Innovative practice in the manufacture of aseptic surgical environments in the late nineteenth century

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ABSTRACT
Contemporary spaces for surgery are highly energy intensive, much of which is attributed to powerful air conditioning systems intended to force air down onto the patient, surgical staff and instruments to keep airborne pathogens from sedimenting on patients and equipment during surgery. The carbon footprint from these systems is prodigious in a service required to dramatically cut emissions. Sufficient doubts have arisen from experimental modelling and data collected in surgical theatres that pathogens are expelled efficiently to encourage broader speculation about the fundamental configuration of spaces for surgery. One prospective avenue is the investigation of the aseptic movement’s operating room designs of the late nineteenth and early twentieth centuries before the adoption of air conditioning. Historical review and testing of theatre design, as part of the Excising Infections in Surgical Environments (ExISE) project, identified a carefully designed and innovative operating room in Hamburg’s general hospital. The St. Georg’s Operationshaus (1899) is reconstructed digitally, analysed theoretically and modelled experimentally to determine modern utility as a green theatre. Results are promising but are affected by the parallel intent to introduce prodigious natural daylighting; however, the effects of this on the airflow patterns in the space could be managed by modern materials and control technologies.

KEYWORDS
Surgical site infections; aseptic environments; surgery; ventilation

The UK National Health Service England (NHS) is required to cut its direct Carbon Footprint to net zero emissions by 2040, and to have achieved an 80% reduction by 2028–32. The NHS Sustainable Development Unit estimated the 2017 health and social care related emissions to be 27.1 MtCO\textsubscript{2}e, some 6.3% of the national footprint, a reduction of 18.5% since 2007 but against a 27.5% increase in activity in that period.\textsuperscript{1} The retained NHS estate is responsible for approximately 15% of total NHS related carbon emissions, 0.915 MtCO\textsubscript{2}e. The Estates Returns Information Collection ERIC Summary for 2018–
19 reports 11.2 billion kWh total energy usage across the NHS Estate. Acute hospitals contribute the greater proportion and, within this, the Royal College of Surgeons (RCS) reports that the carbon footprint of spaces dedicated to surgery, less the significant emissions associated with anaesthetic gases, contribute significantly, some 200ktCO$_2$e. The RCS further reports that 58% of all carbon emissions associated with theatres is from the energy directly consumed, at some 14 kg CO$_2$ for each 60 min of operating time. Extrapolated across the 4.54 million procedures recorded in 2013–14, this yields 109ktCO$_2$e from the direct use of energy in theatre, and in total 473ktCO$_2$e annual emissions associated directly with surgery including consumables and staff travel. Much of this energy is consumed in driving conditioned air through the theatres to remove airborne pathogens to reduce surgical site infections (SSIs). Effective ventilation to disperse and remove airborne pathogens appears to have driven operating theatre design intermittently since the later nineteenth century, coupled with the environmental intent to maximise natural light. Here an AHRC AMR funded research team explores potential learnings from a late nineteenth-century aseptic operating theatre in Hamburg, much reported at the time with apparently good outcomes; in the context of earlier experimental modelling of a contemporary heavily serviced laminar flow theatre, which revealed unwelcome turbulent flows that might spread airborne pathogens.

**Ventilation for prevention of surgical site infections (SSI)**

The NHS is obligated to maintain safe environments in mitigating the effects of the changing climate and eliminating infection, whilst dramatically reducing energy use and resultant carbon emissions, a challenging conundrum that Sir Simon Stevens wrote in October 2020 would require, ‘direct interventions within estates and facilities’. However, the interventions suggested in the Greener NHS consultation focussed almost entirely on renewable energy technologies and operational economies applied to ‘business as usual’ theatre design, and not on more fundamental re-engineering possibilities which may be more effective in closing the gap. Operating specialised mechanical ventilation and air conditioning systems with High Efficiency Particle Arrestor HEPA filtration accounts for a significant proportion of the energy consumption reported, although precise disaggregated figures are generally unavailable. In the NHS England hospitals involved in the ExISE study, some ventilation systems were found to be continuously left at full airflow volume and temperature regulation in readiness, even when the theatre is not in use. Is this practice effective clinically, and therefore necessary?

Airborne-related infections are believed to be largely the outcome of pathogens present in the surgical space, usually bacteria or fungi. They can become airborne through surgical procedures that aerosolize droplets containing microorganisms from the patient’s own body or on skin squames, which may sediment into woundsites or on to instruments about to be inserted where they may become highly problematic or arise from previous surgeries and non-sterile items. The late 1960s reinvention of the operating theatre as a laminar air flow chamber was largely prompted by the belief that the highly energy consumptive mechanical introduction of rapid flows of pre-cooled air over the patient, surgical team and instruments would eliminate SSIs. Research suggests that SSIs may occur at double the recorded rate and that the resulting costs in lengthy readmissions may reach £700 million/year in the UK. A recent meta-
analysis on ‘all surgical wounds, anywhere in the body’, showed an infection rate of 9%, and Inui and Bandyk report on vascular wound infections presenting after 10–20% of operations, despite the prodigious energy consumed in manufacturing artificial theatre environments to eliminate SSIs.

Stacey and Humphries reported that, ‘Few have convincingly demonstrated a direct relationship between the microbiological quality of operating theatre air and postoperative wound infection’. They date a revival of interest in air as a significant source of SSIs from the 1930s but they record the first influential study in 1946 by Bourdillon and Colebrook reporting on an experimental pressurised environment for a burns unit, noting that theatres in general were only equipped with mechanical exhausts to remove steam. Charnley published the now ubiquitous laminar flow ultraclean ventilation (UCV) theatre concept through the late 1960s. Bacteriological standards for supply air (35 bacteria carrying particles BCP per cubic metre of air) and air within the operating zone (180 BCP per cubic metre averaged) were published in 1972, reinforced in 1983, and applied to UCV theatres. Health Technical Memorandum 2025, intended as guidance, codified all official policy on operating theatre ventilation, freezing innovation. Reduced energy consumption and associated carbon emissions did not figure as important goals in the documentation. These concepts were introduced over a decade later in the Greener NHS consolation and corresponding policy document, ‘Delivering a “Net Zero” National Health Service’.

**Historical design of ventilation and aseptic techniques in the nineteenth century**

As part of its review of operating theatre ventilation, the ‘Excising Infections in Surgical Environments’ (ExISE) project is investigating the largely naturally conditioned designs for surgical environments proposed and built in the 30–80 years (c. 1890–1940) before sealed artificial environments became customary. Contemporary Operating Theatres have been described as ‘heavily controlled environments’ but controlled by whom and for whose benefit? The researchers applied a well-validated experimental methodology to assess the likely comparative performance in expelling airborne pathogens and the replicability of the design of St. Georg’s Operationshaus to inform prospective modern, lower carbon designs for operating theatres. ExISE researchers have reconstructed and analysed the aseptic operating theatre in the 1897 Operationshaus of the Allgemeines Krankenhaus St Georg Hamburg, considered an innovative and important design, published internationally on completion. The reconstruction included conservation of an historic, but carefully and rationally configured architectural design, with modern controls added, as understanding practical, modern use was the objective.

By the mid-nineteenth century, there was significant interest in the use of aseptic techniques across Europe to increase survival of the surgical patient. Aseptic techniques, proposed by German and Austrian surgeons in the 1870s and 1880s, required a more comprehensive design response than Lister’s antisepctic protocols. Depending on architectural means of environmental control, aseptic surgical environments were first developed in the 1860s, very particularly intended to reduce post-operative infection rates by removing possible contaminants, especially transported in air-borne particles. Surgeons set out to oversee pre- and post-operative procedures with the same ferocity for oversight as with surgery and their fervour had spatial consequences. Operating theatres...
became less prevalent than operating suites consisting of a series of spaces dedicated to particular pre- and post-operative surgical routines, evident in the plans of St. Georg and its near contemporaries the Nuremburg General Hospital and the Rudolfinerhaus, Sophien-Spital and Wilhelminen-Spital in Austria.20

**St Georg’s operationshaus design details**

Figure 1 shows the building inspector (and apparent designer) Ruppel’s ground plan drawing of the Operationshaus at St Georg, a freestanding building in the centre of the new hospital campus.21 The declared intention for St. Georg was to deliver the environment of a hospital in the countryside, but in a city. All access was external. There are three theatres. Figure 2 shows a reconstruction of the aseptic operating theatre in the Northwest quadrant from the contemporary publication celebrating its opening.22 The aseptic operating theatre is part enclosed by a double glazed envelope through which air was drawn largely naturally but assisted by an electric air pump in the basement and recirculated through the cavity between the glazing. Its near

![Figure 1. The Ground floor plan of the 1897 Operationshaus of the Allgemeines Krankenhaus St Georg Hamburg with arrows indicating warmed air supply (red) and exhaust (blue). The study focusses on the aseptic Operationssaal I. Between Op I and II is the sterilisation room, the prep. Room for OpII with a patient elevator a wardrobe for doctors and the prep. Room for OpIII, added after 1906. Across the corridor are waiting rooms for men and women and a room for post-operative observation and rest.](Image)
Figure 2. The Aseptic Operating Theatre in the ‘Operationshaus’ at Hamburg’s St Georg General Hospital of 1897. Plan and sections reconstructed by C A Short and Slaine Campbell from archival research by Dr. Kathryn Schoefert. Key: 1. External air intake supplies direct operating space ventilation; 2. First charcoal filter; 3. Pre-tempering chamber, cooling over ice in summer or heating over hot water batteries (4) in winter; 5. Electric air pump; 6. Supply air outlets in the operating theatre above; 7. Location of supply outlets on plan; 8. Fresh air supply to cavity glazing on Northwest and Northeast sides of the theatre; 9. Location of space for tempering supply air direct into the theatre; 10. Wide cavity between outer clear and inner translucent glazing; 11. opening lights exhaust air within the glazed cornice; 12. Glazed roof void collects exhaust air from cavities and, it appears, from the theatre before returning it through natural circulation to the heating plenum below the theatre floor 13.
contemporary in Nuremburg pursued a similar highly glazed sealed envelope with interstitial convective heating.

Wallraff wrote that this air was customarily kept at 18°C with one air change per hour, also his recommendation for doctors’ surgeries. Perhaps not coincidentally this is the performance specification for Le Corbusier’s respiration exacte contained within his double glazed mur neutralisant. The St. Georg operating space was pressurised with air pumped in at low level by a centrifugal fan and filtered through charcoal and gravel. Air changes could be adjusted, such that low-level ventilation could be used during surgery and this could be significantly increased between surgeries to eliminate contaminants from the room. The intake could be primed with ice in hot weather and had heater batteries installed in winter. Dr. Deneke, the first Director of St. Georg, explained in the 1906 guide to the hospital that the fundamental design concept of the operating theatres was to admit only germ-free air into the interiors through an advanced ventilation system. He explained that microorganisms settling on dust and soot particles would contaminate the whole surgical environment and enter wounds. His own experiments in trying to cultivate germs in filtered air in a petri dish suggested that a thin layer of sand as a filter medium was quite adequate, requiring a moderate pressure differential.

The ventilation strategy is as follows: Figure 3 shows a directly fresh air intake (1) at low level protected by bird mesh above ground to the Northwest opening directly into a sequence of basement chambers. Another sectional drawing Abb.8 u.9 shows a longer below ground fresh air supply duct, possibly to theatre (2) Air passes through a flat shallow 50 cm filter 2. of crushed coal, Koks, progressing into a pre-tempering chamber cooled by ice in summer and warmed by two heating coils in winter. It is being driven through by a quiet 220volt ¼ Horsepower electric air pump (3) Through a pressurised second filter (4) described in the inset drawing, a miniature gasometer in effect before being discharged under pressure into two ducts taking it up into the operating theatre. Deneke describes this final filter in detail, a 2 m² plan area sand filter raised 20 cm, a mesh supporting layers of gravel and sand, increasingly fine grained, 1.0–0.28 mm, 60 cm deep overall. The upper layers can be scraped away and replenished but Deneke explains that the air will not be germ free but as clean as country air. The whole theatre can be filled with steam to settle out particles. The filtered air enters the theatre under pressure through two ducts part made from linoleum to deaden noise (6&7). Deneke explains that care must be taken to strictly avoid the opening of doors and windows during operations to maintain pressurisation except in extraordinary circumstances. It seems that the opening lights in the inner glazed layer are not opened during operations (11). There are three heating systems serving the aseptic Op. The floor is warmed by the warmed air flowing beneath through the sub floor plenum (13) into the 40–50 cm cavity (10) between the inner and outer glazed walls. The inner glass is translucent, the outer clear. Deneke testifies in the 1906 text after several years of operations that there is no condensation even in frosty conditions. The warmed air rises into the glazed roof void (12), cools and is ducted down into the pre-heating plenum (13) to be recirculated, but not through the theatre. In hot weather, it seems a fan can be engaged to lift cool air out of the basement into the theatre. The air supplied to the theatre directly is pre-warmed and the surgical team can control the flow directly. This warmth is boosted by radiators inset below the glazed walls behind thin nickel plate covers to mitigate dust settling on the heat emitters behind.
It is possible now to investigate the claims made for the ventilation for the St Georg Hospital operating theatre. Would the strategy lead to a tempered and fresh internal environment? In an attempt to understand and assess how effective this design might have been, it is useful to review some of the principles of air flow in operating theatres and explore the role of such air flows in dispersing airborne aerosols, about which there is still uncertainty. Although Deneke does not provide the quantitative specifications for the flow rates and air temperatures, we have Wallraff’s generic advice, and can develop a general picture of the type of air flow by assessing the overall pattern of flow under different plausible conditions. A simple model is derived the flow pattern is illustrated with some analogue laboratory models replicating the basic St. Georg configuration based on a simplified physical experimental system.

In assessing the flow, St Georg’s double skin plenum is likely to be significant. In theory, it enables the theatre to be insulated from heat loss or heat gain to the exterior,
and would contribute substantially to the maintenance of a thermally comfortable space. The air circulated through this plenum is pre-conditioned to buffer the theatre from fluctuations in the external conditions but owing to the relatively high conductivity of the glass, it may have affected heat transfer across the theatre envelope which would lead to unplanned convective mixing in the theatre. Depending on the season, this would likely lead to either a net cooling or net heating effect, with either upflow or downflow on the sides of the theatre. These flows would interact with the ventilation flows in the theatre and this particular detail is explored in the modelling herein. Stacey and Humphreys comment that by the late 1960s both displacement (St. Georg) and turbulent ventilation systems were thought to be bacteriologically equivalent.\textsuperscript{25}

From a fundamental perspective, air entering the theatre would be key for maintaining a fresh and well mixed environment in the theatre. Deneke explains that the incoming air for the theatre would be tempered for summer or winter conditions so as to be thermally comfortable for the occupants. This air would then be mixed through the theatre air owing to the convection associated with the heat loads in the theatre. The heat load associated with the operation would be located near the patient. These heat loads typically heat up the air and lead to a plume of warm air rising to the top of the theatre. This warm layer of air would then mix through the upper part of the theatre with some of the air being discharged through the outflow vents.

The design would enable the air in the theatre to ventilate from the space and thereby remove any airborne infection-bearing aerosols from the space. However, the flow regime does lead to some significant mixing in the operating theatre. For infection control there is a balance between the rate of flushing of the air and reduction of the concentration of such airborne aerosol, and the rate of dispersal of the aerosol prior to flushing from the space, which will lead to some exposure of the occupants, as examined below first through a model of the flow patterns and then through physical experiments which illustrate some of these principles.

**A theoretical model of the St. Georg aseptic theatre**

Figure 4 illustrates possible flow regimes associated with (i) summer and (ii) winter conditions. The flow in the theatre is assumed to include a low-level supply of ventilation air, a plume rising above the patient, and either upflow or downflow on the walls of the theatre owing to the heat transfer with the plenum. In order to assess the flow regime, we can draw from models of the convective fluxes in such plumes which suggest that with a heat flux \( Q \) produced from a localised source, the volume flux \( V_p \), is given by Morton, Taylor and Turner.\textsuperscript{26}

\[
V_p(h) = 0.1 (gQ/CT)^{1/3} h^{5/3}
\]

where \( C \) is the specific heat, \( T \) the temperature, \( g \) the acceleration of gravity, and \( h \) the height above the heat source, while the volume flux up or down a wall, owing to a temperature contrast \( DT \) (or \( -DT \)) between the wall and the interior air is given by Holman.\textsuperscript{27}

\[
V_w(h) = 2.75 \times 10^{-3} DT^{2/5} (H - h)^{6/5}
\]

where \( h \) is the height above the base of the wall, in the case of upflow (\( DT > 0 \)); for
downflow, with $DT < 0$, the volume flux in the wall plume depends on the distance from the top of the wall, $H-h$ and we use the absolute value of $DT$ in the above relation. If the ventilation air is supplied with a flux $V_v$ from inflow openings at a low-level in the space, and removed from a higher level, then this will interact with the convective flows produced by the warmed patients and the temperature differential on the walls.

**Summer Regime:** If we consider the case in summer when the plenum may be warm, this may lead to an additional upflow near the walls. Two situations can arise. First, the ventilation flow may be larger than the natural convective flows:

$$V_v > V_w + V_p$$

In this case, the natural convective flows entrain some of the supply ventilation air and carry this up to the top of the space, while the remainder of the ventilation flow rises through the rest of the space towards the outflow (Figure 3a). In the regime, we can envisage that airborne aerosols are carried upwards if the flow speed exceeds the fall speed of the aerosols; however, larger aerosols can settle out through the space.

Second, the ventilation flow may be smaller than the natural convective flows in the upper part of the space. In this case, there is a height at which the natural convective flows match the ventilation flow, and all the ventilation air at that height is carried upwards in the convective flows. Below that height, the air in the operating theatre is composed of the ventilation air, while above that height, the air is composed of the air
which has risen up in the convective plumes. In this region, the air recirculates as the convective flows mix and carry more air upwards (Figure 4b). Aerosols in this situation would rise up to high levels in the space and then spread laterally, from where they might fall out and settle back into the lower part of the space.²⁸

Winter regime. In this regime, the plenum may be colder than the operating theatre, and the heat flow from the operating theatre would lead to a downflow around the sides of the theatre. In this case, the upflow in the convective plume above the operating zone would carry air upwards both from the ventilation supply and also from the cold downflow around the sides of the space. If the upflowing plume has a smaller flux than the sum of the ventilation flow and the cold downflow around the sides of the theatre, then there would be a net upflow in the rest of the operating theatre to balance the air flow (Figure 4c). Conversely, if the plume has a larger flow, then there will be a net downflow at high level in the rest of the OT to balance the air flows (Figure 4d).

To illustrate the conditions under which these different regimes might have developed, in Figure 5, we compare the convective upflow in the plume (red) rising above the patient and the ventilation flow supplied to the space (green, black or blue) lines corresponding to 6, 12 and 24 air changes per hour. Panel A is for the summer case with an assumed heat load of 0.5 kW in the theatre, and we assume a convective upflow on the sides of the theatre owing to the heating from the warm outer plenum, while Panel B is for the winter case in which we assume the plenum is cooler, and so there is a downflow on the walls of the theatre. The point at which the red line intersects the blue, black or green lines corresponds to the height in the room at which the interface between the upper and lower levels will develop.

**Figure 5.** (a) Summer mode: Comparison of the ventilation flow minus the upward flow along the walls of the space with the volume flow in the plume above the patients/doctors, as a function of the height in the room. At the height where these are equal, the interior air in the room is static (ie the red curve meets the blue, black or green curve) and the region of air above is warm and below is cool (Figure 4a,b). (b) Winter mode: Comparison of the ventilation flow plus the downward flow along the walls with the upward convective plume above the patient doctor area. In the low ventilation case, there is an interface high in the room, but with higher ventilation, the room is well mixed. In these models, the heat load is assumed to be about 0.5 kW for the historical operation, while the glass walls are assumed to sustain a 2°C temperature contrast from the plenum to the operating theatre.
It is seen that in the summer (panel A) the steady interface is between about 1.25 m and the top of the space depending on the ventilation rate which we have taken to be between 6 and 24 air changes per hour. This leads to a two layer stratified theatre (Figure 4a), except with the very highest ventilation, in which case the incoming supply air fills the entire space (Figure 4b), with both upflow in the convective plume and in the surrounding air; resulting in a higher second layer at the top and a well-mixed layer over the patient and surgeons.

In contrast, in the winter case, Figure 4(c,d), there is downflow on the walls of the theatre, and so there is a greater supply of air to the base of the theatre. Typically this exceeds the flow in the plume rising above the patient, and so the interface rises to the ceiling, as the convective upflow above the patients is unable to carry both (a) the ventilation air from the base to the top of the space and also (b) the upward return air to supply the downflow on the sides of the theatre. This leads to a well-mixed interior.

A laboratory model representing the configuration of the St. Georg aseptic operating theatre

In order to illustrate some of the broad principles of the flow regimes which may arise, and the impact of these regimes on the dispersal of airborne infection, a series of simplified analogue laboratory experiments were conducted. In the experiments, water is the working fluid rather than air, but, as explained in the following paragraphs, the flows are scaled so that the turbulent nature of the air flow in a building is replicated with the small scale water bath, where we create a similar balance between the ventilation flow and the natural convective flows associated with the sources of buoyancy.

To achieve these goals, our experiments work with relatively fast or long length scales of fluid flow, so that the inertia of the fluid dominates the frictional resistance to motion, and so the forces applied to the fluid either by the pressurisation of the ventilation supply or the gravitational forces associated with warm, low density fluid rising, are balanced by changes in the fluid momentum, which occurs in large part through turbulent fluid mixing. In fluid mechanics, this is known as high Reynolds number flow, in which the ratio $uL/\nu$ is much larger than 1, where $u$ is the typical speed, $L$ the typical length scale and $\nu$ the fluid kinematic viscosity. For air flows, $u \sim 0.01$–$0.1$ m/s, $L \sim 0.1$–$1.0$ m and $\nu \sim 10^{-5}$ m$^2$/s, leading to a Reynolds number of about $10^3$–$10^4$. In the laboratory, typically flows are of speed $0.01$–$0.1$ m/s and length scale $0.01$–$0.1$ m, with $\nu = 10^{-6}$ m$^2$/s, leading to similar Reynolds number.

In order to produce a turbulent convective plume analogous to that which results from the heat released by the various people involved in the operation (the patient, nurses and doctors), an analogue system is used in which fresh water is released into a tank filled with aqueous saline solution. By ensuring the Reynolds number of the plume is in excess of about 1000,$^{29}$ the fresh water rises as a turbulent plume, entraining and mixing with the saline solution, and carrying this ambient fluid upwards, in a directly analogous way to the mixing in a convectively rising plume of warm air in a room. The ventilation fluid consists of saline solution added through a series of diffuse openings located on two sides of the space, in a system similar to the design for the air ingress through the walls of the operating theatre.
By using the analogue system, it is possible to model the flow in a very small scale tank, with sides 40 cm long, which represents a fraction of about 0.05 of the original operating theatre. Also, the flow is visualised by dying the different fluids and observing how this fluid moves through the space. This provides an invaluable insight into the air pathways through the space and hence potential flow path of small airborne aerosol, < 5 micron, which move approximately with the air, and only settle out on time scales longer than about 1800s.

In Figure 6, we illustrate the flow produced by the convection above the warm patient zone by dying the fresh water we supply to model the heat release. This series of three images illustrates how a pulse of dye in the plume of fresh water is dispersed by the flow, as illustrated in the cartoon of Figure 4. This series of images is taken from an experiment in which the ventilation system was running in summer mode, and the images have been mapped into false colour to help visualise the flow. Panel A shows the plume of fresh water (representing the warm air) rising from the model operating zone to the upper part of the space, where the flow is ventilated from the system. The dyed water is shown in false colour. As the fresh water rises, it mixes with ambient fluid, so that the volume flux reaching the top of the space in the plume is greater than the ventilation flow. As a result, some of the plume fluid spreads out in the upper part of the space, shown in panels B and C, forming a zone of relatively fresh water representing an upper layer of warm air, as seen in the time series of images.

By the time of the third panel, the dye in the inflow water modelling the plume has been removed, and we see the upper layer is now well mixed, and it remains dyed for some time, until the continuing upward displacement ventilation flow flushes away the dye. This provides a model of the mixing of air and contaminants in the space prior to their ventilation.

The second series of images, Figure 7, illustrate how the ventilation air circulates through the space. In the model, the air is supplied from the sides and spreads laterally across the lower level of the operating space. This is illustrated by the orange fluid in the

![Figure 6](image1)

**Figure 6.** Series of images of the analogue experiment in which a fresh water plume models the hot air rising through the operating theatre above the patient. This plume fluid spreads out to form a layer of relatively fresh water at the top of the tank (yellow and orange) modelling the layer of warm air which accumulates at the top of the OT. In the third panel, the dye in the inflow water modelling the plume is removed. We find the upper layer remains dyed for some time, until the continuing ventilation flushes away the dye (as a model of the flushing of air and contaminants from the space).
model. This lower layer gradually deepens as the supply air is entrained into the plume above the operating area, and fills the lower layer. As this inflowing air is entrained and carried upwards by the plume, it gradually enters the upper layer or relatively fresh water just below the ceiling, as may be seen in panels 4 and 5, and the enlarged false colour image of panel 4 also shown in Figure 7. As in Figure 6, the fluid in the plume spreads out in the upper layer, but this fluid is now clearly sourced from the supply ventilation fluid, illustrating the key role of the mixing, and also the formation of the stratification in the space.

**Implications of the ventilation for infection**

In terms of infection dispersal, the path followed by the fine airborne aerosols smaller than about 5 micron is similar to the path followed by the ventilation flows; one can therefore infer that there is very effective dispersal of airborne aerosols by the ventilation flows likely to have occurred in the St Georg Operating Theatre. However, the key question relates to the ventilation time of the air compared to the settling time of the aerosols, as this impacts the concentration of the aerosols in the space and also the balance between aerosols which are vented and those which settle out in the operating theatre.

Our experiments illustrate that the pulse of dye gradually decays in intensity as the ventilation flow continues and dilutes the dye. As a simple model for the mixing and settling of aerosols, if one can assume the air is well mixed in the upper layer by the ventilation, and that the air ventilates this layer with a flow rate \( Q \), then the time for 90% of the air in this layer to be replaced is about

\[
T_1 = 2.3Ah/Q
\]

In contrast, the settling time of aerosols through this layer is

\[
T_2 = h/v,
\]

![Figure 7](image-url). Illustration of the mixing of the supply ventilation air through the lower parts of the theatre based on the laboratory analogue model (panels i-iii) and of the role of the convection in mixing this air into the plume rising from the patient; this carries this air upwards into the upper layer of the warm air in the operating theatre (panel iv, shown enlarged in false colour in panel v).
where \( v \) is the fall speed of the aerosols. We can compare these two times to estimate the fraction of the aerosols which settle in the space according to the relation

\[
F = \frac{T_1}{T_1 + T_2}
\]

In Figure 8, we illustrate this result for a series of ventilation rates (6 (black line), 12 (red line) and 24 (blue line) Air changes per hour). The figure identifies that with poor ventilation (six air changes per hour – black line), only aerosols smaller than 5–10 micron will be ventilated rather than settling in the space, while with 24 air changes per second (blue line) much larger droplets, up to 10–30 micron will be ventilated, thereby reducing the accumulation of infectious droplets in the theatre. Although there will be a range of droplet sizes produced by breathing and other sources, the high ventilation may lead to much more effective removal of aerosols from the space.

The figure identifies that the introduction of the ventilation system in the St Georg hospital leads to the removal of air borne infection and the provision of a tempered and comfortable environment. However, while reducing the fraction of the aerosol that settle in the space rather than being ventilated from the space, the ventilation system also acts to disperse and mix the aerosols through the space. Although the model calculations are simplified, they show some similarity with modern operating theatres, and depending on the rate of ventilation supply, the theatre might have been effective in limiting the impact of airborne aerosol through reduction in the concentration of the aerosol in suspension.

**Figure 8.** Illustration of the fraction of the droplets which may be ventilated from the space. This figure illustrates how the design of good ventilation may lead to a reduction in the fraction of droplets which settle in the space rather being ventilated from the space as the ventilation rate is increased from 6 air changes per hour (black), 12 (red) to 24 (blue).
Conclusion

Theoretical analysis and experimental modelling of the St Georg aseptic operating theatre reveals that the fundamental pattern of airflow involved the development of a displacement layer at a level in the space which might slow the exhaust of pathogens, but maintain them at higher level. A high flow rate is critical to lift this displacement layer to the exhaust outlets. Under high flow, the theatre shows promise in effectively reducing airborne aerosol through reduction in the concentration of the aerosol in suspension, comparable to the conditions achieved in modern operating theatres. However, the theatre worked under gentle pressurisation at a fraction of contemporary UCV theatre energy use to prevent the inflow of contaminated air. In fact, the exhausts seem to have been closed during surgery to slow the airflow, the system being used to flush the space before and after surgery. Given the lack of evidence for airborne contaminates resulting in SSI (Stacey and Humphreys 2002), real-world experiments would be required to determine which conditions, high ventilation during or between surgeries, both or neither, would be best for SSI prevention.

The desire for excellent natural lighting is inextricably bound up with ventilation strategy, cocooning the operating space in a convectively warmed double glass envelope, an idea which became fashionable in the late 1920s and again over the last 30–40 years. Min-gotti et al demonstrate that such doppelfassades are not necessarily beneficial in energy consumption but highly dependent on latitude and climate. In St. Georg the fluid flow analysis and modelling shows the volatility of heat losses and gains through the glazed walls would profoundly affect airflow within. This is an important clue for designing a contemporary naturally lit theatre, something for which the surgeons consulting with ExISE have expressed a strong preference. These potential problems in Hamburg were not reported. Dr. Deneke was very upbeat some years after completion, but these downdraughting effects could in any case be mitigated by current glazing technology, renewable sources of heat and coolth, modern materials with anti-bacterial finishes and surgical staff in constant direct contact with the natural world outside with an understanding of how to control the space. Medical equipment heat loads are currently much higher than over the last 100 years, given the level of technology used in theatres today. Until the surgical device industry responds to the NHS carbon reduction plan, the heat loads from this equipment is likely to result in theatres designed for healthy airflows to have little to no recirculation. The ExISE team will publish a viable alternative Operating Theatre with distinct parallels to the aseptic school thriving in Austria and Germany in the early Twentieth Century in late 2021.

Notes

1. NHS England and NHS Improvement, Delivering a ‘net zero’ National Health Service. Report for the UK National Health Service 2020. https://www.england.nhs.uk/greenernhs/wp-content/uploads/sites/51/2020/10/delivering-a-net-zero-national-health-service.pdf
2. Sustainable Development Unit for NHS England, and Public Health England, Reducing the use of natural resources in health and social care, Report for the UK National Health Service 2018.
3. A. Whiting et al., ‘Surgery and the NHS Carbon Footprint’, The Bulletin of the Royal College of Surgeons of England, 102, no.5 (2020): 182–5.
4. See note 2.
5. J. Charnley and N. Eftekhar, ‘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, no. 9 (1969): 641–9.

6. D. J. Leaper et al., ‘Surgical Site Infection–A European Perspective of Incidence and Economic Burden’, *International Wound Journal*, 1, no. 4 (2004): 247–73.

7. N. Hyldig et al., ‘Meta-Analysis of Negative-Pressure Wound Therapy for Closed Surgical Incisions’, *Journal of British Surgery*, 103, no. 5 (2016): 477–86.

8. T. Inui and D.F. Bandyk, ‘Vascular Surgical Site Infection: Risk Factors and Preventive Measures’, *Seminars in Vascular Surgery* 28, nos. 3–4 (2015): 201–7.

9. A. Stacey and H. Humphreys, ‘A UK Historical Perspective on Operating Theatre Ventilation’, *Journal of Hospital Infection*, 52, no. 2 (2002): 77–80.

10. R. B. Bourdillon and L. Colebrook, ‘Air Hygiene in Dressing Rooms for Burns or Major Wounds’, *The Lancet* 247, no.6400 (1946): 601–5. doi: 10.1016/S0140-6736(46)90447-3

11. J. Charnley, ‘A sterile-Air Operating Theatre Enclosure’, *British Journal of Surgery* 51, no. 3 (1964): 195–202. doi: 10.1002/bjs.1800510308

12. Medical Research Council, *Ventilation in Operation Suites*, Report to the Department of Health and Social Security, 1972.

13. W. Whyte, R. Hodgson, and J. Tinkler, ‘The Importance of Airborne Bacterial Contamination of Wounds’, *Journal of Hospital Infection*, 3, no. 2 (1982): 123–35.

14. NHS Estates, *Health Technical Memorandum 2025*, National Health Service Guidance note (1994).

15. See note 1.

16. P.F. Linden, ‘The Fluid Mechanics of Natural Ventilation’, *Annual Review of Fluid Mechanics* 31 no.1 (1999): 201–38; C. Gladstone and A.W. Woods, ‘On Buoyancy-Driven Natural Ventilation of a Room With a Heated Floor’, *Journal of Fluid Mechanics* 441 (2001): 293–314.

17. Edward Fletcher Stevens, *The American Hospital of the Twentieth Century: A Treatise on the Development of Medical Institutions, Both in Europe and in America, since the Beginning of the Present Century* (New York: Architectural Record Company, 1921).

18. Ulrich Tröhler, ‘Statistics and the British Controversy About the Effects of Joseph Lister’s System of Antisepsis for Surgery, 1867–1890’, *Journal of the Royal Society of Medicine*, 108, no.7 (2015): 280–7.

19. T. Schlich, ‘Surgery, Science and Modernity: Operating Rooms and Laboratories as Spaces of Control’, *History of Science*, 45, no.3 (2007): 231–56.

20. Axel Hinrich Murken, *Die bauliche Entwicklung des deutschen allgemeinen Krankenhauses im 19. Jahrhundert* (Göttingen: Vandenhoeck und Ruprecht, 1979); E. Hofmokl, *Wiener Heilanstalten* (Vienna: Alfred Hölder, 1910).

21. F. Ruppel, *Das allgemeine Krankenhaus St. Georg* (Hamburg: Ernst, 1917).

22. T. Deneke, *Die Neubauten des Allgemeinen Krankenhauses St. Georg* (Hamburg Jena: Fischer, 1906).

23. H. Wallraff, *Bau und Einrichtungen des neuen städtischen Krankenhauses* (Nuremberg: Nürnberg 1898).

24. Le Corbusier, *Precisions on the Present State of Architecture and City Planning*, trans. Edith Schreiber Aujame, ed. M. M. Mitache (Paris, France: MIT Press, 1930).

25. See note 9.

26. B. R. Morton, G. I. Taylor, and J. S. Turner, ‘Turbulent Gravitational Convection from Maintained and Instantaneous Sources’, *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 234, no. 1196 (1956): 1–23.

27. J. P. Holman, *Heat Transfer* (5th edition) (New York: McGraw-Hill 1981).

28. N. Mingotti and A.W. Woods, ‘On the Transport of Heavy Particles Through an Upward Displacement-Ventilated Space’, *Journal of Fluid Mechanics* 772 (2015): 478–507.

29. A.W. Woods, ‘Turbulent Plumes in Nature’, *Annual Review of Fluid Mechanics* 42 (2010): 391–412.

30. N. Mingotti et al., ‘The Mixing of Airborne Contaminants by the Repeated Passage of People Along a Corridor’, *Journal of Fluid Mechanics* 903 (2020).
31. N. Mingotti, T. Chenvidyakarn, and A.W. Woods, ‘Combined Impacts of Climate and Wall Insulation on the Energy Benefit of an Extra Layer of Glazing in the Façade’, Energy and Buildings 58 (2013): 237–49.
32. C. A. Short et al., ‘An Alternative Approach to Delivering Safe, Sustainable Surgical Theatre Environments’, Buildings and Cities (Special issue: Alternatives To Air Conditioning: Policies, Design, Technologies, Behaviours) (2021).

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