Validation of a Neutral Pressure Isolation Room

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SUMMARY

The principles behind a new design of isolation room are set out. The process of validating the design is described using a range of physical modelling techniques. A CFD model was also constructed and compared to the basic operational mode. Characterisation of the internal airflow patterns was used to assess the level of mixing under steady state conditions. The techniques were extended to cover the response of the design to various challenges such as door opening. There are two reasons for using an isolation room – the patient is a source of infection and the patient is at risk from infection. The concept of a protection factor is introduced as a measure of the effectiveness in protecting staff or a patient against a source of infection. The PPVL isolation room provides a protection factor of $10^5$ between the corridor outside and the isolation room (all doors closed) and a factor of $10^3$ within the isolation room.

INTRODUCTION

The UK Department of Health (UKDH) has issued guidance for the design of a neutral pressure isolation room. The design incorporates a positively pressurised ventilated lobby (PPVL). The PPVL provides a barrier to airborne infection originating within the isolation room (i.e. equivalent to the negative type isolation rooms) and a barrier to airborne infection originating in the corridor (i.e. equivalent to the positive type). A static pressure differential between the isolation room and the adjacent corridor of close to zero is intended in the design - hence the term neutral pressure isolation room. [N.B. It is probable that the UKDH will adopt the terminology of PPVL rather neutral to make its purpose clear and unambiguous].

Air is supplied mechanically into the lobby through a central ceiling mounted supply diffuser. The supply flow rate was 220 l.s$^{-1}$. The majority of the air supplied to the lobby passes into the isolation room (160 l.s$^{-1}$) via a pressure stabiliser fitted above the door between the lobby and the isolation room. A proportion of the air leaves the lobby and enters the corridor via gaps around the door. Air also enters the isolation room via gaps around the door below the pressure stabiliser. Air is extracted from a ceiling mounted grille in the ensuite bathroom and so air is drawn from the isolation room via a low-level transfer grille in the ensuite door. The extract flow rate was 160 l.s$^{-1}$. The design intent is for around 10 air changes per hour (ac.h.$^{-1}$) to be delivered to the isolation room with good mixing, which is equivalent to 60 ac.h.$^{-1}$ in the lobby.

The mechanical stabiliser is set to maintain a nominal pressure difference of +10 Pa between the lobby and the isolation room when all doors are closed. As the static pressure differential between the isolation room and the corridor is intended to be
close to zero, the static pressure in the lobby is also designed to be around +10 Pa above the corridor when all the doors are closed.

In a PPVL isolation room, effectiveness is achieved by means of diluting airborne pathogens in the vicinity of the patient by a well-mixed pattern of room air movement. Therefore, the contaminant is removed from the isolation room by means of the mechanical extract system. Tracer gas (nitrous oxide) was used to simulate airborne infections. It was released into the isolation room and its concentrations were measured around and outside the room using tubes connected to analysers, to investigate the dilution, transport and removal of a contaminant. Further tests were done with the source in the lobby and with doors being opened and closed to simulate personnel movement.

Dilution ventilation is only one of the protective features afforded by the design. Challenges such as high-speed ejection of infectious material (e.g. a cough, sneeze or excretion of bodily fluids) or direct contact routes of infection are handled by use of appropriate PPE and/or barrier nursing procedures. Other factors come into play when considering the situation where the patient is at risk from their surroundings. However, this paper is not concerned with operational and maintenance issues [1] or the rationale for selecting a particular ventilation strategy.

The following schematic is taken from the recommended guidelines [1], upon which the principles of design and operation were based, where the minimum requirements for such a facility are listed.

Figure 1. Single Room for Isolation [1]
The independent validation exercise was carried out to build and test a PPVL isolation room in a laboratory. It was decided in the outset of the project to validate the performance of the PPVL design with the following key issues:

1. Can the PPVL concept be built (within the test facility environment)?
2. Is it a robust design (from the point of view of construction, commissioning, maintenance, integration and testing – as far as the laboratory permits?)
3. Are the preferred design flow patterns achieved within the space, and are they stable?
4. Is the performance of the facility compromised with the lobby door left open to the main isolation room?
5. How do the internal conditions withstand challenges from door openings and personnel movement?
6. Is the thermal comfort of the patient and staff acceptable under normal operating conditions?
7. Is the performance acceptable with regards to infection control?
8. How does layout of furniture affect the room performance?

METHOD

Test facility

The design was based upon a specific configuration of PPVL isolation room, adapted for the laboratory environment. The isolation facility was constructed within the boundaries of an existing purpose built chamber, in order to maintain stable conditions and hence repeatable results. As far as practically possible, preferred suppliers and fitters of the Health Service were used to fit out the chamber. This helped to aid the authenticity of the project and to highlight any key issues with building the design. The construction included door fitting and sealing, pressure stabiliser balancing, and the use of hospital furniture and fittings within the isolation room, ensuite and lobby. The adjacent laboratory space still within the outer environmental chamber was used to model the corridor of the hospital.
Measures to provide a stable and quantitative environment for the test facility were
employed from the onset to gain repeatable results. Cables and sample tubes were
passed into the chamber through sealed glands, data acquisition and power metering
of all heat loads (IT, occupancy and lighting) within the facility was used, and
volumetric flow rates from the mechanical supply and extract were monitored using
Air Movement and Control Association (AMCA) standard nozzle boxes. The
dedicated data logging system with custom designed software took regular spot
measurements of air temperature, air speed, power consumption, internal and external
wall surface temperatures and inter-room static pressure differentials. Further details
on the techniques used within the project are presented elsewhere, see [2] and [3].

Test Procedure

The principal aim of the test facility was to establish whether the ventilation patterns
inherent in the isolation room were operating as a single, well-mixed zone. Sufficient
mixing of fresh air from the lobby with the room air, effective extraction from the
ensuite, and maintaining the pressure barrier with the stabilisers, were the key aspects
in making the design work.

The design also required a wholly stable environment from which tests could be
repeated with confidence in producing repeatable test results. All instrumentation
used that is key to understanding the physics of the facility was calibrated at regular
intervals to provide confidence in the results.

Multiple routes to validate the design were explored throughout the project, including:

- Air leakage performance through pressurisation to commissioning standard in
  [1].
- Room Air Movement (RAM) survey to measure temperature and air speed
  over a regular 11 x 13 grid at 11 heights within the facility. This provides
  information to calculate the thermal comfort parameters, such as draught risk.
- Flow visualisation using smoke pencils for local effects, and smoke generators
  for facility air mixing visualisation.
- Gas Tracer Tests (GTT) to study the release of nitrous oxide (N2O) into the
  isolation room as the source of contaminant from the patient, analysed at
  multiple points within the facility through analysers. Protection levels and air
  change rates were deduced.
- Computational Fluid Dynamics (CFD) to accurately model the facility as built
  and to compare predictive computed results against the physical results found
  with the RAM surveys.

RESULTS

Fundamentally, it was found that the chosen configuration could be built, and that the
isolation room does operate as a single zone and as a well-mixed space under standard
conditions.
The design provides a nominal 10 ac.h\(^{-1}\) from the mechanical ventilation supply to the lobby, working with the pressure stabilisers. The test facility exhibited approximately 8 ac.h\(^{-1}\) within the isolation room, demonstrating the predominantly well-mixed behaviour that was predicted.

The main findings are reported below as an overview. Figure 3 shows air temperature and air speed results from two RAM surveys within the facility, one under standard operating conditions (Test 5), and the other when the lobby door to the isolation room has been left open (Test 6). It would not be expected that the door would be left open for a prolonged period, however tracer gas tests demonstrated that the isolation room still behaved as a single zone, but with air interchange between the lobby and the isolation room. The mixing in the isolation room (door closed) was characterised by a factor of 0.89; the corresponding factor for door open was 0.53.

The plots in Figure 3 demonstrate the supply air jet from the balancing diffuser entering the isolation room (door closed), and highlight the uniform distribution of air temperature within the entire space. Satisfactory levels of thermal comfort are experienced across the floor space. Opening the lobby door removes the supply jet as expected, and introduces a level of stratification to the facility. Analysis of the results was performed for four tests, with results being averaged for each anemometer height within the zone that were conducted under thermally steady state conditions:

Test 3: All doors closed, no furniture in room, original pressure stabiliser used
Test 4: All doors closed, no furniture in room, alternative pressure stabiliser used
Test 5: All doors closed, furniture introduced, alternative pressure stabiliser used
Test 6: Lobby to isolation room door open, with furniture in room

![Figure 3. RAM Survey visualisation plots, Tests 5 and 6.](image-url)
Figure 4 demonstrates the room averaged air temperature and air speed profiles at the anemometer heights within the facility. Good levels of air mixing within the space can clearly be seen in Tests 3, 4 and 5, with the significant temperature stratification present in Test 6 when the lobby to isolation room door is opened.

![Speed vs Height](image1.png) ![Temperature vs Height](image2.png)

Figure 4. RAM Survey thermal analysis. a) Speed (m.s⁻¹), b) Temperature (°C).

The distribution of contaminant (tracer gas) with the patient as a source has been studied and reported. [4]

Single failure modes were explored within this project and included supply and extract fan failures. The simulated supply fan failure indicated no significant leak of tracer gas into the corridor, with the isolation room remaining effectively well mixed and under negative pressure. Extract fan failure lead to increased levels of detection within the room as expected, but the lobby still provided a layer of protection to the corridor. A patient vulnerable to infection would not be at a significantly higher risk as long as the doors remained closed in this particular failure mode. The worst-case failure mode explored within this project is for the lobby door to be left propped open. Tests show that under these conditions the tracer gas can pass into the lobby, with barely detectable levels reaching the corridor.

Determination of the level of protection presented by the isolation facility (from the PPVL) was a major objective in the project. Minimum detection levels of 10ppm (parts per million) of N₂O against 100% (10⁶ ppm), implies a dilution ratio of 10⁵. This is expressed as the protection factor.

The principal conclusion is that the PPVL design is considered to be validated. The main qualifications to this principal conclusion are set out below:

- Full size room with ensuite successfully constructed following published guidance. Construction follows ethos of guidance with standard lighting and HVAC components. Specific recommendations were followed with regard to key features such as pressure stabilisers.
- Isolation room functioned as expected once commissioned.
- Preferred flow patterns were characterised by smoke, anemometry techniques, CFD prediction (base case) and tracer gas tests. Stability and repeatability were clearly demonstrated.
• Transient issues were addressed mainly through remote door operation to simulate personnel movement. Only scenarios compatible with proper use were considered (e.g. scenario such as both doors open was not relevant).

• Standard thermal comfort indices provide standard basis for assessment and comparison but individuals vary widely in their perception. Medical conditions may have significant impact. Potential mismatch between patient and nurse clothing level and metabolic rate is a consideration applying to all types of isolation room.

• Airborne infection covered for scenarios where tracer gas is a good model for the infection mechanism. A $10^5$ protection factor was introduced and established.

DISCUSSION

The test facility demonstrated exhibited well-mixed (turbulent) air distribution, operating as a single zone of movement under standard operating conditions. The introduction of transient situations (opening and closing of doors) proved successful in indicating that the isolation room can return to its initial well-mixed state when disturbed.

The protection factor was introduced as a measured degree of effectiveness in protecting staff and patients against a source of contamination.

There are two reasons for using an isolation room – the patient is a source of infection and the patient is at risk from infection. The PPVL isolation room provides a protection factor of $10^5$ between the corridor outside and the isolation room (all doors closed). Conformance with air tightness standards in construction coupled with the operation of the isolation room itself at near neutral pressure differential relative to the corridor is a further safety factor.

There is a further role other than isolation. The patient has to be nursed and medical examinations and minor procedures have to be carried out. Where the patient is a source of infection, potential hazards must be reduced to provide a safe and ideally comfortable environment. The dilution ventilation strategy is based on dilution of airborne pathogens by the incoming fresh air. The validation using tracer gas has shown that normalised concentrations within the isolation room (doors closed) are within a range of 0.5 and 2.0. This expresses the typical variation in concentrations that would be expected in the working zone of nursing staff away from the immediate source of aerosol ejection. The alternative view is to regard the ventilation within the isolation rooms providing a conservative protection factor of $10^3$. For the patient at risk from infection, a similar protection factor can be assigned with regard to the dilution ventilation as viewed by the patient.

It has been established that a configuration of the design presented in HBN4 [1] can be built and operated as intended, through the use of multiple established validation techniques. The PPVL concept provides a quantifiable barrier of protection for the patient from the corridor, and for the inhabitants of the corridor from the patient. The design as tested will operate correctly as an isolation room if built as an isolated system. Sanitation, mechanical ventilation and power supplies need to be independently sourced for it to function effectively for extended periods of time.
The PPVL isolation room design offers real potential to control infection in hospitals contributing to a healthy and productive environment.

REFERENCES


