Door-opening motion can potentially lead to a transient breakdown in negative-pressure isolation conditions: the importance of vorticity and buoyancy airflows

J.W. Tang\textsuperscript{a,*}, I. Eames\textsuperscript{b}, Y. Li\textsuperscript{c}, Y.A. Taha\textsuperscript{d}, P. Wilson\textsuperscript{e}, G. Bellingan\textsuperscript{f}, K.N. Ward\textsuperscript{a}, J. Breuer\textsuperscript{d}

\textsuperscript{a}Division of Infection and Immunity, Centre for Virology, Royal Free and University College Medical Schools, London, UK
\textsuperscript{b}Department of Mechanical Engineering, University College London, London, UK
\textsuperscript{c}Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, China
\textsuperscript{d}Skin Virus Laboratory, Institute of Cell and Molecular Science, Queen Mary College, London, UK
\textsuperscript{e}Department of Microbiology, University College London Hospitals NHS Foundation Trust, London, UK
\textsuperscript{f}Intensive Care Unit, Department of Medicine, University College London, London, UK

Received 28 January 2005; accepted 18 May 2005

KEYWORDS
Chickenpox; Varicella; Nosocomial; Aerosol; Transmission; Negative-pressure isolation room

Summary A patient with severe chickenpox was admitted to a negative-pressure isolation room. He remained sedated, intubated and mechanically ventilated throughout his admission. He was managed only by nurses immune to chickenpox. A non-immune male nurse occasionally handed equipment through the doorway, without entering the room. Ten days later, he also developed chickenpox. Sequencing of viruses from the patient and nurse showed the same rare genotype, indicating nosocomial transmission. An experimental model demonstrated that, despite negative pressure, opening the door could have resulted in transport of infectious air out of the isolation room, leading to a breakdown in isolation conditions.

\textsuperscript{*} Corresponding author. Address: Department of Microbiology, The Chinese University of Hong Kong, Prince of Wales Hospital, Shatin, New Territories, Hong Kong SAR, China. Tel.: +852 2632 2329; fax: +852 2647 3227.
E-mail address: julian.tang@cuhk.edu.hk

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doi:10.1016/j.jhin.2005.05.017

Introduction

This paper describes a case of hospital-acquired chickenpox in a medical intensive care unit (ICU), despite negative-pressure isolation. It suggests a possible route of aerosol transmission using
principles from fluid dynamics and a simple model. This demonstrates how such airborne infections can be spread, even in modern isolation facilities.

Case report

A 62-year-old Caucasian man was admitted to the ICU with a four-day history of severe haemorrhagic chickenpox with pneumonitis. The patient was nursed using respiratory isolation measures in a negative-pressure single room. He remained sedated, intubated and mechanically ventilated throughout his stay. All respiratory care was performed using a closed-suction system with no recorded breaks in his closed-airway system. To keep the patient warm, a Bair Hugger blanket was used. Only staff with a history of chickenpox were allowed to enter the room. Despite full ICU support and intravenous aciclovir 10–15 mg/kg every 8 h, the patient died of multi-organ failure.

Ten days after admission of the patient, a male ICU nurse developed chickenpox. This nurse gave no other history of contact with chickenpox. He was known to be seronegative for varicella zoster virus (VZV) and had therefore not been allocated to this patient’s care. However, the nurse did admit that several times a day he would spend up to 2 min handing equipment through the door to colleagues attending this patient inside the isolation room. During this activity, the nurse wore no personal protective equipment (i.e. no gloves, mask or apron). The doorway of the patient’s isolation room was approximately 3 m from the patient’s bed. The patient’s room was at a negative pressure of approximately 3 Pa (Pascals), and underwent eight total air changes/h. The hinged door opened into the isolation room.

Methods

Vesicle swabs were taken from the skin of the patient and the nurse during the time of their chickenpox rash. Deoxyribonucleic acid (DNA) from vesicle swabs was extracted using QIAmp DNA Mini Kit (QIAGEN Ltd, Crowley, UK) according to the manufacturer’s instructions. Viruses were genotyped using single nucleotide polymorphism (SNP) and R1 published methods. Initially, a total of 13 SNPs were used to determine the genotype (A–C). Then a DNA fragment, comprising VZV R1 variable region, was amplified and directly sequenced in a GeneAmp 2700 polymerase chain reaction machine. Viral DNA sequences were analysed using BioEdit v 7.0.1 and Chromas2 software.

To test the hypothesis of airborne transmission experimentally, a water tank was built with food dye to simulate infectious aerosols in an isolation room. This tank was constructed to simulate the flow of air across a full-size doorway, with an inward-opening door, by using water to simulate air in a scaled-down model using the principle of Reynolds number equivalence, where water can be used to simulate air (the Reynolds number is a dimensionless number equal to the ratio of inertial to viscous forces where fluids, i.e. gases or liquids, are in motion). The motions of the door and food

![Figure 1](image-url)
dye were captured on video camera with a time scale (Figure 1).

Results and discussion

VZV was cultured from both the patient’s and the nurse’s vesicular fluid. No other pathogens were identified. Typing of viruses from both sources showed VZV genotype A (Centers for Disease Control and Prevention M type). The R1 variable region length and pattern of nucleotide repeats were identical in the two isolates.

From analysis of the video footage of the model water tank (Figure 1), it can be seen that after the door was opened to about 45° [Figure 1(a) and (b)] the food dye started to move into the clean area on the other side of the door [Figure 1(b)]. This was mediated by the large vortex generated by the door-opening motion. After a time, the food dye can be seen dispersing into the clean area [Figure 1(c)].

Genotype A is found in fewer than 10% of strains circulating in the UK.² The R1 region comprises variable numbers of nucleotide repeats and is highly polymorphic. These R1 sequences in the patient and the nurse were identical. These results therefore indicate nosocomial transmission of VZV from the patient to the nurse.

The simple water tank and food dye model shows that movement of air from opening the door could have resulted in the exposure of the susceptible nurse to airborne VZV from the patient in the isolation room (Figure 1). Although the negative-pressure system inside the isolation room would have acted to reduce the movement of infectious air from inside to outside across the open doorway, the negative-pressure gradient may have been transiently reversed if the door-opening motion was too rapid.

Such behaviour of airflows across open doorways has been well described, and depends on the temperature and density of the air, the velocity of door opening, and the angle to which the door is opened.³ Based on these principles, Figure 2(a) and (b) show the predicted airflow currents upon opening the door into a room. An inward air current flowing into the room from outside (blue, light arrows), and vortices of possibly infected air from cooler outside (in the corridor) and warmer air inside a hypothetical isolation room. At the doorway itself, differences in air temperature and density with height are marked by the faces: red (dark) face, head height; blue (light) face, just above the floor.

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Figure 2  (a) Top-down view of the possible airflow currents that result from the opening (inwards, in this example) of a standard hinged door. W, angular velocity at which the door is opened; θ, angle through which the door moves; red (dark) face, person moving towards the doorway; red (dark) arrows, air moving out of the room; blue (light) arrows, air moving into the room. (b) View from inside the room of the situation illustrated in (a), showing a three-dimensional view of possible airflow trajectories induced by the movement of the door opening into a hypothetical isolation room. The red (dark) face represents a person entering the room, through the doorway, who may be exposed to infectious air. (c) Same view from inside the room as illustrated in (b), but this time showing the possible airflow trajectories taking into account the temperature and density differences between
inside (red, dark arrows) circulating around the open door are present. Thus, a person (represented by the red dark face) walking into this area of air circulation would be exposed to and may inhale infectious air emerging from the isolation room.

The negative-pressure gradient may also have been transiently reversed if the temperature gradient across the doorway was too steep. Figure 2(c) shows that if a temperature gradient existed between the warm air inside the room and the cooler air outside, this would have created a 'two-way buoyancy flow'. This would have encouraged the warm air to rise as it flowed out of the room (red, dark arrows), while cool air from the corridor flowed in at floor level (blue, light arrows). This potentially increased the exposure of the nurse to infected room air (as shown by the red, dark arrows) leaving the room at head level (as shown by the red, dark face).

In this case report, the hinged door opened into the patient's isolation room, which was at a negative pressure of approximately 3 Pa. Although previous guidelines of the Centers for Disease Control and Prevention\(^4\) required a minimum of 0.25 Pa of negative pressure, this requirement has been replaced by the American Institute of Architects' guidelines\(^5\) that recommend a minimum of 2.5 Pa of negative pressure. In the UK, a recent recommendation by the National Health Service Estates Agency\(^6\) has adopted a slightly different approach. Instead of a negative pressure in the isolation room, the outside corridor pressure will be at a positive pressure of 10 Pa. This will have a similar aerosol containment effect but it is likely to be more effective at this higher pressure difference.

Aerosolized VZV DNA has been detected in the environment around patients with varicella and shingles, and the nosocomial transmission of VZV via aerosol is well established.\(^7,8\) Therefore, there is a distinct possibility that despite the negative pressure inside the room, transmission of VZV may have occurred via infectious aerosol as the nurse stood at the door.

In summary, we report a case of nosocomial transmission of VZV to a nurse that may have occurred via aerosol transmission, despite negative-pressure isolation of the infected patient. Other infectious agents, such as severe acute respiratory syndrome\(^9\) and tuberculosis,\(^10\) are also transmitted by aerosol and may pose a similar risk. Sliding rather than hinged doors (with an airlock-like arrangement) or an anteroom at the entrance would reduce airflow perturbation caused by staff entering the isolation room through the door. This cross-infection incident should not be taken as a warning that all existing negative-pressure rooms will inevitably fail. However, care should be taken in reducing adverse airflow and bidirectional flow through a doorway when the door is open.

Thus, this case report recommends that susceptible personnel should not stand at the entrances of isolation rooms containing patients with respiratory infections since, despite negative pressure, nosocomial transmission via an airborne route may still be possible.

Acknowledgements

Our special thanks to the ICU staff nurse for his permission and co-operation in the writing of this report.

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