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Factors affecting ventilation effectiveness in SARS wards

Key Messages

1. The major factors affecting the ventilation performance in severe acute respiratory syndrome (SARS) wards were air change rate, airflow direction, and airflow pattern.
2. Despite the use of state-of-the-art technologies, 26% of the SARS wards in nine hospitals failed to meet the ventilation requirement of 12 air changes per hour and 60% had the wrong airflow direction for the toilets/bathrooms. All SARS wards satisfied the requirement of no air leakage to the corridor.
3. Regular checks of airflow direction and air change rates are highly recommended.
4. Specific education or training on ward ventilation systems is recommended for hospital maintenance technicians and health care workers.

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Introduction

Health care workers (HCWs) were the group most affected during the 2003 severe acute respiratory syndrome (SARS) epidemics. A total of 22% of confirmed SARS cases in Hong Kong were HCWs. Large outbreaks were reported in hospitals in Hong Kong,[1,2] Singapore,[3] Taiwan,[4] Beijing,[5] Toronto,[6] and Vietnam.[7] Immediately after the SARS epidemic, the Hong Kong SAR Government decided to spend HK$410 million (US$52.5 million) on constructing more than 500 isolation rooms with a capacity of 1300 beds in nine existing major acute public hospitals.[8] The SARS wards were retrofitted from existing wards, rather than newly built. By late September 2003, the first batch of 33 new isolation beds was ready for use in Princess Margaret Hospital.[9] According to the Hong Kong Hospital Authority (HA), 558 isolation rooms with a total capacity of 1324 beds were constructed in 14 public hospitals by the end of 2003. Of these, 30% (168/558) had single beds, 39% (217/558) had two beds, 1% (6/558) had three beds, 24% (134/558) had four beds, and the remaining 6% had five or six beds.

At the time construction began, there were no specific design guidelines for isolation rooms. The Hong Kong Institution of Engineers formed an expert group in May 2003 to investigate and develop an effective air-conditioning system for SARS wards.[10] Some of the design principles put forward by the expert group were subsequently adopted in the final designs of the new SARS wards.

Previous studies have reported that up to 50% of the tested isolation rooms failed to provide negative pressure.[11-16] The main factors that disrupted negative pressurisation included poor reliability of pressurisation control and monitoring devices, strong diffuser flow directed at the door, interaction with other exhaust ventilation systems, and poor airtightness of the suspended false ceiling.[12] Daily smoke testing is recommended for an isolation ward occupied by a potentially infectious patient, whether or not continuous monitoring devices are used.[12] Various measurement techniques have been suggested for negative pressure isolation rooms, including theatrical fog and tracer gas methods.[13,17,18]

We carried out field measurements in selected isolation rooms in the new SARS wards between May and August 2005, followed by theoretical analysis, computational fluid dynamics simulations, and laboratory tests. Given the fact that the 558 SARS isolation rooms were designed and constructed at nearly the same time and represented state-of-the-art technologies, it was expected that these isolation rooms would have a better ventilation performance than those reported in the literature.[11-19]

The current concern about the risk of pandemic influenza from avian influenza A (H5N1) has made this field study timely as it is expected that some of these SARS wards will be used for H5N1 patients if one or more human H5N1 cases occur.

Aims and objectives

This project aimed to study the factors affecting the effectiveness of SARS wards in terms of air distribution and the removal of virus aerosols. The data obtained will facilitate decision-making about various ventilation designs for different hospitals. This will allow us to propose possible improvement measures within

the space, financial and ward operational constraints and to develop guidelines for operation and maintenance of SARS wards in relation to ventilation in Hong Kong.

Methods

Field measurement

Nine HA hospitals with large numbers of new SARS wards were selected. Additional field measurements were conducted in two hospitals with natural ventilation. Simple thermal breathing mannequins were used to model in-patients and HCWs.

Most field measurements were carried out between May and August 2005. We measured pressure differences, airflow direction through doorways, air change rates, and local ventilation effectiveness. Measuring devices were all calibrated by the respective manufacturers 2 months prior to the first measurement. To measure doorway flows, smoke was released at different heights when the door was open. Air leakage locations were identified by releasing smoke close to the suspected wall or ceiling.

The air change rates were measured using four methods: (i) direct measurement at supply openings, (ii) direct measurement at exhaust openings, (iii) the constant emission tracer gas method, and (iv) the decay tracer gas method. In the tracer gas method, sulphur hexafluoride (SF6) was injected into the cubicle at a known constant emission rate using a multipoint sampler and doser (Type 1303, Brüel & Kjær, Denmark).

Theoretical analysis, computational fluid dynamics simulations, and laboratory measurements

We carried out the first detailed theoretical analysis of the pressure difference across doorways of isolation rooms to provide a theoretical basis for how large the pressure difference should be. Both steady and transient computational fluid dynamics simulations were carried out to understand field measurement, as well as investigate the roles played by bed curtains and pressure stabilisers, etc. Additional laboratory studies were performed to investigate the effectiveness of high-efficiency particulate air filters.

Results

Ventilation performance of SARS wards

The majority (97%) of the 38 rooms tested met the recommended negative pressure difference of 2.5 Pa between corridor and anteroom. Similarly, 89% of 48 rooms tested met the same requirement between anteroom and cubicle. No air leakage out to the corridor was found. Some 60% of the toilets/bathrooms were operating under positive pressure. Over 90% of the corridor-anteroom or anteroom-cubicle doors had a bi-directional flow when the door was open. Of the 35 tested cubicles, 26% had an air change rate of less than 12 air changes per hour (ACH). The local ventilation effectiveness was non-uniform in the cubicles.

Airflow direction of toilet and bathroom doors

Of the 57 toilet or bathroom doors tested, only 60% had airflows in the wrong direction. In 40% of the rooms, air flowed out of the toilet/bathroom to the cubicle when the toilet/bathroom doors were closed, although there was no mechanical air supply in the toilets/bathrooms. This backflow phenomenon was found in six of eight tested hospitals.

Discussion

Relationship between negative pressure and airflow direction

The purpose of maintaining sufficient negative pressure is to ensure that air flows from a high-pressure region to a low-pressure region. When the door was closed, all tested SARS wards had inward airflows or no outward airflows, suggesting that they effectively secured no leakage of cubicle air into the corridors, even when some of the cubicles failed to maintain a negative pressure difference higher than 2.5 Pa.

The bi-directional flows were probably caused by the temperature differences between two spaces. To minimise bi-directional flows, the air temperature in the two spaces needs to be controlled as closely as possible. Alternatively, turbulent airflows at the doorway caused by the jet flow of the supply diffuser either in the cubicles or in the corridor might also be responsible for the observed bi-directional flows. The existence of bi-directional flows when a door was open is an interesting phenomenon that needs further investigation.

The importance of air change rate

During the tracer gas measurements, the decay method was found to be more reliable than the constant emission method. Although all isolation rooms were designed to operate at a ventilation rate of 12 ACH, the average ventilation rate measured was 19.6 ACH, with the highest rate found to be 30 ACH. A very high air change rate will produce a greater dilution effect; the pollutant decay rate is also known to be significantly reduced. Nonetheless, a very high air change rate also implies high-energy consumption, an important consideration in hot and humid Hong Kong. The energy cost of treating outdoor air intake is high. There are currently insufficient data to quantify or specify the optimum outdoor air ventilation rate for isolation rooms.

Despite the fact that the SARS wards were designed at about the same time utilising state-of-the-art technologies, we found that of 35 tested cubicles, 26% had an air change rate lower than 12 ACH. All of the failed cubicles were from three of the nine hospitals tested. The HA was informed of these deficiencies and remedial action was taken.

Non-uniform distribution of local ventilation effectiveness

Ideally, for a fully mixed ventilated room, the local

ventilation effectiveness should be unity everywhere. The fact that the local ventilation effectiveness was not uniform in all tested cubicles indicated that the air in these rooms was not well-mixed. The ability of the lower exhaust to capture pollutants varied from bed to bed. An uneven exhaust flow rate, the thermal plumes arising from lying patients and the airflow from the transfer air duct or the pressure stabiliser may have affected the overall airflow pattern and consequently led to dispersal of pollutants between beds. The results clearly indicated that beds on opposite sides of a ward generally had higher local ventilation effectiveness than beds next to the test bed. It is therefore recommended that wards be filled by placing incoming patients in opposite beds, rather than placing them in neighbouring beds first.

Conclusions

1. When the door was closed, all tested wards had an inward airflow or no outward airflow, suggesting that SARS wards effectively achieved no leakage of cubicle air into the corridors, even when some of the cubicles failed to maintain a negative pressure difference higher than 2.5 Pa.
2. Despite the use of state-of-the-art technologies, 26% of the tested new isolation rooms failed to meet the 12 ACH ventilation requirement, and 60% had wrong airflow directions for the toilets/bathrooms. All rooms satisfied the requirement of no air leakage to the corridor. Regular checks of airflow direction and air change rates should be conducted.

Recommendations

1. Regular checks of airflow direction and the air change rate in addition to the continuous monitoring of negative pressure differences are highly recommended. Airflow can be checked easily using a hand-held smoke tube. All doors inside the ward, ie the corridor-anteroom, anteroom-cubicle, and cubicle-toilet doors should be checked. The supply diffusers and exhaust grilles should also be checked to ensure that they are operating properly. The cubicle air change rates can be monitored by checking the supply airflow rate with an anemometer. Visual checks needing a large amount of smoke or tracer gas measurement can only be carried out in unoccupied wards to avoid any possible health implications for in-patients and HCWs. Leakage from false ceilings can be identified by releasing a small amount of smoke around the suspect region. Special attention should be paid to areas where HCWs work inside curtains, when the curtains surrounding the patient bed are closed and no air supply goes to the patient region.
2. Hospital engineers and HCWs should be educated about basic ventilation so that they can alert the appropriate authorities if the ventilation system or any component is not operating properly.
3. There is a need for further study of the use of natural ventilation, the use of window exhaust methods as well as the overall airflow control in hospitals.

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