.2012.04.008

Gladstone, C., & Woods, A. W. (2001). On buoyancy-driven natural ventilation of a room with a heated floor. Journal of Fluid Mechanics, 441, 293–314. DOI: https://doi.org/10.1017/S0022112001004876

Hansen, D., Krabs, C., Benner, D., Braukziepe, A., & Popp, W. (2005). Laminar airflow provides high air quality in the operating field even during real operating conditions, but personal protection seems to be necessary in operations with tissue combustion. International Journal of Hygiene and Environmental Health, 208, 455–460. DOI: https://doi.org/10.1016/j.ijheh.2005.08.008

Hofmokl, E. (1910). Wiener Heilanstalten. Alfred Holder.

Humphreys, H. (2009). Preventing surgical site infection. Where now? Journal of Hospital Infection, 73, 316–322. DOI: https://doi.org/10.1016/j.jhin.2009.03.028
Humphreys, H., & Hoffman, P. (2020). The conundrum of ultraclean air, deep infections, and artificial joint replacement. Journal of Hospital Infections, 104, 123–124. DOI: https://doi.org/10.1016/j.jhin.2019.09.016

Humphreys, H., Taylor, E. W., Bannister, G., Bennett, A., Chesworth, T., Greig, M., Hoffman, P. N., Jones, E., Ridgway, G. L., Smyth, E. T. M., Stacey, A., Williams, J., & Woodhead, K. (2002). Operating theatre ventilation standards and the risk of postoperative infection. Journal of Hospital Infection, 50, 85–90. DOI: https://doi.org/10.1053/jhini.2001.1126

Hyldig, N., Birke-Sorensen, H., Kruse, M., Vinter, C., Joergensen, J. S., Sorensen, J. A., Mogensen, O., Lamont, R. F., & Bille, C. (2016). Meta-analysis of negative-pressure wound therapy for closed surgical incisions. British Journal of Surgery, 103(5), 477–486. DOI: https://doi.org/10.1002/bjs.10084

Ibrahim, O. A., Sharon, V., & Eisen, D. B. (2011). Surgical-site infections and routes of bacterial transfer: which ones are most plausible? Dermatologic Surgery, 37, 1709–1720. DOI: https://doi.org/10.1111/j.1524-4725.2011.02183.x

Kimmonth, J. B., Hare, R., Tracy, G. D., Thomas, C. G., Marsh, J. D., & Jantet, G. H. (1958). Studies of theatre ventilation and surgical wound infection. British Medical Journal, 2, 407–411. DOI: https://doi.org/10.1136/bmj.2.5093.407

Korol, E., Johnston, K., Waser, N., Sifakis, F., Jafri, H. S., Lo, M., & Kyaw, M. H. (2013). A systematic review of risk factors associated with surgical site infections among surgical patients. PLoS ONE, 8 (12). DOI: https://doi.org/10.1371/journal.pone.0083743

Leaper, D. J., van Goor, H., Reilly, J., Petrosillo, N., Geiss, H. K., Torres, A. J., & Berger, A. (2004). Surgical site infection—A European perspective of incidence and economic burden. International Wound Journal, 1(4), 247–273. DOI: https://doi.org/10.1111/j.1742-4801.2004.00067.x

Lidwell, O. M. (1981). Airborne bacteria and surgical infection. American Journal of Medicine, 70, 693–697. DOI: https://doi.org/10.1016/0002-9343(81)90598-2

Lidwell, O. M., Lowbury, E. J., Whyte, W., Blowers, R., Stanley, S. J., & Lowe, D. (1982). Effect of ultraclean air in operating rooms on deep sepsis in the joint after total hip or knee replacement: A randomised study. British Medical Journal (Clinical Research), 285, 10–14. DOI: https://doi.org/10.1136/bmj.285.6334.10

Linden, P. F. (1999). The fluid mechanics of natural ventilation. Annual Review of Fluid Mechanics, 31, 201–238. DOI: https://doi.org/10.1146/annurev.fluid.31.1.201

Loomans, M., de Leeuw, J., Middendorf, G., & Nielsen, P. V. (2020). COVID-19 and recirculation. REVHA Journal, May, 5–9.

Loomans, M. G. L. C., De Visser, I. M., Loogman, J. G. H., & Kort, H. S. M. (2016). Alternative ventilation system for operating theaters: Parameter study and full-scale assessment of the performance of a local ventilation system. Building and Environment, 102, 26–38. DOI: https://doi.org/10.1016/j.buildenv.2016.03.012

Lutz, B. D., Jin, J., Rinaldi, M. G., Wickes, B. L., & Huycke, M. M. (2003). Outbreak of invasive Aspergillus infection in surgical patients, associated with a contaminated air-handling system. Clinical Infectious Diseases, 37, 786–793. DOI: https://doi.org/10.1086/377537

Lydon, G. P., Ingham, D. B., & Moursheed, M. M. (2014). Ultra clean ventilation system performance relating to airborne infections in operating theatres using CFD modelling. Building Simulation, 7, 277–287. DOI: https://doi.org/10.1007/s12273-013-0145-4

MacNeill, A. J., Lillywhite, R., & Brown, C. J. (2017). The impact of surgery on global climate: A carbon footprinting study of operating theatres in three health systems. Lancet Planetary Health, 1, e381–e388. DOI: https://doi.org/10.1016/S2542-5196(17)30162-6

McHugh, S. M., Hill, A. D., & Humphreys, H. (2015). Laminar airflow and the prevention of surgical site infection. More harm than good? The Surgeon: Journal of the Royal Colleges of Surgeons of Edinburgh and Ireland, 13, 52–58. DOI: https://doi.org/10.1016/j.surge.2014.10.003

Meeks, D. W., Lally, K. P., Carrick, M. M., Lew, D. F., Thomas, E. J., Doyle, P. D., & Kao, L. S. (2011). Compliance with guidelines to prevent surgical site infections: As simple as 1-2-3? American Journal of Surgery, 201, 76–83. DOI: https://doi.org/10.1016/j.amjsurg.2009.07.050

Mingotti, N., Wood, R., Noakes, C., & Woods, A. (2020). The mixing of airborne contaminants by the repeated passage of people along a corridor. Journal of Fluid Mechanics, 903. DOI: https://doi.org/10.1017/jfm.2020.671

Morton, B., Taylor, Sir G. I., & Turner, S. (1956). Turbulent gravitational convection from maintained and instantaneous sources. Proceedings of the Royal Society A, 234, 1196. DOI: https://doi.org/10.1098/rspa.1956.0011

Murken, A. H. (1979). Die bauliche Entwicklung des deutschen allgemeinen Krankenhauses im 19. Jahrhundert. Vandenhoeck & Ruprecht.
NHS England & NHS Improvement. (2020). Delivering a ‘net zero’ National Health Service. https://www.england.nhs.uk/greenernhs/wp-content/uploads/sites/51/2020/10/delivering-a-net-zero-national-health-service.pdf

NICE. (2019). Surgical site infections: Prevention and treatment. National Institute for Health and Care Excellence (NICE). https://www.nice.org.uk/guidance/ng125/

Noakes, J., & Sleight, P. A. (2009). Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards. Journal of the Royal Society Interface, 6. DOI: https://doi.org/10.1098/rsif.2009.0305.focus

Operating Theatre Hygiene Subcommittee. (1962). Design and ventilation of operating room suites for control of infection and for comfort: A report to the medical research council by the Operating-Theatre Hygiene Subcommittee of the Committee on Control of Cross-Infection. The Lancet, 280, 945–951. DOI: https://doi.org/10.1016/S0140-6736(62)90724-9

Pada, S., & Perl, T. M. (2015). Operating room myths: What is the evidence for common practices. Current Opinion in Infectious Diseases, 28, 369–374. DOI: https://doi.org/10.1097/QCO.0000000000000177

PHE. (2017). Infections associated with heater cooler units used in cardiopulmonary bypass and ECMO: Information for healthcare providers in the UK, Version 2. Public Health England. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/605639/Infections_Associated_with_Heater_Cooler_Units_Used_in_Cardiopulmonary_Bypass_and_ECMO.pdf

Rizan, C., Steinbach, I., Nicholson, R., Lillywhite, R., Reed, M., & Bhutta, M. F. (2020). The carbon footprint of surgery and the NHS carbon footprint. Bulletin of the Royal College of Surgeons of England, 102, 182–185. DOI: https://doi.org/10.1308/rcsbull.2020.152

Sadrzadeh, S., Aganovic, A., Bogdan, A., Wang, C., Afsari, A., Hartmann, A., Croitoru, C., Khan, A., Kriegel, M., Lind, M., Liu, Z., Sköldenberg, O., & Cao, G. (2021). A systematic review of operating room ventilation. Journal of Building Engineering, 40, 102693. DOI: https://doi.org/10.1016/j.jobe.2021.102693

Schlich, T. (2002). Diagnosis and treatment of Aspergillus flavus sternal wound infections after cardiac surgery. Clinical Infectious Diseases, 35, 887–890. DOI: https://doi.org/10.1086/342699

Vandecasteele, S. J., Boelaert, J. R., Verrelst, P., Graulus, E., & Gordts, B. Z. (2002). Diagnosis and treatment of Aspergillus flavus sternal wound infections after cardiac surgery. Clinical Infectious Diseases, 35, 887–890. DOI: https://doi.org/10.1086/342699

Wallroff, H. (1898). Bau und Einrichtungen des neuen städtischen Krankenhauses. Nuremberg.

Whiting, A., Tennison, I., Roschnik, S., & Collins, M. (2020). Surgery and the NHS carbon footprint. Bulletin of the Royal College of Surgeons of England, 102, 182–185. DOI: https://doi.org/10.1308/rcsbull.2020.152

Woods, A., Short, A., Mingotti, N., Schoefert, K., Drumright, L., & Zia, R. (2021). Innovative practice in the manufacture of aseptic surgical environments in the late nineteenth century. Journal of Architectural Conservation, 27(3). DOI: https://doi.org/10.1080/13556207.2021.1982541

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