A clean bill of health: a state-of-the-art general, trauma and orthopaedic surgical centre

Dr Henry Skates
Griffith University, School of the Environment

ABSTRACT: Potential drawbacks to the use of Ultra Clean Ventilation (UCV) technology in modern operating theatres include difficulties with locating pendant lighting, excessive noise levels and excessive operational costs. The main benefits of using UCV technology however, is a reduction in postoperative Surgical Site Infection (SSI) rates. To solve the above challenge a novel surgical theatre centre has been designed to accommodate three state-of-the-art theatre suites, a seven-bed recovery ward, a fifteen-bed orthopaedic ward and attendant ancillary spaces. At the heart of the complex, the three unique theatre environments utilize innovative skirt-less ultra-clean laminar-flow ventilation canopies to help control airborne infection during surgical procedures. The novel approach allows uninterrupted use of multi-flexible lighting and surgical pendants, has been designed to minimise noise levels and utilises heat recovery to minimise running costs. The innovative approach to infection control is continued through into the detailed design of the theatre wall, ceiling and floor systems, and integrates with the overall strategy of creating a dramatic and stimulating working environment where traditionally aesthetic sterility was de rigueur.

Conference Theme: Construction Technology, Sustainability Issues
Keywords: Ultra Clean Ventilation, Theatre Operating Environments

INTRODUCTION

A new Trauma and Orthopaedic Centre has been designed to be at the cutting edge of surgical theatre design. Located at Craigavon Area Hospital in Craigavon, Northern Ireland, United Kingdom (UK), the £9.4million Unit is part of an overall strategy to dramatically reduce the time people in Northern Ireland have to wait for fracture and orthopaedic treatment.

Figure 1: Surgical insertion of the new trauma and orthopaedic centre into the aging infrastructure of Craigavon Area Hospital

Figure 1 shows the surgical insertion of the new Trauma and Orthopaedic Centre into the ageing infrastructure of Craigavon Area Hospital. Figures 2 and 3 show how the new accommodation links directly to the existing hospital internal theatre street allowing bed-bound and ambulant patients privacy and dignity from admission, through both surgery and recovery to final discharge. The new theatre suites comprise of 2No. Trauma and orthopaedic surgery
The new centre provides state-of-the-art theatre facilities where patient dignity, infection control and a healing environment were key requirements of the brief. The design process adopted by the design team closely followed the RIBA Plan of Work. The strategy of including regular stakeholder engagement with clinical, nursing and surgical staff along with the local Health Estates Department allowing full consultation for all major design decisions. Regular meetings on site with end users continued throughout the construction process allowing the less technically minded to more readily visualise the end result. One result of early consultation was that a number of areas were designed with more space than required by the regulatory space standards, because of particular working practices of the staff. An example is the 65 square metre orthopaedic theatre being some 10 square metres larger than the HTM standard, along with enlarged preparation rooms and dirty utility areas. Increased storage areas were also included for the vast number of parts required for orthopaedics with enlarged departmental corridor and equipment bays. Security and control of visitors is maintained via strategically placed reception areas, while two alarmed escape staircases link all three floors (Figure 4) and are for emergency use only. The design team worked closely with the infection control department in developing details and materials used for interior surfaces were chosen that would not only be robust but would also facilitate infection control.

In addition, the design team incorporated a number of technical design innovations that not only contributed to the overall aims of the brief but also improved the working environment for staff and the overall functionality of the operating environment. These include innovative skirt-less ultra-clean laminar-flow ventilation canopies to help control airborne infection during surgical procedures and the inclusion of LED theatre lighting.

All of the interior spaces within the facility have been carefully designed to reflect the core value of respect in caring for the individual. Respect for the privacy and dignity of patients is evident from the moment they enter the facility at reception, all the way through surgery and recovery to general wards and finally going home. The general layout places the main reception, consultation rooms, theatre suites and recovery areas theatre staff changing and theatre staff rest areas all on the ground floor and linked to the existing hospital theatres allowing separation of visitors and ambulant and non-ambulant patients. The wards and general staff changing and rest areas are located on the first floor with maximum access to daylight and views. Areas are provided where private conversations can be held and careful thought has been given to acoustic and visual separation including the use of integral privacy blinds to all single room doors. All wards contain ensuite bathroom facilities that encourage patient mobility and contribute to the overall respect for patient modesty, privacy and dignity. An internal courtyard with art pieces at first floor level was created as part of the design strategy to ensure each patient had access to the external environment. The use of strong colours and textures in this area creates a genuine sense of place and contributes to the overall ambiance.

Figure 2: Ground floor plan showing relationship between new theatres and existing theatre department

Source: (Author)
1. THE DESIGN CHALLENGE

The key element in any operating theatre is the cleanliness of the immediate environment above and surrounding the operating table where airborne contaminants may enter the surgical site and cause postoperative Surgical Site Infection (SSI). Orthopaedic surgery sites are particularly susceptible to life threatening infection.

1.1 Ultra clean ventilation (UCV) technology

In the mid-19th century Pasteur recognized contamination by air as a potential source of wound infection. Various means of creating cleaner air in operating environments have evolved over the years and include (in early days) the use of disinfectant sprays that reduced infection rates by 50%. More recently ultraviolet (UV) light has been used to sterilize the air with infection rates. Lowell et al. (1980) is reported to have introduced UVA to the Brigham Hospitals in Boston where infection rates in hip and knee arthroplasty fell by 5 and 30 times, respectively. Both of the above methods however have adverse health effects on operating personnel. For example, where UV sterilization is used theatre staff must cover all skin and operating staff usually wear two theatre hats to minimise the effects of UV radiation and in addition all staff must also wear visors. Air filtration is a third method of sterilizing and is the most widely used method in theatre environments in the UK. Conventional theatre filtered plenum ventilation systems
involve 20 air changes per hour (ACH) and typically allow 3.4% infection rates. A plenum-ventilated theatre is regarded as efficient where the number of colony forming units (CFUs) per cubic metre of theatre air does not exceed 35 CFU/m³. Filtered plenum ventilation systems are by far the most commonly used theatre ventilation systems in the UK. A further development in theatre ventilation adopted by Charnley (1979) is vertical laminar flow. Charnley is reported as using 300 air changes per hour and reducing infection rates down to 1% (Bannister 2003), however the energy required to condition such large quantities of air prohibits widespread use.

The Department of Health’s Health Technical Memorandum HTM 03-01: Specialised ventilation for healthcare premises – Part A requires that laminar flow systems produce ultraclean air in which less than 10 CFU/m³ are produced.

### 1.2 Design Strategy employed at Craigavon

Figure 5 shows a typical operating theatre ventilation system but ideally the AHU should be located remotely from the theatre to reduce potential vibration and noise. For UCV theatre systems there is the addition of a HEPA filter at the theatre supply diffuser. Because the air extracted from a UCV theatre is cleaner than fresh air, air recirculation systems are employed to help prolong filter life and reduce energy use.

![Figure 5: Typical Operating Theatre Ventilation System](source)

The strategy employed at Craigavon (Figure 6) was to locate the plant room on the third floor and the theatres on the ground floor to keep them remote. This allowed all of the air-conditioning equipment to be located outside of the operating room, except for the unidirectional air-flow terminal, terminal filter, air diffuser and the return-air grilles (see Figure 7). Advantages of using this arrangement include:

- recirculation fans are located outside the theatre, thus reducing noise and multiple recirculation fans can be replaced by a single fan unit with its drive out of the air stream;
- casual heat gains from recirculation fan(s), canopy lights, equipment and people within the theatre can be removed by a chiller battery in the return air stream. This helps prevent heat build-up in the theatre and return-air filters can be changed without needing access to the theatre, making routine maintenance more feasible.

![Figure 6: Air handling units in the third storey plant room](source)
The normal method of controlling the laminar flow in the centre of the operating theatre is to use a down-stand skirt as seen in Figures 7 and 8 to prevent short-circuiting of the air supply to the return air grills. This however has implications for the height of the horizontal arms of pendant units and can restrict the movement of staff around the operating table.

The main design/research question addressed at Craigavon was therefore ‘could an HTM compliant recirculation, heat recovery UCV system be designed in such a way that a down-stand skirt would not be required’. HTM 03-01 requires that the down-flow of supply air from a laminar flow ventilation system should cover a minimum projected area of 2.8 m by 2.8 m to accommodate the surgical site and instruments. To achieve the omission of the skirt, a larger than normal 3.2 m x 3.2 m UCV canopy was designed that was partially recessed into the ceiling by some 150mm with high frequency fluorescent lighting built into the up-stand. To help ensure an even distribution of air across the floor, variable rate low-level extract vents were placed in all four corners and in the centre of the walls of each theatre as shown in Figure 9. These were subsequently tuned to ensure equal airflow across the floor from the ‘red line’ inside the UCV canopy area.
The pressure differential air-flow from the theatre is also designed to ensure that clean air is delivered not only to the operating table but also to all of the key areas such as the prep room and anaesthetic room, and that potentially contaminated air is extracted or directed to non clean areas such as the scrub area and dirty utility areas. The air filtration system employed has G4 Filters followed by G9 within the plant room, and H10 HEPA filters within the UCV. The G4 filter is a 'general' filter which is graded in terms of it’s “synthetic dust weight arrestance”. This represents the percentage of a test dust captured by a filter. “Arrestance” provides a good indication of a filter’s ability to remove the larger, heavier particles found in outdoor air. These are of a size to block finned batteries and large enough to settle out in the air distribution system. A G4 filter has >90% arrestance. The F9 filter is a "fine" filter that is graded in terms of its “atmospheric dust spot efficiency”. This is a measure of the filter’s ability to remove the very fine staining particles found in outdoor air. It will indicate how ‘visibly’ clean a filter will keep a ventilated space. The staining particles are approximately the same size as most common bacteria so it is also a rough measure of the filters’ ability to remove them. The F9 filter employed has an efficiency of >95% and is often employed as a basic HEPA filter for certain clean rooms (level 8). The H10 HEPA filter in the UCV canopy is a ‘high-efficiency’ filter which is graded in terms of its’s ability to capture it’s “most penetrating particle size” (MPPS). The H10 filter is 85% efficient at most penetrating particle size.

1.3 Test Results
Commissioning and testing was carried out by the independent company; Labs & Theatres Ltd. The required tests to be carried out under HTM03-01 to ensure clean air delivery are as follows:
1. Challenge tests to ensure that:
   • the UCV terminal unit is correctly assembled and sealed so that no air will bypass the filters; Visual and particle testing demonstrated correct assembly.
   • the terminal filters are correctly sealed in their housings; Visual and particle testing demonstrated correct sealing.
   • the terminal filters are of the same grade, of uniform quality and undamaged. Visual testing confirmed and certificates produced by HEPA filter manufacturer.

2. Air velocity measurements to ensure that:
   • a sufficient quantity of air is being delivered by the terminal; The method of testing air velocity is to divide the area under the UCV canopy into 100 equal squares of 280mm sides on a 10 x 10 grid as shown in Figure 10. Air-flow is then measured at the centre of each square at a height of 2m and 1m. Each theatre passed the minimum requirement of 0.38m/s at 2m height and 0.2m/s at 1m height across all 100 squares.
   • the terminal quadrants are in balance; Dividing the area under the canopy into 4, the average air flow for each of the quadrants is required to be within 6% of the total average. This was achieved.
   • the air flow has sufficient velocity to reach the working plane. See quantity test above.

3. An entrainment test to ensure that contaminants arising outside of the UCV terminal footprint are not drawn into it. The entrainment test is based on the research of Whyte et al (1974) and Whyte et al (1983). This test introduces a vertical flow of contaminated air immediately adjacent to the canopy and measures the quantity of particles that enter the laminar airflow. The contaminated air is taken from outside the theatre environment. Three zones are defined using the 10x10 grid. Zone one is the first two outer rows of the 10x10 grid. Zone two is the inner 6x6 squares with with zone three being the centre position of the UCV canopy. The number of particles is measured in the contaminated air outside zone one and this number is used as a reference. Zone one must contain less than 10% of the particle count of the reference air. Zone two must contain on average less than 1% of the particle count of the reference air and zone three less than 0.1%. This was achieved.

4. Visualisation techniques to gain an understanding of the overall system performance. In this test smoke was used to gain a visual understanding of the overall performance of the system but the results are not used to produce a contractually definitive measure of performance.
5. Noise measurement to ensure that working conditions are satisfactory. Ambient noise levels of 45 dB(A) were achieved inside the theatre with the ventilation system operating. It was so quiet that a number of experienced theatre staff asked if the ventilation system had broken down.

6. Control system checks to ensure that the system operates as specified. These were carried out and confirmed.

7. Biological monitoring to determine how effective the system is in use. HTM03-01 recognises that there is little value in performing microbiological sampling in a new theatre supplied with ultra-clean ventilation. The filter challenge tests, air velocity measurements and entrainment test demonstrate that the system operates satisfactorily and achieves the contracted level of performance. The HEPA filters are certified to remove bacteria-sized particles from the air supplied through the UCV terminal therefore there will be an insignificant number of bacterial and/or fungal CFU present until the theatre is actually used. Once in use regular sample testing within 300 mm of the wound during surgical procedures is carried out to ensure that air sampled does not contain more than 10 CFU/m3.

1.2 Theatre Lighting
CIBSE lighting guide LG2 and BSEN 12464-1 give detailed information on lighting requirements for theatres and these standards were followed. Operating luminaires employed at Craigavon comply with the photometric requirements detailed in BS EN 60601. One difficulty with using conventional theatre light fittings with laminar flow ventilation is that their shape and the heat given off by the lamps can cause turbulence in the laminar flow. To overcome this proprietary low temperature LED lamps have been used with adjustable luminosity of up to 160,000 lux. High levels of illumination of the surgical site and the ability to adjust the colour temperature depending on the surgical procedure improve the surgeon’s visual environment and helps reduce fatigue during long operating procedures. Theatre 5 has a single 5 I-LED theatre light while the trauma and orthopaedic theatres each have twin 5 I-LED lighting pendants along with integrated high definition video capability. The benefits of using such lamps includes that the light temperature can be adjusted between 3,500 and 5,000 Kelvin. This means that, regardless of whether surgeons are operating on tissues in which the blood flow is heavy or light, they can make contrasts more visible by changing colour temperatures. The lamp fittings also use a multi-lens matrix to distribute the light volume emitted by the LEDs as evenly as possible. The lamps consists five segments positioned next to one another, each of which has a multitude of single convergence lenses much like the compound eye of insects. The ‘cold’ IR-free light of the LEDs means that even directly under the lamp, practically no heat emission can be felt.

Source: (Author)
Figure 11: Trauma theatre showing LED lighting pendants

1.3 Theatre wall system
Theatre 5 had used a gasket system that was identified as a potential location for harbouring bacteria. Having identified this during the construction of the new facilities, the design team developed a new high pressure laminate wall panel system with colour coordinated glued joints that aid infection control was and this was incorporated into two of the theatres. Glass is used as worktops in theatres and glass screens improve visibility and permeability of the interior. Natural lighting was utilised through the deep plan building including in the theatres. Cleanliness is further emphasised throughout the centre by the strategic location of LED illuminated wash hand basins reflecting the ‘clean hands – safe hands’ culture of the hospital. Details such as blinds integrated into glazed screens, negative step skirting details and copper ironmongery along with ample provision of daylight and individual room colours all combine to create a healthy and healing environment.

2. OTHER CONSIDERATIONS
2.1 Aesthetics
The design concept dispenses with the visually sterile white image of the majority of surgical facilities and instead utilises bright colours combined with sharp detailing to provide the stakeholders with a clean but visually stimulating...
and attractive modern internal environment. This is probably most evident within the operating theatres where theatre specific individual feature wall colours and inlaid colours within the floors and ceilings dispense with the typical white theatre image. At key focal points, materials and finishing details have been borrowed from the hospitality sector and adapted to a clinical environment to create and evoke a heightened sense of quality. This is particularly evident at the reception areas where the use of natural materials combined with colour and texture have been integrated to provide a welcoming environment. The overall appearance of the accommodation is bright and cheery and uses colour to create visual interest and help with way-finding. Patients are encouraged to be mobile as soon as possible to aid their recovery, and encouraged to explore and use the facilities provided in the building. The use of non-standard lighting throughout the facility including general circulation, reception, office and patient areas enhances the overall ambience and feeling of wellbeing.

2.2 Working environment
The interior has intentionally been designed to enrich the daily routine of the staff, and create an inspirational sense of space and a therapeutic environment for visitors and patients alike. This has been achieved using a combination of space, form, materials, texture, colour and light. From each reception area, through circulation areas to theatres and wards and even in the ancillary areas, the form, textures, colours, natural and mood lighting infuse each of the spaces with a sense of place and purpose. In corridors, waiting areas and above the main nurses stations on the first floor, natural light is provided using feature coloured roof lights which also act as smoke vents in case of fire, create points of visual interest and provide orientation and a means of way-finding. Large tensile artworks are located within the roof light void over the central staff base area and cast coloured light on to the walls and floor depending on the location of the sun. Patient areas arranged around and opening onto this central space can borrow light and enjoy the therapeutic quality of this central space. Each patient/staff area has been provided with as many views as possible within the deep plan building, ranging from glazed screens utilising borrowed light through views to the outside via windows to the innovative internal courtyard filled containing both natural and man made features.

CONCLUSION
A novel surgical theatre centre has been designed to accommodate three state-of-the-art theatre suites, a seven-bed recovery ward, a fifteen-bed orthopaedic ward and attendant ancillary spaces. At the heart of the complex, the three unique theatre environments utilise innovative skirt-less ultra-clean laminar-flow ventilation canopies to help control airborne infection during surgical procedures. In addition, the use LED lighting not only aids surgical procedures, but contributes to the ultra clean ventilation requirements. The new wall system developed by the design team further reduces the risk of contaminated air within the theatre environment.

ACKNOWLEDGEMENTS
Client - SH&SCT Southern Health & Social Care Trust,
Project Manager - Health Estates Investment group
Lead consultant Milligan Reside Larkin,
Architect - Internals, external works theatre planning Milligan Reside Larkin,
Architect - External Envelope P O'Hagan Associates,
M&E consulting Engineers Beattie Flanigan,
Structural engineers – Greg Seelely Consulting/Nicholas O’Dwyers,
Quantity Surveyors Eoin Lawless Partnership/Macaulay Heaney
CDM Co-ordinator Nicholas O’Dwyers,
Landscape Architect – Dorothy Allen Associates,
Contractor Team
Main Contractor – Farrans Healthcare,
Electrical contractors – Dowds electrical,
Mechanical contractor - R&F Mechanical Services.

REFERENCES
T. Chow, Zhang Lin, Wei Bai (2006); The Integrated Effect of Medical Lamp Position and Diffuser Discharge Velocity on Ultra-clean Ventilation Performance in an Operating Theatre, Indoor Built Environ 2006;15;4:315–331

45th Annual Conference of the Architectural Science Association, ANZAScA 2011, The University of Sydney