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Natural Ventilation for Infection Control in Health-Care Settings

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The cover photographs show health-care facilities in (from top to bottom) Myanmar, South Africa, Peru, Nepal, Hong Kong SAR and Nepal.

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Contents

Tables

Figures

Foreword

In June 2007, the World Health Organization (WHO) released a guideline document on infection prevention and control entitled *Infection prevention and control of epidemic- and pandemic-prone acute respiratory diseases in health care — WHO interim guidelines* (WHO, 2007). In this new guideline, natural ventilation is considered for the first time among the effective measures to control infections in health care. Such a recommendation from WHO demonstrates a growing recognition of the role of ventilation and natural ventilation for infection control.

The 2007 guideline demonstrated that further study was required in areas such as minimum requirements for natural ventilation and design, construction, operation and maintenance for effective natural ventilation systems for infection control.

Over the past two years, a multidisciplinary team of engineers, architects, infection-control experts and microbiologists has been working to produce this WHO guideline, providing a design and operation guide for hospital planners, engineers, architects and infection-control personnel. The recommendations in this WHO guideline followed a systematic review of the literature on the association of ventilation and disease transmission, as well as effective natural ventilation solutions for infection control.

This WHO guideline should be used in conjunction with other relevant infection-control guidelines.

There are very few studies on natural ventilation for infection control in hospitals. The authors of this guideline have attempted to document what is known today. Any comments from the users and readers of this guideline will be useful for future revisions and further information may be obtained at http://www.who.int/csr/natvent (and follow the ‘natvent’ links), or at http://www.who.int/csr/bioriskreduction/natvent/en/.

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Executive summary

In June 2007, the World Health Organization (WHO) released new guidelines entitled *Infection prevention and control of epidemic- and pandemic-prone acute respiratory diseases in health care — WHO interim guidelines* (WHO, 2007). In this guideline, natural ventilation was considered among the effective environmental measures to reduce the risk of spread of infections in health-care settings.

The purpose of this latest guideline is twofold:

- to promote natural ventilation design for infection control in health care (Part 1); and
- to describe the basic principles of how to design, construct, operate and maintain an effective natural ventilation system for infection control (Part 2).

This guideline is primarily developed for engineers and architects who design or operate health-care facilities. The guideline is also useful for health-care workers, particularly infection-control professionals who work in health-care facilities. The guideline recognizes that the hospital designers, operators and health-care workers need to work together for effective infection control.

This guideline applies to diseases that can be transmitted through fine droplets or through droplet nuclei. The guideline describes how an airborne precaution room and its adjacent areas can be designed to provide natural ventilation control of infections. However, this guideline does not include thorough descriptions for other infection-prevention and control measures.

The development of this guideline involved:

- a two-day multidisciplinary consensus meeting on the scope and main elements on use of natural ventilation for infection control (May 2007);
- a systematic review of the literature covering the association between ventilation and infection, and natural ventilation solutions (March–December 2008) (see Annex A for details);
- WHO external panel review and outline of the main recommendations (November–December 2008); and
- WHO internal and external peer review (January–May 2009).

The main recommendations are listed in the following box.

Main recommendations

1. To help prevent airborne infections, adequate ventilation in health-care facilities in all patient-care areas is necessary.

Overall ranking: Strong recommendation

2. For natural ventilation, the following minimum hourly averaged ventilation rates should be provided:
   - 160 l/s/patient (hourly average ventilation rate) for airborne precaution rooms (with a minimum of 80 l/s/patient) (note that this only applies to new health-care facilities and major renovations);
   - 60 l/s/patient for general wards and outpatient departments; and
   - 2.5 $l/s/m^3$ for corridors and other transient spaces without a fixed number of patients; however, when patient care is undertaken in corridors during emergency or other situations, the same ventilation rate requirements for airborne precaution rooms or general wards will apply.

The design must take into account fluctuations in ventilation rate.

When natural ventilation alone cannot satisfy the recommended ventilation requirements, alternative ventilation systems, such as hybrid (mixed-mode) natural ventilation should be considered, and then if that is not enough, mechanical ventilation should be used.

Overall ranking: Conditional recommendation

3. When designing naturally ventilated health-care facilities, overall airflow should bring the air from the agent sources to areas where there is sufficient dilution, and preferably to the outdoors.

Overall ranking: Conditional recommendation

4. For spaces where aerosol-generating procedures associated with pathogen transmission are conducted, the natural ventilation requirement should, as a minimum, follow Recommendation 2. Should the agent be airborne, Recommendations 2 and 3 should be followed.

Overall ranking: Conditional recommendation

These four recommendations were developed by the systematic review external panel using the GRADE appraisal system during the panel's meeting in Geneva in November 2008 (see Annex B). In areas where vector-borne disease is endemic (e.g. malaria, dengue), the use of natural ventilation should not affect in any way the usage policy or practice of mosquito nets.

Only basic principles of design, construction, operation and maintenance are described in this guideline, and the designers will need to consult engineering design guides and textbooks for technical details of natural ventilation. The readers are reminded about the limitations of natural ventilation when there is a lack of natural forces, such as winds and breezes, especially for the delivery of the high airflow rates recommended in this guideline for airborne precaution rooms. Users are reminded not to rely solely on this guideline for design guidance for their naturally ventilated facilities.

Naturally ventilated hospitals or airborne precaution rooms need to be designed properly for natural ventilation to provide the recommended ventilation rates, otherwise, factors such as the lack of directional control of airflow may lead to a potential for transmission of infection. Interested readers should obtain or consult the referenced technical documents when contemplating renovation or construction using natural ventilation.

This guideline will be reviewed five years after its publication to include new data on the association between natural ventilation rates and infection.

Implementation plan

The guideline is a new area so there is no adaptation plan available.

A follow-up project has already started and covers "low-cost health-facility design with naturally ventilated infection-control characteristics". It aims at providing design assistance for naturally ventilated, low-cost health facilities in low-income settings. More information regarding this may be found at http://www.who.int/csr/natvent.

WHO intends to provide sample designs, plans and guidance for the renovation and construction of health facilities to be posted on a web page for free downloading. This will build on the current guideline to encourage and facilitate the provision of low-cost health-care facilities with infection-control characteristics, in low-income countries, that use affordable and sustainable means and (if feasible) natural ventilation.

Acronyms and definitions of terms

Acronyms

ACH	air changes per hour
PPE	personal protective equipment
SAR	Special Administrative Region
SARS	severe acute respiratory disease
TB	tuberculosis
WHO	World Health Organization

Definitions of terms

Administrative controls	Set of managerial measures to warrant the needed conditions for the application of infection control principles in health care. These include establishment of sustainable infection control infrastructures and activities, clear policies on early recognition of infections, implementation of appropriate infection control measures, regular supplies and organization of services (e.g. creation of patient triage system and placement). The health-care facility management should also have staff planning to promote an adequate patient-to-staff ratio, provide staff training, and establish staff health programmes (e.g. vaccination, prophylaxis) to enhance the general health of the health-care workers (WHO, 2007).
Aerosol-generating procedure associated with pathogen transmission	High-risk procedures that may increase the potential of generating droplet nuclei because of the mechanical force of the procedure (e.g. intubation, cardiopulmonary resuscitation, bronchoscopy, autopsy, and surgery where high-speed devices are used) (WHO, 2007).
Aerosol-generating procedures	A procedure that can induce the production of fine respiratory droplet in the patient.
Airborne precaution room	A room with ≥12 air changes per hour (ACH) and controlled direction of air flow. An airborne precaution room can be naturally or mechanically ventilated. In addition to the requirement of ≥12 ACH, in a mechanically ventilated airborne precaution room, negative pressure is created to control the direction of air flow. It is equivalent to the "airborne infection isolation room" described by the United States Centers for Disease Control and Prevention. In naturally ventilated airborne precaution rooms the air flow should be directed to areas free of transit, or permit the rapid dilution of contaminated air into the surrounding areas and the open air (WHO, 2007).

Airborne transmission	The transmission of disease caused by dissemination of droplet nuclei that remain infectious when suspended in air over long distance and time. Airborne transmission can be further categorized into obligate and preferential airborne transmission. Obligate airborne transmission refers to pathogens that are transmitted only by deposition of droplet nuclei under natural conditions (e.g. pulmonary tuberculosis). Preferential airborne transmission refers to pathogens that can initiate infection by multiple routes, but are predominantly transmitted by droplet nuclei (e.g. measles, chickenpox) (WHO, 2007).
Air changes per hour (ACH)	For a positive pressure room — the ratio of the volume of outdoor air flowing into a given space in an hour divided by the volume of that space. For a negative pressure room — the exhaust airflow rate is used for calculation.
Anteroom	A small room leading from a corridor into another room, often an isolation room.
Balanced mechanical ventilation systems	A system where supplies and exhausts have been tested and adjusted to meet particular design specifications.
Droplet nuclei	Dried-out residuals of droplets <5 μm in diameter.
Droplets	Inspirable particles larger than 5 μm in diameter, which can be deposited on upper respiratory tract levels and mucosa.
Envelope opening	Purpose-built openings in buildings for natural ventilation (e.g. windows, doors, solar chimneys, wind towers, trickle ventilators).
Exfiltration	Outflow through unintended leakages in buildings.
High-tech natural ventilation system	A natural ventilation system that uses modern computer control systems, and may be assisted by mechanical ventilation systems.
Hybrid ventilation	Combination of both mechanical and natural ventilation (also called mixed-mode ventilation).
Infiltration	Air flow through unintended leakages into buildings.
Mixed-mode ventilation	See hybrid ventilation.
Natural ventilation	Use of natural forces to introduce and distribute outdoor air into or out of a building. These natural forces can be wind pressures or pressure generated by the density difference between indoor and outdoor air.
Negative pressure mechanical ventilation system	A mechanical ventilation system that uses an exhaust fan through which air is released.
Negative pressure room	The difference in air pressure between two areas. A room that is under negative pressure has a lower pressure than adjacent areas, which keeps air from flowing out of the room and into adjacent rooms or areas.

Opportunistic airborne transmission	Transmission of droplet nuclei at short range during special circumstances, such as the performance of aerosol-generating procedures associated with pathogen transmission.
Piston (or plug-flow) ventilation system	The ideal displacement in which ventilation air is pushed from one side of the room to the other without any recirculation and minimal air mixing. The piston ventilation system is the most efficient method of air exchange.
Positive pressure mechanical ventilation system	A mechanical ventilation system that uses a supply fan through which air is pushed into the room.
Quantum	A quantity or an amount of particles.
Recirculated airflow rate	The amount of the returned air (for recirculation). Although recirculated air can be filtered, its air quality is often worse than the outdoor air for most conventional applications. Therefore, filtered, recirculated air cannot replace outdoor air for ventilation.
Respiratory droplet	Depending on the size of the particles (which range from large droplets to small droplet nuclei), respiratory droplets can be divided into large droplets, fine inhalable aerosols and droplet nuclei (see Annex C for more details).
Short-circuiting airflow pattern	The pattern of airflow that occurs when part of the air is stagnant in a ventilated room, and the ventilation air can bypass the stagnant air and move directly to the exhaust outlets.
Transmission-based precautions	A set of practices that apply to hospital inpatients with specific infections for which precautions beyond the standard precautions are needed to control infection in the health-care setting.
Ventilation	Ventilation provides outdoor air into a building or a room and distributes air within the building. The purpose of ventilation in buildings is to provide healthy air for breathing by diluting pollutants originating in the building with clean air, and by providing an airflow rate to change this air at a given rate. Ventilation is also used for odour control, containment control and climatic control (temperature and relative humidity).

Part 1 — Infection control and ventilation

The purpose of Part 1 is to establish the recommendations for natural ventilation in the context of infection control. Chapter 1 explains the general principles of infection control as related to ventilation. Chapter 2 describes the basic concept of ventilation, as well as justifications for the use of natural ventilation for infection control. Chapter 3 discusses the association between ventilation and airborne infection, and gives the rationales and the World Health Organization consensus on the minimum requirements of natural ventilation design for infection control.

1 General principles of infection control

1.1 The concept of isolation precaution and an historical review

Isolation precaution is an important strategy in the practice of infection control. The spread of some infections can be impeded if infected patients are segregated from those who are not yet infected. Although there is no single study showing the effectiveness of isolation, there are many reports documenting the efficacy of the various components of isolation, including use of private rooms (Anderson et al., 1985), and protective equipments such as masks, gloves and gowns (Klein, Perloff & Maki, 1989; Maki, 1994; Maloney et al., 1995).

The concept of isolation can be traced back to biblical times when lepers were segregated from the rest of the populace. Towards the end of the 19th century, there were recommendations for patients with infectious diseases to be placed in separate facilities, which ultimately became known as infectious diseases hospitals (Lynch, 1949). However, in the early 1950s, many of these infectious diseases hospitals closed and the patients were moved to general hospitals. The need for proper isolation of infections in the context of these general hospitals thus became an important issue. Since then, several isolation systems evolved (NCDC, 1970; Lowbury et al., 1975; Garner & Simmons, 1983) with transmission-based precautions the most widely used, which included standard precautions (to avoid direct, unprotected contact with blood and body fluids), contact precautions, droplet precautions and airborne precautions (Gardner, 1996; Siegel et al., 2007).

Spatial separation is critically important when using isolation precautions because, as Florence Nightingale observed, many infectious diseases spread mainly through direct contact when patients are near to one another. Usually, special ventilation controls are not required; these are needed for diseases that can be transmitted over long distances by droplet nuclei (Gardner, 1996). Most diseases are not of this category. However, the infectious diseases that can be transmitted through long distance by aerosols (i.e. airborne infections) can result in large clusters of infection in a short period. Therefore, the proper isolation of these diseases is critically important.

Specific natural ventilation recommendations for isolation of airborne infections are discussed in detail in this guideline (see section 3.2).

1.2 Isolation practices for infection control

This guideline does not describe the details of the various transmission-based precautions, except for airborne precautions. Details of the other categories can be found in the relevant references (Siegel et al., 2007; WHO, 2007).

When using isolation precautions, three levels of controls must be considered (Gerberding, 1993).

The first level of control is administrative controls, which are measures taken to ensure that the entire system is working effectively. These controls include:

- implementing proper procedures for triage of patients
- detecting infections early
- separating infectious patients from others
- transporting the patients
- educating the patients and staff
- designating responsibilities clearly and correctly
- communicating with all relevant partners.

The second level is "environmental and engineering controls", including cleaning of the environment, spatial separation and the ventilation of spaces.

The third level of control to further decrease the risk of transmission is personal protection, which is the provision of the proper personal protective equipment (PPE) (e.g. masks, respirators).

When setting up an isolation system in the hospital, all levels of controls (administrative controls, environmental and engineering controls, and personal protection) must be given proper attention for the system to work effectively, and for the different levels to support each other.

1.3 Isolation practices for airborne infections

Airborne transmission occurs by dissemination of droplet nuclei over long distance from infectious patients (for more details on respiratory droplets, see Annex C). For pathogens to be disseminated via droplet nuclei, some requirements must be met, including:

- existence of viable pathogen inside the droplet at the source;
- survival of the pathogen inside the droplet after being expelled from the source, and retention of its ability to infect after exposure to physical challenges (evaporation, light, temperature, relative humidity, etc.);
- attainment of sufficient infective dose to cause infection in a susceptible host; and
- exposure of a susceptible host.

Infectious agents that may be dispersed over long distances by air currents and infect other susceptible individuals include *Mycobacterium tuberculosis* (Riley et al., 1957, 1959), rubeola virus (measles) (Bloch et al., 1985) and Varicella-zoster virus (chickenpox) (Gustafson et al., 1982). Preventing the spread of airborne infections involves implementing airborne precautions, which requires the three controls (see above in section 1.2): administrative controls; environmental and engineering controls — patient room with special air handling and ventilation; and PPE — the use of particulate respirators by health-care workers whenever possible (WHO, 2007).

Patients who require airborne isolation precautions should be placed in an airborne precaution room (WHO, 2007). An airborne precaution room is a room with ≥12 air changes per hour (ACH) (e.g. equivalent to ≥80 l/s for a 4×2×3 m^3 room) and controlled direction of airflow, and can be used to contain airborne infections (AIA, 2001; Wenzel, 2003; Mayhall, 2004; WHO, 2007). A mechanically ventilated room is equivalent to the airborne infection isolation room described by the United States Centers for Disease Control and Prevention, which should have special features in air handling and airflow direction, including (CDC, 2003):

- a negative pressure differential of ≥2.5 Pa (0.01-inch water gauge);
- an airflow differential >125-cfm (56 l/s) exhaust versus supply;
- clean-to-dirty airflow;
- sealing of the room, allowing approximately 0.5 square feet (0.046 m^2) leakage;
- ≥12 ACH for a new building, and ≥6 ACH in existing buildings (e.g. equivalent to 40 l/s for a 4×2×3 m^3 room) for an old building; and
- an exhaust to the outside, or a HEPA-filter if room air is recirculated.

The concept of natural ventilation for airborne precaution rooms was discussed in the recent World Health Organization interim guidelines (WHO, 2007). Natural ventilation can be used in airborne precaution rooms. The purpose of this document is to provide basic design guidance for the use of natural ventilation for infection control. More detailed "design guides" will follow the publication of this document.

1.4 Infection control for high-risk procedures

Airborne precautions were advised after the severe acute respiratory syndrome (SARS) epidemic for patients infected with open pulmonary tuberculosis, measles, smallpox and chickenpox. However, people also started to notice that there were situations in which other, non-airborne pathogens could be transmitted through droplet nuclei when patients had certain health-care procedures.

Presently, there is no clear definition or a precise list of high-risk health-care procedures during which some pathogens (e.g. SARS-Coronavirus, influenza) can be spread through droplet nuclei over short distances. The mechanism of this transmission is described as an opportunistic airborne transmission (Roy & Milton, 2004), and high-risk procedures may increase the potential of generating droplet nuclei because of the mechanical force of the procedure (Ip et al., 2007). Some of these procedures have been associated with a significant increase in the risk of disease transmission, and have been termed aerosol-generating procedures associated with pathogen transmission (WHO, 2007). These procedures include intubation, cardiopulmonary resuscitation, bronchoscopy, autopsy, and surgery where high-speed devices are used (WHO, 2007).

As in all areas of infection control, administrative controls, environmental and engineering controls plus the use of PPE should play a part in controlling the spread of infections during high-risk procedures.

For administrative control, it is critically important to limit these procedures to those patients who need them. Adequate staff training and the provision of safe equipment may also be important for reducing the risk. The proper use of PPE, including the use of particulate respirators, eye protection, gowns and gloves, will also provide additional protection to health-care workers. Finally, performing such procedures in a well-ventilated location, away from other patients and health-care workers, may help prevent the spread of infection. Although no studies have evaluated the impact of ventilation on reducing the risk of infectious droplet nuclei during aerosol-generating procedures, it would be best to perform these procedures in an adequately ventilated room, particularly for patients infected with known life-threatening pathogens (e.g. SARS, avian influenza).

However, it might be difficult to implement the measures stated above, especially during an emergency situation (e.g. resuscitating a collapsed patient in an outpatient department). Therefore, it is important to have in place contingency plans for such scenarios and have an emergency department that is appropriately equipped and well ventilated. Patients could then be moved rapidly to a safe location with good ventilation that is already identified for such purposes. Crowd control is also important to keep patients separate from other people. Appropriate PPE should be worn by health-care workers before starting the high-risk procedure.

1.5 Summary

In summary, although there is little evidence from studies to show an association between isolation precautions and infection control, reports and case studies indicate that some types of isolation (e.g. using private rooms and PPE) may help to prevent the spread of infection in health-care facilities.

All levels of control in an isolation system (administrative controls, environmental and engineering controls, and personal protection) are important, and should be taken into account when designing an isolation system in a hospital. Furthermore, isolation systems should be designed to prevent the spread of disease via respiratory droplets over long distances, with particular consideration paid to controlling transmission during high-risk health-care procedures (such as intubation, cardiopulmonary resuscitation, bronchoscopy, autopsy, and surgery where high-speed devices are used).

2 Concepts and types of ventilation

2.1 Ventilation

Ventilation moves outdoor air into a building or a room, and distributes the air within the building or room. The general purpose of ventilation in buildings is to provide healthy air for breathing by both diluting the pollutants originating in the building and removing the pollutants from it (Etheridge & Sandberg, 1996; Awbi, 2003).

Building ventilation has three basic elements:

- *ventilation rate* — the amount of outdoor air that is provided into the space, and the quality of the outdoor air (see Annex D);
- *airflow direction* — the overall airflow direction in a building, which should be from clean zones to dirty zones; and
- *air distribution or airflow pattern* — the external air should be delivered to each part of the space in an efficient manner and the airborne pollutants generated in each part of the space should also be removed in an efficient manner.

There are three methods that may be used to ventilate a building: natural, mechanical and hybrid (mixed-mode) ventilation.

2.1.1 What is natural ventilation?

Natural forces (e.g. winds and thermal buoyancy force due to indoor and outdoor air density differences) drive outdoor air through purpose-built, building envelope openings. Purpose-built openings include windows, doors, solar chimneys, wind towers and trickle ventilators. This natural ventilation of buildings depends on climate, building design and human behaviour.

2.1.2 What is mechanical ventilation?

Mechanical fans drive mechanical ventilation. Fans can either be installed directly in windows or walls, or installed in air ducts for supplying air into, or exhausting air from, a room.

The type of mechanical ventilation used depends on climate. For example, in warm and humid climates, infiltration may need to be minimized or prevented to reduce interstitial condensation (which occurs when warm, moist air from inside a building penetrates a wall, roof or floor and meets a cold surface). In these cases, a positive pressure mechanical ventilation system is often used. Conversely, in cold climates, exfiltration needs to be prevented to reduce interstitial condensation, and negative pressure ventilation is used. For a room with locally generated pollutants, such as a bathroom, toilet or kitchen, the negative pressure system is often used.

In a positive pressure system, the room is in positive pressure and the room air is leaked out through envelope leakages or other openings. In a negative pressure system, the room is in negative pressure, and the room air is compensated by "sucking" air from outside. A balanced mechanical ventilation system refers to the system where air supplies and exhausts have been tested and adjusted to meet design specifications. The room pressure may be maintained at either slightly positive or negative pressure, which is achieved by using slightly unequal supply or exhaust ventilation rates. For example, a slight negative room pressure is achieved by exhausting 10% more air than the supply in a cold climate to minimize the possibility of interstitial condensation. In an airborne precaution room for infection control, a minimum negative pressure of 2.5 Pa is often maintained relative to the corridor (CDC, 2003).

2.1.3 What is hybrid or mixed-mode ventilation?

Hybrid (mixed-mode) ventilation relies on natural driving forces to provide the desired (design) flow rate. It uses mechanical ventilation when the natural ventilation flow rate is too low (Heiselberg & Bjørn, 2002).

When natural ventilation alone is not suitable, exhaust fans (with adequate pre-testing and planning) can be installed to increase ventilation rates in rooms housing patients with airborne infection. However, this simple type of hybrid (mixed-mode) ventilation needs to be used with care. The fans should be installed where room air can be exhausted directly to the outdoor environment through either a wall or the roof. The size and number of exhaust fans depends on the targeted ventilation rate, and must be measured and tested before use.

Problems associated with the use of exhaust fans include installation difficulties (especially for large fans), noise (particularly from high-power fans), increased or decreased temperature in the room and the requirement for non-stop electricity supply. If the environment in the room causes thermal discomfort spot cooling or heating systems and ceiling fans may be added.

Another possibility is the installation of whirlybirds (whirligigs or wind turbines) that do not require electricity and provide a roof-exhaust system increasing airflow in a building (see Figure I.2 in Annex I).

2.2 Assessing ventilation performance

Ventilation performance in buildings can be evaluated from the following four aspects, corresponding to the three basic elements of ventilation discussed above.

- Does the system provide sufficient ventilation rate as required?
- Is the overall airflow direction in a building from clean to dirty zones (e.g. isolation rooms or areas of containment, such as a laboratory)?
- How efficient is the system in delivering the outdoor air to each location in the room?
- How efficient is the system in removing the airborne pollutants from each location in the room?

Two overall performance indices are often used. The air exchange efficiency indicates how efficiently the fresh air is being distributed in the room, while the ventilation effectiveness indicates how efficiently the airborne pollutant is being removed from the room. Engineers define the local mean age of air as the average time that the air takes to arrive at the point it first enters the room, and the room mean age of air as the average of the age of air at all points in the room (Etheridge & Sandberg, 1996). The age of air can be measured using tracer gas techniques (Etheridge & Sandberg, 1996).

The air exchange efficiency can be calculated from the air change per hour and the room mean age of air (Etheridge & Sandberg, 1996). For piston-type ventilation, the air exchange efficiency is 100%, while for fully mixing ventilation the air exchange efficiency is 50%. The air exchange efficiency for displacement ventilation is somewhere in between, but for short-circuiting the air exchange efficiency is less than 50%.

Ventilation effectiveness can be evaluated by either measurement or simulation (Etheridge & Sandberg, 1996). In simple terms, the ventilation flow rate can be measured by measuring how quickly injected tracer gas is decayed in a room, or by measuring the air velocity through ventilation openings or air ducts, as well as the flow area. The airflow direction may be visualized by smoke. Computational fluid dynamics and particle image velocimetry techniques allow the air distribution performance in a room to be modelled (Nielsen, 1974; Chen, 1996; Etheridge & Sandberg, 1996).

2.3 Comparison of mechanical and natural ventilation

2.3.1 Mechanical ventilation

If well designed, installed and maintained, there are a number of advantages to a mechanical system.

- Mechanical ventilation systems are considered to be reliable in delivering the designed flow rate, regardless of the impacts of variable wind and ambient temperature. As mechanical ventilation can be integrated easily into air-conditioning, the indoor air temperature and humidity can also be controlled.
- Filtration systems can be installed in mechanical ventilation so that harmful microorganisms, particulates, gases, odours and vapours can be removed.
- The airflow path in mechanical ventilation systems can be controlled, for instance allowing the air to flow from areas where there is a source (e.g. patient with an airborne infection), towards the areas free of susceptible individuals.
- Mechanical ventilation can work everywhere when electricity is available.

However, mechanical ventilation systems also have problems.

- Mechanical ventilation systems often do not work as expected, and normal operation may be interrupted for numerous reasons, including equipment failure, utility service interruption, poor design, poor maintenance or incorrect management (Dragan, 2000). If the system services a critical facility, and there is a need for continuous operation, all the equipment may have to be backed up — which can be expensive and unsustainable.
- Installation and particularly maintenance costs for the operation of a mechanicalventilation system may be very high. If a mechanical system cannot be properly installed or maintained due to shortage of funds, its performance will be compromised.

Because of these problems, mechanical ventilation systems may result in the spread of infectious diseases through health-care facilities, instead of being an important tool for infection control.

2.3.2 Natural ventilation

If well installed and maintained, there are several advantages of a natural ventilation system, compared with mechanical ventilation systems.

- Natural ventilation can generally provide a high ventilation rate more economically, due to the use of natural forces and large openings.
- Natural ventilation can be more energy efficient, particularly if heating is not required.
- Well-designed natural ventilation could be used to access higher levels of daylight.

From a technology point of view, natural ventilation may be classified into simple natural ventilation systems and high-tech natural ventilation systems. The latter are computer-controlled, and may be assisted by mechanical ventilation systems (i.e. hybrid or mixed-mode systems). High-tech natural ventilation may have the same limitations as mechanical ventilation systems; however, it also has the benefits of both mechanical and natural ventilation systems.

If properly designed, natural ventilation can be reliable, particularly when combined with a mechanical system using the hybrid (mixed-mode) ventilation principle, although some of these modern natural ventilation systems may be more expensive to construct and design than mechanical systems.

In general, the advantage of natural ventilation is its ability to provide a very high air-change rate at low cost, with a very simple system. Although the air-change rate can vary significantly, buildings with modern natural ventilation systems (that are designed and operated properly) can achieve very high air-change rates by natural forces, which can greatly exceed minimum ventilation requirements.

There are a number of drawbacks to a natural ventilation system.

- Natural ventilation is variable and depends on outside climatic conditions relative to the indoor environment. The two driving forces that generate the airflow rate (i.e. wind and temperature difference) vary stochastically. Natural ventilation may be difficult to control, with airflow being uncomfortably high in some locations and stagnant in others. There is a possibility of having a low air-change rate during certain unfavourable climate conditions.
- There can be difficulty in controlling the airflow direction due to the absence of a well-sustained negative pressure; contamination of corridors and adjacent rooms is therefore a risk.
- Natural ventilation precludes the use of particulate filters. Climate, security and cultural criteria may dictate that windows and vents remain closed; in these circumstances, ventilation rates may be much lower.
- Natural ventilation only works when natural forces are available; when a high ventilation rate is required, the requirement for the availability of natural forces is also correspondingly high.
- Natural ventilation systems often do not work as expected, and normal operation may be interrupted for numerous reasons, including windows or doors not open, equipment failure (if it is a high-tech system), utility service interruption (if it is a high-tech system), poor design, poor maintenance or incorrect management.
- Although the maintenance cost of simple natural ventilation systems can be very low, if a natural ventilation system cannot be installed properly or maintained due to a shortage of funds, its performance can be compromised, causing an increase in the risk of the transmission of airborne pathogens.

These difficulties can be overcome, for example, by using a better design or hybrid (mixed-mode) ventilation. Other possible drawbacks, such as noise, air pollution, insect vectors and security, also need to be considered. Because of these problems, natural ventilation systems may result in the spread of infectious diseases through health-care facilities, instead of being an important tool for infection control.

Table 2.1 summarizes the advantages and disadvantages of ventilation systems for hospitals.

Table 2.1 Summary of advantages and disadvantages of different types of ventilation systems for hospitals

	Mechanical ventilation	Natural ventilation	Hybrid (mixed-mode) ventilation
Advantages	Suitable for all climates and weather with air-conditioning as climate dictates	Suitable for warm and temperate climates — moderately useful with natural ventilation possible 50% of the time	Suitable for most climates and weather
	More controlled and comfortable environment	Lower capital, operational and maintenance costs for simple natural ventilation	Energy-saving
	Smaller range of control of environment by occupants	Capable of achieving high ventilation rate	More flexible
		Large range of control of environment by occupants	
Disadvantages	Expensive to install and maintain	Easily affected by outdoor climate and/or occupant's behaviour	May be expensive
	Reported failure rate in delivering the required outdoor ventilation rate	More difficult to predict, analyse and design	May be more difficult to design
	Potential for noise from equipment	Reduces comfort level of occupants when hot, humid or cold	
		Inability to establish negative pressure in isolation areas, but may be provided by proper design; depends on situation	
		Potential for noise intrusion	
		High-tech natural ventilation shares some of the limitations and disadvantages of mechanical ventilation	

2.4 Mechanical versus natural ventilation for infection control

The decision whether to use mechanical or natural ventilation for infection control should be based on needs, the availability of the resources and the cost of the system to provide the best control to counteract the risks.

For example, in the United Kingdom, the National Health Service policy tends to limit the adoption of mechanical ventilation to the principal medical treatment areas such as airborne infection isolation rooms, operating theatres and associated rooms. Patient wards are usually not required to be mechanically ventilated and natural ventilation through opening windows is usually the most common solution (Mills, 2004). Mills (2004) also states that "One of the major energy users in hospitals is air treatment. The low-energy hospital study identified this as an area for saving by naturally ventilating all 'non-clinical' areas, and current NHS guidance has adopted this conclusion." Conversely, in the American Society of Heating, Refrigerating and Air-Conditioning Engineers design guide (ASHRAE, 2007a, 2007b) all areas are required to be ventilated mechanically.

Mechanical ventilation is expensive to install and maintain in isolation rooms. It often does not deliver the recommended ventilation rate and may fail to maintain negative pressure (and may even be under positive pressure). For example, Pavelchak et al. (2000) evaluated 140 designated airborne infection isolation rooms in 38 facilities during 1992 to 1998 and found that unwanted directional airflow out of the patient room was observed in 38% of the facilities. Primary factors that were associated with the incorrect operation of the airborne infection isolation rooms included:

- ventilation systems not balanced (54% of failed rooms)
- shared anterooms (14%)
- turbulent airflow patterns (11%)
- automated control system inaccuracies (10%).

In addition, a number of problems related to the use of mechanical ventilation can arise from the lack of active collaboration between medical and technical personnel, which can also occur with natural ventilation. For example (ISIAQ, 2003):

- building repair, without adequate control, may adversely affect nearby areas with high cleanliness requirements;
- sophisticated and expensive ventilation systems are often not properly integrated into the building design, and then maintained, or even used; and
- medical staff often have poor knowledge of the intended operational performance of ventilation systems, even with regard to their protective functions; systems that were originally properly designed can be misused to the extent that the intended functionality is reduced, leading to increased risks.

Other problems with mechanical ventilation include the loss of negative pressure differential in isolation rooms due to the opening of the doors; clogged filters; and adjacent, negatively pressurized spaces (Fraser et al., 1993; Dahl et al., 1996; Sutton et al., 1998; Pavelchak et al., 2001; Rice, Streifel & Vesley, 2001).

In response to the 2003 severe acute respiratory syndrome (SARS) outbreak, the government of Hong Kong SAR constructed 558 SARS isolation rooms with more than 1300 beds in 14 hospitals. The negative pressure, airflow path, air-change rate and local ventilation effectiveness were measured in selected isolation rooms in nine major hospitals (Li et al. 2007). Of the 38 rooms tested, 97% met the recommended negative pressure difference of 2.5 Pa between corridor and anteroom; and 89% of the 38 rooms tested met the same requirement between anteroom and cubicle. Although no leakage of air to the corridor was found, 60% of the toilets/bathrooms were operated under positive pressure. More than 90% of the corridor–anteroom or anteroom–cubicle doors had a bi-directional flow when the door was open. Of the 35 cubicles tested, 26% had an air-change rate less than 12 air changes per hour (ACH).

Most of these problems can also occur with natural ventilation.

A comparative analysis of mechanical and natural ventilation systems looked at eight hospitals in Lima, Peru (Escombe et al., 2007). Five of the hospitals had an "old-fashioned" design (built before 1950) and three had a "modern" design (built from 1970 to 1990). Seventy naturally ventilated clinical rooms for infectious patients were studied. These rooms were compared with 12 mechanically ventilated, negative-pressure respiratory isolation rooms built after 2000. The analysis found that:

- opening windows and doors provided a median ventilation of 28 ACH — more than double the recommended 12 ACH in mechanically ventilated, negative-pressure rooms, but relies on correct door and window operation; none of the rooms were normally operated with windows and doors open; and
- facilities built more than 50 years ago, characterized by large windows and high ceilings (larger values of the volume to patient ratio), with windows and doors open, had greater ventilation than modern, naturally ventilated rooms (40 ACH versus 17 ACH).

However, these results should be used with caution. The ventilation rates in the analysis were reported without detailed information on climatic conditions, such as wind velocity and direction. The ventilation rate measurements were also affected by the carbon dioxide measurement device, and the fact that measurements were taken in buildings with multiple, inter-connected spaces, which would have affected the mixing conditions within the measured interior space.

2.5 Summary

The use of outdoor air for natural ventilation, combined with natural cooling techniques and the use of daylight, have been essential elements of architecture since ancient times and up to the first part of the 20th century (ASHRAE, 2007b). Classical architecture with H, L, T or U-shaped floor plans was used, together with open courts, limited plan depth and maximum windows sizes, to exploit natural ventilation and daylight. In recent times, natural ventilation has been largely replaced by mechanical ventilation systems in high- and middle-income countries. At first, full mechanical heating, ventilation and air-conditioning systems appeared to be able to solve all the practical problems of natural ventilation for year-round control of indoor environmental conditions.

However, mechanical ventilation also requires careful design, strict equipment maintenance, adoption of rigorous standards, and design guidelines that take into consideration all aspects of indoor environmental quality and energy efficiency (ASHRAE, 2007b). The same is also true for high-tech natural ventilation. Natural ventilation is not without its problems, particularly for facilities in countries where winters are cold. More work is needed to design low-cost and reliable ventilation systems for rooms that encourage rather than prevent the flow of air and yet allow internal temperature control.

It follows that natural and mechanical ventilation systems can, in practice, be equally effective for infection control. However, natural ventilation only works when natural forces are available, for example, winds or breezes, and when inlet and exhaust apertures are kept open. On the other hand, the difficulties involved in properly installing and maintaining a mechanical ventilation system may lead to a high concentration of infectious droplet nuclei and ultimately result in an increased risk of disease transmission.

In existing health-care facilities with natural ventilation, this system should be maximized where possible, before considering other ventilation systems. However, this depends on climatic conditions being favourable for its use.

3 Infection and ventilation

3.1 The association between ventilation and infection

There is little evidence that ventilation directly reduces the risk of disease transmission, but many studies suggest that insufficient ventilation increases disease transmission. A number of studies have looked at the possible transmission routes of diseases, but few have looked at the direct impact of ventilation on disease transmission.

Historically, the concept of airborne spread was first described by Wells (1934, 1955) and then by Riley & O'Grady (1961). The Wells–Riley equation (Riley, Murphy & Riley, 1978) was used to evaluate the effect of ventilation, filtration and other physical processes on transmission through droplet nuclei (Nardell et al., 1991; Fennelly & Nardell, 1998).

Detection of pathogens in room air and buildings may suggest a possible, indirect association between ventilation and disease transmission (Artenstein et al., 1967; Sawyer et al., 1994; Aintablian, Walpita & Sawyer, 1998; Mastorides et al., 1999; Suzuki et al., 2002, 2003; Booth et al., 2005; Chen & Li, 2008; Huynh et al., 2008). However, other aspects (e.g. necessary infecting dose, susceptibility of the host, infectivity of the pathogen, other environmental factors) are important for determining the ability of a pathogen to be transmitted. Therefore, data on presence of pathogens in the air does not provide the full evidence for disease transmission, and should be used in conjunction with other data (e.g. epidemiological data).

To develop this guideline, a systematic review of scientific literature up to June 2008 was used (see Annex A) to answer two questions.

1. Does ventilation rate (measured by air changes per hour — ACH — or flow rate in m^3/s) have an effect on decreasing (i) rates of infections or (ii) outbreaks of infectious diseases by agents that are transmitted by each of the modes of transmission listed in Table 3.1, in (a) patients, (b) health-care workers and/or (c) other caregivers such as household members? If yes, what ventilation rate has been associated with each infectious agent?
2. Does airflow or direction have an effect on decreasing (i) rates of infections or (ii) outbreaks of infectious diseases by agents that are transmitted by each of the modes of transmission in (a) patients, (b) health-care workers and/or (c) other caregivers such as household members? If yes, what conditions of airflow or direction have been associated with this?

Table 3.1 The scope and definitions of three transmission models for the systematic review

Mode of transmission	Definition	Examples of the agents
Airborne	Transmission of disease caused by dissemination of droplet nuclei that remain infectious when suspended in air over long distance (>1 m) and time. Airborne transmission can be further categorized into obligate or preferential airborne transmission. Obligate airborne transmission refers to pathogens that are transmitted only by deposition of droplet nuclei under natural conditions. Preferential airborne transmission refers to pathogens that can initiate infection by multiple routes, but are predominantly transmitted by droplet nuclei.	Pulmonary tuberculosis, measles, chickenpox
Opportunistic airborne	Transmission of droplet nuclei at short range during special circumstances, such as the performance of aerosol-generating procedures associated with pathogen transmission.	SARS-Coronavirus, influenza
Droplet	Droplets are generated from an infected (source) person primarily during coughing, sneezing and talking. Transmission occurs when these droplets, containing microorganisms, are propelled a short distance (usually <1 m).	Adenovirus, respiratory syncytial virus, influenza, SARS-Coronavirus

SARS, severe acute respiratory syndrome.

The final selected studies (*n* = 65) (see Annex A for a list of these studies) were included based on an association of ventilation rate or airflow direction with spread of certain infectious diseases. The diseases that showed a possible association between transmission among humans and ventilation were chickenpox (Gustafson et al., 1982), measles (Bloch et al., 1985), smallpox (Wehrle et al., 1970) and pulmonary tuberculosis (TB) (Hutton et al., 1990; Calder et al., 1991; Menzies et al., 2000). In this guideline, these four diseases are referred to as airborne diseases.

There were five main findings of the systematic review.

- Lack of ventilation or low ventilation rates are associated with increased infection rates or outbreaks of airborne diseases.
- High ventilation rates could decrease the risk of infection. For non-isolation rooms, ventilation rates lower than 2 ACH (e.g. equivalent to 13 l/s for a 4 × 2 × 3 m^3 room) are associated with higher tuberculin skin test conversion rates among staff. A higher ventilation rate is able to provide a higher dilution capability and consequently reduce the risk of airborne infections. For this reason, better ventilated areas have a lower risk of transmission of TB and other airborne infections. Annex D contains a more detailed explanation of how ventilation rates reduce the transmission of airborne infections.

- No information exists on the impact of ventilation rate on transmission of droplet-transmitted diseases. This agrees with the physics of droplet transmission, which shows that general ventilation should not affect large droplet transmission.
- The airflow from a contaminated source can lead to infection further away from the source. The rate of infection (attack) reduces as the physical distance from the source increases. One of the essential conditions for airflow-induced infection is that the airborne pathogen concentration in the source location must be sufficiently high (either due to high source strength or a low ventilation rate).
- Although there are not enough data to support this, it appears that the airflow from a contaminated source with sufficiently high dilution may not lead to further infection. No information is available on the exact amount of minimum dilution needed.

Despite more than 100 years of ventilation and infection study, the information is still sparse and incomplete. There are insufficient data to estimate minimum ventilation requirements in isolation rooms or in non-isolation areas in hospitals to prevent the spread of airborne infection. There are also insufficient data to estimate the minimum ventilation requirements in schools, offices and other non-hospital buildings to prevent the spread of airborne infection.

3.2 Ventilation requirements relating to airborne infection control

Central to the difficulties in developing ventilation guidelines for infection control is that there are not enough data to recommend a minimum ventilation flow rate for infection control against droplet nuclei. Ventilation can reduce the concentration of airborne pathogens through removing or diluting airborne droplet nuclei. A higher ventilation rate can provide a higher dilution capability and consequently potentially reduce the risk of airborne infections. In line with this assumption, Menzies et al. (2000) found that the tuberculin conversion among clinical personnel was significantly more rapid and frequent among those working in average ventilation lower than 2 ACH. A higher ventilation rate can dilute the contaminated air inside a space more rapidly than a lower ventilation rate, and can also decrease the risk of transmission of infectious droplet nuclei to individuals in the space. However, the maximum ventilation rate (above which there is no further reduction of infection risk) is not known. The choice of the minimum ventilation flow rate may be influenced by the need to reduce energy consumption (because higher ventilation rates have a higher energy cost for mechanical ventilation).

In this guideline, the rationale for determining the minimum ventilation rate requirements is based on two main aspects (see Annex E):

- the effect of air-change rate on decay of droplet nuclei concentration; and
- mathematical modelling of risk using the Wells–Riley equation to estimate the effect of ventilation rate on infection risk for known airborne diseases.

These underlying principles indicate that the higher the ventilation rate, the more rapid the decay of particles (e.g. droplet nuclei) in the room air. Also, according to the Wells–Riley equation, the probability of infection through infectious droplet nuclei is inversely correlated to the ventilation rate. The parameters used in the Wells–Riley equation include ventilation rate, generation of droplet nuclei from the source (quanta/minute) and duration of exposure

$$P = \frac{D}{S} = 1 - \exp\left(-\frac{Ipqt}{Q}\right)$$

where:

P = probability of infection for susceptibles
D = number of disease cases
S = number of susceptibles
I = number of infectors
p = breathing rate per person (m^3/s)
q = quantum generation rate by an infected person (quanta/s)
t = total exposure time (s)
Q = outdoor air supply rate (m^3/s).

Based on this model, in situations of high quanta production (e.g. high-risk, aerosol-generating procedures), the estimated probability of infection with 15 minutes of exposure in a room with 12 ACH would be below 5% (see Annex E for more details).

When ACH is used to measure ventilation performance, the volume of the enclosed room is clearly an important parameter. For a given ACH, a ward with a larger volume can provide a larger airflow rate (m^3/h or l/s) than a room with a smaller volume.

In some existing guidelines of mechanical isolation rooms (CDC, 2003), a minimum negative pressure needs to be maintained while the minimum ventilation rate is ≥12 ACH. As discussed, a major disadvantage of natural ventilation is the difficulty in achieving a consistent airflow direction, and major fluctuations may occur. Although negative pressure is difficult to achieve with natural ventilation, if dilution is sufficient, air being emitted to the open air presents a minimal risk.

Still, the choice of airborne precaution areas and the placement of patients within the areas need to be planned and designed carefully, so as to further reduce the risk of infection for people in the surrounding areas.

Based on the discussions above, the World Health Organization makes the recommendations contained in section 3.3, below.

3.3 World Health Organization recommendations relating to natural ventilation requirements

Please see the explanations for the overall ranking (i.e. strong versus conditional recommendation) of the recommendations in the respective appraisal tables in Annex B.

1. To help prevent airborne infections, adequate ventilation in health-care facilities in all patient-care areas is necessary (Gustafson et al., 1982; Bloch et al., 1985; Hutton et al. 1990; Calder et al. 1991).

Strong recommendation

Remarks: There is moderate evidence available to suggest that insufficient ventilation is associated with an increase of infection risk and favours the use of ventilation for airborne infection control.

2. For natural ventilation, the following minimum hourly averaged ventilation rates should be provided:
   - 160 l/s/patient (hourly average ventilation rate) for airborne precaution rooms (with a minimum of 80 l/s/patient) (note that this only applies to new health-care facilities and major renovations);
   - 60 l/s/patient for general wards and outpatient departments; and
   - 2.5 $l/s/m^3$ for corridors and other transient spaces without a fixed number of patients; however, when patient care is undertaken in corridors during emergency or other situations, the same ventilation rate requirements for airborne precaution rooms or general wards will apply.

The design must take into account fluctuations in ventilation rate.

When natural ventilation alone cannot satisfy the recommended ventilation requirements, alternative ventilation systems, such as a hybrid (mixed-mode) natural ventilation system, should be considered, and then if that is not enough, mechanical ventilation should be used.

Conditional recommendation

Remarks: The application of natural ventilation depends on climatic conditions being favourable.

3. When designing naturally ventilated health-care facilities, overall airflow should bring the air from the agent sources to areas where there is sufficient dilution, and preferably to the outdoors (Gustafson et al., 1982; Bloch et al., 1985; Hutton et al. 1990; Calder et al. 1991).

Conditional recommendation

Remarks: Despite some evidence suggesting a possible association of airflow direction with spread of airborne infections, such spread was observed at a very low (lower than 4 ACH) ventilation rate (Bloch et al., 1985). It is hypothesized that if the ventilation rate in adjacent spaces is sufficiently high, the risk would be very low to minimal (e.g. as in an open space). However, the precise ventilation rate required in closed spaces adjacent to airborne precaution rooms to reduce the risk of spread is not known. The application of natural ventilation depends on climatic conditions being favourable.

4. For spaces where aerosol-generating procedures associated with pathogen transmission are conducted, the natural ventilation requirement should, as a minimum, follow Recommendation 2. Should the agent be airborne, Recommendations 2 and 3 should be followed.

Conditional recommendation

Remarks: There is indirect evidence to show that some aerosol-generating procedures are associated with an increased risk of infection. Ventilation may play a role, but the minimum ventilation requirements for aerosol-generating procedures deserve further investigation.

3.3.1 Explanation of the World Health Organization recommendations

This guideline recognizes that the current epidemiological evidence of the association between ventilation rate and airborne infection is weak, but appreciates the importance of ventilation from both a theoretical point of view and the current practice in airborne isolation.

The guideline also recognizes the three major disadvantages of natural ventilation: fluctuation of the ventilation rate due to variable driving forces, the difficulty in achieving a consistent airflow direction and a comfortable internal temperature in extreme climates.

Although more research is needed on the effects of ventilation rate on infection risk, the currently recommended mechanical ventilation rate of ≥12 ACH for airborne isolation rooms (CDC, 2003, 2005) is adopted as a reference. Possible rationales (which do not have supporting evidence) for determining the minimum ventilation rate requirements are explained in Annex E. We also suggest that if natural ventilation is used for infection control, the minimum ventilation rate should be higher than the existing requirement for mechanical ventilation to compensate for the expected fluctuations in ventilation rate and difficulties in controlling airflow direction.

This guideline suggests the use of the volume of the room, the ventilation rate (litre per second per patient or l/s/patient or l/s/p) rather than air changes per hour (ACH) rate, although air-change rate is used commonly in other guidelines. The use of ventilation rate (l/s/patient) recognizes the direct link between exposure level and ventilation rate, as well as the direct association with the number of patients the space is designed to hold. However, for corridors and other spaces without a fixed number of patients, the ventilation rate is based on the volume of the space.

Other documents recommend 12 ACH for an airborne precaution room, which is equivalent to, for example, 80 l/s/patient in a $4 \times 2 \times 3$ m^3 room. This guideline recommends double this ventilation rate for naturally ventilated airborne precaution rooms. Therefore, for a room with similar volume, an hourly averaged ventilation rate of 160 l/s/patient is recommended. At the same time, the guideline also recommends a minimum ventilation rate of 80 l/s/patient at all times.

Refer to Annex B for factors considered in the appraisal of specific recommendations.

3.3.2 Review and assessment of recommendations

The recommended requirements of natural ventilation for infection control will need to be reviewed and updated once new data on the impact of ventilation are available.

The recommendations were developed by the systematic review external panel using the GRADE appraisal system during its meeting in Geneva in November 2008 (see Annex B).

Recommendation 1 was based mainly on the studies of Gustafson et al. (1982) (chickenpox), Bloch et al. (1985) (measles), Hutton et al. (1990) (TB) and Calder et al. (1991) (TB). These studies provided evidence of an association of ventilation with the spread of certain infectious diseases. Lack of ventilation or low ventilation rates were associated with an increase of infection rates or disease outbreak for either airborne transmission or opportunistic airborne transmission.

Recommendation 2 was based mainly on the studies of Menzies et al. (2000) and Bloch et al. (1985), which provided evidence of an association between low ventilation rate (lower than 2 ACH) and the spread of TB (Menzies et al., 2000) and measles (Bloch et al., 1985). These studies suggest an association of airflow direction with the spread of airborne infectious diseases.

For Recommendation 4, no study providing evidence of association between ventilation features and infection due to aerosol-generating procedures was found. However, there is indirect evidence to show that some aerosol-generating procedures are associated with an increased risk of infection.

3.4 Summary

The design of proper, general ventilation systems can play an important role in preventing the spread of infections. Patients with infectious diseases that spread easily through air (e.g. chickenpox, measles, tuberculosis) should be placed in airborne precaution rooms. However, there is often a delay between admission of these patients to the health-care facility, and the diagnosis of their infectious disease. Disease transmission to other patients or staff can occur while these patients are waiting in common areas (e.g. waiting room, emergency departments). Paying more attention to ventilation requirements in these common, non-isolation spaces could lead to significant infection-control benefits.

However, the strategies for disease control and prevention involve the assessment of threats and resources, and then applying appropriate administrative controls, environmental and other engineering controls, and PPE, in conjunction with using a suitable ventilation system.

Part 2 — Designing for natural ventilation

Part 2 provides an introduction to the basic elements of design for natural ventilation for infection control. This guideline focuses only on basic principles that will be expanded in a follow-up World Health Organization project.

The follow-up design project will build on the introduction provided in this guideline, and is aimed principally at providing the means with which to adapt health-care facilities to natural ventilation, thereby maximising outbreak preparedness while minimising costs and emissions. It is based on the premise that clear and well thought-out design guidance can assist health authorities, particularly in low-income countries. Such guidance will be available for download from a web page free of charge. By providing sound design advice, a relatively small investment in financial and staffing terms can achieve far-reaching results in areas of critical global significance.

Readers are reminded that naturally ventilated health-care facilities, or airborne precaution rooms, need to be properly designed if they are to function as intended.

4 Understanding natural ventilation

4.1 The driving forces of natural ventilation

Three forces can move the air inside buildings:

- wind pressure
- stack pressure (buoyancy)
- mechanical force.

The first two forces are explained in the following sections. Natural forces drive natural ventilation, while mechanical fans drive mechanical ventilation. Mechanical force can be combined with natural forces in a hybrid, or mixed-mode, ventilation system.

4.1.1 Wind pressure

When wind strikes a building, it induces a positive pressure on the windward face and negative pressure on the leeward face. This drives the air to flow through windward openings into the building to the low-pressure openings at the leeward face (see Figure 4.1). It is possible to estimate the wind pressures for simple buildings. Wind flows around buildings are complex and the subject of a number of textbooks, for example Aynsley, Melbourne & Vickery (1977) and Liu (1991).

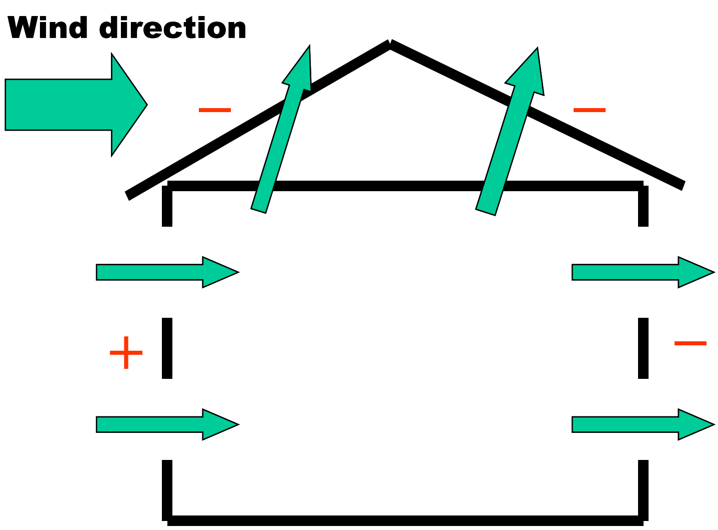


Figure 4.1 Wind-induced flow directions in a building

For single-sided ventilation with the rooms otherwise hermetically sealed, there is no contribution from mean wind pressures, only from the fluctuating components (see Figure 4.2). Etheridge & Sandberg (1996) covered the topic of unsteady pressures in some detail. This is a common design; however, over time, there becomes significant leakage around doors and other room penetrations. It must be remembered that just because a window is open, sufficient air changes per hour (ACH) may not necessarily be achieved.

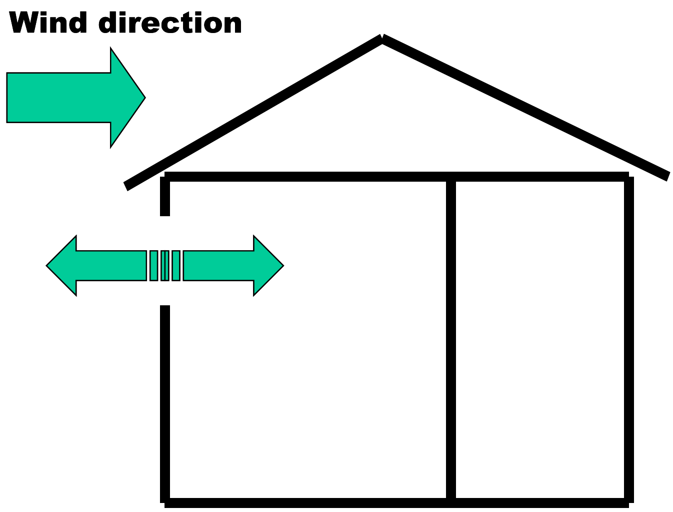


Figure 4.2 Fluctuating components contributing to single-sided airflow

The wind pressure generated on a building surface is expressed as the pressure difference between the total pressure on the point and the atmospheric static pressure. Wind pressure data can usually be obtained in wind tunnels by using scale models of buildings. If the shape of the building, its surrounding condition and wind direction are the same, the wind pressure is proportional to the square of outdoor wind speed. Thus, the wind pressure is usually standardized by being divided by the dynamic pressure of the outdoor wind speed. The standardized wind pressure is called the wind pressure coefficient and symbolized as C_p. The outdoor wind speed is usually measured at the height of the eave of the building in the wind tunnel:

$$C_p = \frac{P_T - P_{AS}}{\frac{1}{2}\rho V_H^2}$$

where:

C_p = wind pressure coefficient (–)
P_T = total pressure (Pa)
P_{AS} = atmospheric static pressure at the building height (Pa)
ρ = density of air (kg/m^3)
V_H = wind velocity at a remote site from surrounding influences at the building height (m/s).

4.1.2 Stack (or buoyancy) pressure

Stack (or buoyancy) pressure is generated from the air temperature or humidity difference (sometimes defined as density difference) between indoor and outdoor air. This difference generates an imbalance in the pressure gradients of the interior and exterior air columns, causing a vertical pressure difference.

When the room air is warmer than the outside air, the room air is less dense and rises. Air enters the building through lower openings and escapes from upper openings.

The flow direction reverses, to a lesser degree, when the room air is colder than the outside air; the room air is denser than the outside air. Air enters the building through the upper openings and escapes through the lower openings.

Stack (or buoyancy) driven flows in a building are driven by indoor and outdoor temperatures. The ventilation rate through a stack is a function of the pressure differential between the two openings of that stack.

Pressure differential can be calculated as follows:

$$\Delta P_s = (\rho_o - \rho_i) g H = \rho_o g H \frac{T_i - T_o}{T_o}$$

where:

P_s = stack (or buoyancy) pressure (Pa)
ρ_o = density of outdoor air (kg/m^3)
ρ_i = density of indoor air (kg/m^3)
g = gravity acceleration (9.8 m/s^2)
H = height between two openings (m)
T_i = indoor air temperature (^{o}K)
T_o = outdoor air temperature (^{o}K).

4.2 Ventilation flow rate

As a rule of thumb, wind-driven natural ventilation rate through a room with two opposite openings (e.g. a window and a door) can be calculated as follows:

$$\text{ACH} = \frac{0.65 \times \text{wind speed (m/s)} \times \text{smallest opening area (m}^2) \times 3600 \text{ s/h}}{\text{room volume (m}^3)}$$

Ventilation rate (l/s) = 0.65 × wind speed (m/s) × smallest opening area (m^2) × 1000 l/m^3

Table 4.1 provides estimates of the ACH and ventilation rate due to wind alone, at a wind speed of 1 m/s, assuming a ward of size 7 m (length) × 6 m (width) × 3 m (height), with a window of 1.5 × 2 m^2 and a door of 1 m^2 × 2 m^2 (smallest opening).

Table 4.1 Estimated air changes per hour and ventilation rate for a 7 m × 6 m × 3 m ward

Openings	ACH	Ventilation rate (l/s)
Open window (100%) + open door	37	1300
Open window (50%) + open door	28	975
Open window (100%) + closed door	4.2	150

The wind speed refers to the value at the building height at a site sufficiently away from the building without any obstructions (e.g. at an airport).

For stack (or buoyancy) natural ventilation, the ACH can be calculated as:

$$\text{Air changes per hour (ACH)} = \frac{0.15 \times \text{smallest opening area}\,(m^2) \times 3600\ \text{s/h} \times \sqrt{(\text{indoor} - \text{outdoor air temperature}\ (^{\circ}\text{K})) \times \text{stack height (m)}}}{\text{room volume}\,(m^3)}$$

$$\text{Ventilation rate (l/s)} = 0.15\ \text{x}\ 1000\ \text{l/m}^3 \times \text{smallest opening area}\,(m^2) \times \sqrt{(\text{indoor} - \text{outdoor air temperature}\ (^{\circ}\text{K})) \times \text{stack height (m)}}$$

Advanced design tools for both analysis and opening sizing are also available (CIBSE, 2005).

4.3 Summary

Before designing a purely natural ventilation system, designers need to understand the main driving forces of natural ventilation — wind pressure and stack (or buoyancy) pressure. These forces control how air moves within and through a building, and they can be combined, as needed, to design an optimal natural ventilation system.

5 Design and operation

5.1 Designs for natural ventilation and hybrid ventilation systems

This section outlines the main design categories of natural ventilation and hybrid (mixed-mode) ventilation systems.

5.1.1 Natural ventilation systems

As previously defined, natural ventilation is the use of natural forces to introduce and distribute outdoor air into or out of a building. These natural forces can be wind pressures or pressure generated by the density difference between indoor and outdoor air.

There are four design methods available for natural ventilation systems:

- *cross flow* (no corridor) — the simplest natural ventilation system with no obstacles on either side of the prevailing wind (i.e. windows of similar size and geometry open on opposite sides of the building);
- *wind tower* (wind catcher/wind extractor) — the positive-pressure side of the wind tower acts as a wind catcher and the negative-pressure side of the wind tower acts as a wind extractor;
- *stack* (or buoyancy), simple flue — a vertical stack from each room, without any interconnections goes through the roof; this allows for air movement based on density gradients; and
- *stack* (or buoyancy), solar atrium — a large stack that heats due to solar radiant loading, which induces air movement due to density (temperature) differentials; without radiant loading, the atrium provides minimal ventilation.

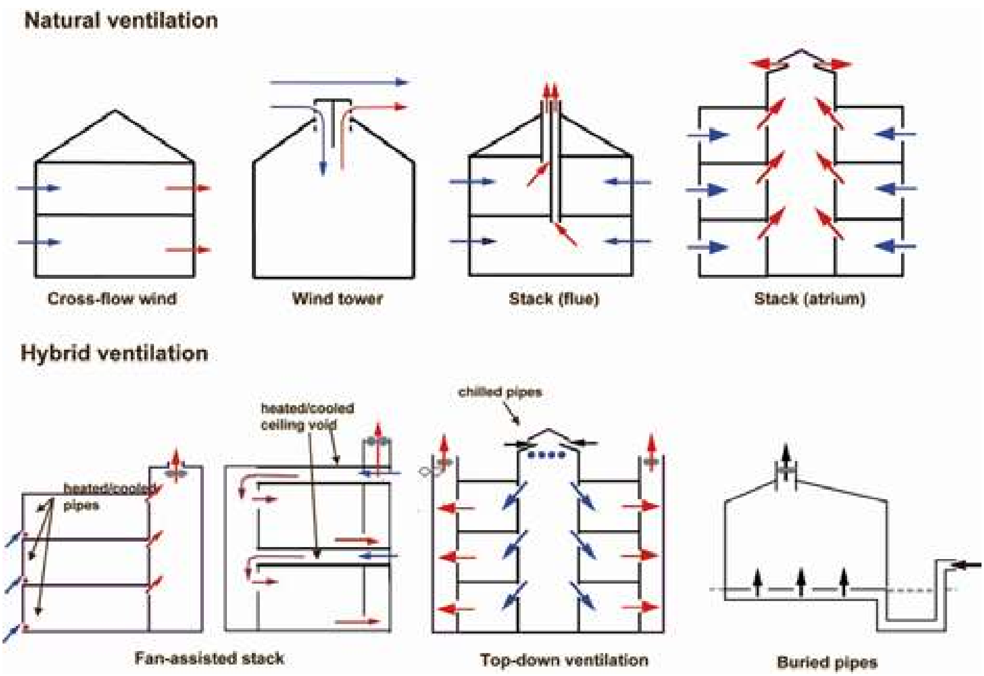
5.1.2 Hybrid (mixed-mode) ventilation systems

As previously defined, hybrid (mixed-mode) ventilation relies on natural driving forces to provide the desired (design) flow rate. It uses mechanical ventilation when the flow rate is lower than that required to produce natural ventilation.

Three design methods are available for hybrid ventilation systems.

- *Fan-assisted stack* — when there is insufficient solar radiant loading on the stack (i.e. evenings and inclement days) the ventilation rate is supplemented by extraction fans. Inlet air is heated and cooled to maintain comfort for building occupants.
- *Top-down ventilation* (fan-assisted stack plus a wind tower) — when there is insufficient solar radiant loading on the stack (i.e. evenings and inclement days) the exhaust ventilation rate is supplemented by extraction fans while the supply ventilation rate is supplemented by the wind tower (wind scoop). Inlet air is heated and cooled to maintain comfort for building occupants.
- *Buried pipes* — when land is available, ventilation pipes (ducts) can be buried. If air remains underground for long enough, the air will approach the steady-state underground temperature (i.e. warming or cooling the outside air). This system is not ideal for high ventilation rates.

Figure 5.1 illustrates the different systems of natural and hybrid ventilation.



Source: Courtesy of Professor Martin Liddament, VEETECH, Coventry, UK.

Figure 5.1 Different natural ventilation and hybrid ventilation systems

5.2 Basic design concepts for natural ventilation

Developing the design concept for a naturally ventilated building that incorporates infection control involves three basic steps, described in more detail in section 5.4.

1. Specify the desired airflow pattern from the inlet openings to the outlet openings.
2. Identify the main available driving forces that allow the desired airflow pattern to be achieved.
3. Size and locate the openings so that the required ventilation rates can be delivered under all operating regimes.

A general procedure for natural ventilation starts from the architectural design, system layout and component selection, vent sizing and design-control strategy. The procedure is concluded by detailed design drawing.

Converting an existing building or designing a new building to use natural ventilation for controlling airborne infection would, ideally, include the presence of single-bedded isolation rooms with operable windows and ensuite toilets. However, in resource-poor contexts, the number of such isolation rooms may need to be limited, with additional cohort isolation being provided, when necessary, by contingency facilities (e.g. outdoor isolation tents open to the wind).

There is a need to develop effective and appropriate engineering technologies and innovative architectural features to maximize the use of natural ventilation for different climatic conditions worldwide.

Unlike other types of buildings, when the prevailing wind direction and average velocity may be used, the design of natural ventilation for infection control should consider the worst situation — that is, when the wind is absent, and where supplementary mechanical ventilation may be needed.

5.3 Climatic and other considerations in ventilation design

A number of factors need to be considered when designing a building to effectively use natural ventilation for infection control.

High air-change rates are needed when infection control is the main building design objective. The impacts of the high air-change rates on the overall indoor environmental conditions should be considered; these include thermal comfort, indoor air quality and fire safety. Other likely unfavourable ambient environmental factors such as noise and air pollution, and their impacts on indoor environmental quality have to be assessed before building design starts. In cold climates, the need for warmth inside the building can be at odds with the high air-change rate needed for infection control. In transient seasons of hot and humid climates, moisture condensation in the ward interior can lead to wet beddings and floors, rainy ceilings, and mould and mildew growth — resulting in unpleasant and unhealthy conditions. However, large openings in the building envelope make it easier for insects, wild animals and other unwanted intruders, and may also cause problems relating to security and vector-borne infectious disease control.

5.3.1 Maintaining thermal comfort

In temperate and warm climates and under good ambient air quality conditions, a higher ventilation rate is good for both thermal comfort and indoor air quality. However, this is not true for cold climates where outdoor air infiltration should be minimized for thermal comfort. When the ambient air temperature stays above 30 °C, the thermal conditions in a naturally ventilated ward may become intolerable. Therefore, in a naturally ventilated building, more effort needs to be spent on the architectural and envelope design to achieve acceptable indoor thermal comfort than for a building with mechanical ventilation. This includes the selection of windows, proper external shading, envelope insulation and the properties of external surface materials with regard to solar absorption and thermal radiation. A design engineer must also understand that a final design is a compromise between the conflicting requirements in hot summer and cold winter conditions. Thermal performance simulation tools are available to help quantitatively assess and compare theeffectiveness of different design options. A more detailed explanation of the technology options and simulation techniques are provided in ASHRAE (2009).

5.3.2 Considerations for hot summers

Architectural design features

When the land area allows, active use of ground-to-sky radiation will greatly reduce the effective radiant temperature. Semi-open architectural design is preferred, and should allow direct long-wave radiation from ground to sky to occur. The semi-opening should be on the shade side of a building to avoid direct solar irradiation — this is how a sunshade works (see Figure 5.2).

Solar heat gain should be minimized by using proper external shading or the more sophisticated glazing systems. The buoyancy effects of the solar heat on airflow can be used to lead the warm air to the higher levels of the building. Fortunately, this is in line with the desired airflow patterns for infection control.

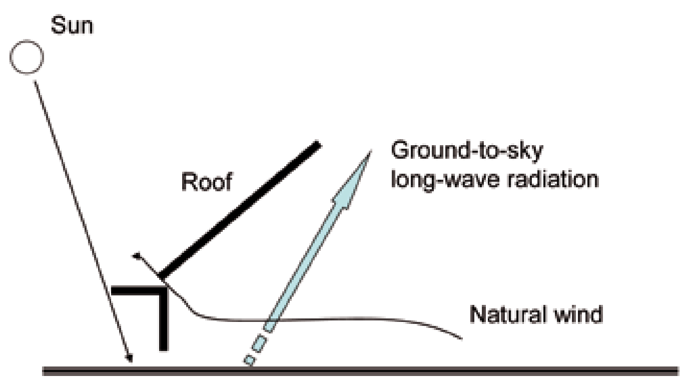


Figure 5.2 Semi-open design allowing ground-to-sky thermal radiation can greatly improve the thermal comfort in hot summer

Low-energy mechanical cooling

A high air change rate may be favourable for thermal comfort in cold weather; however, on muggy and calm days, high air change would make conditions uncomfortable. In low-wind conditions, air change that is caused by buoyancy may not generate enough internal air movement.

Mechanical cooling fans

In addition to hybrid (mixed-mode) ventilation systems, air movement can be improved using electric cooling fans — although improving air movement by introducing an artificial "breeze" does not necessarily increase the air-change rate.

ASHRAE (2009) provides design guides that use the widely accepted predicted mean vote (PMV) model, which takes into account the air temperature, radiant temperature, air velocity, clothing level and people's activity level. Designers can use the PMV model to estimate the raised air velocity required at higher air temperatures. When the temperature is below 30 ºC, acceptable thermal comfort can be achieved using elevated air speed (Xia et al., 2000). Temperatures above 30 ºC will inevitably cause thermal stress in the building's occupants.

Cooling fans with multiple speeds should be used, and people should be able to adjust the fan speed as needed. Using fans in this way greatly reduces energy consumption, compared with air-conditioning.

On hotter days when air temperature is above 30 ºC, using a cooling fan only would not be sufficient to keep the building cool enough for occupants. Instead, a low-cost evaporative cooling method can be used — and is particularly useful when there is a high air-change rate. This strategy also has a relatively low cost, compared with a full air-conditioning system (Zhang et al., 2000).

5.3.3 Considerations for winter

In cold winter conditions, a high air-change rate is not desirable for thermal comfort, particularly as windows may be closed to keep the building warm. Even if normal heating is introduced, with a high air-change rate the effects might be insignificant, and energy efficiency will be low. Therefore, heating strategies must be planned carefully. Building envelope design should be able to capture the solar heat and minimize conduction loss through the wall. Proper insulation of walls and the use of double glazing are desirable. For extremely cold climates, a rigorous assessment using simulation techniques should be undertaken, so that the degree of coldness can be quantified. This can be used to determine whether the natural ventilation strategy could be adopted for the climate being considered.

When considering active heating strategies, targeted radiant or direct near-body heating methods are more effective, and are preferred for two reasons. First, due to buoyancy effects, the warm air from the common convective radiators tends to float to the upper part of a space. Second, at a high air-change rate, the heat loss is tremendous. Modern, electric radiant heaters are readily available, and are a better option than other commonly used electric radiators.

Electrically heated mattresses are also available and typically use about 50–100 watts. They are effective for in-bed patients, and may allow patients to tolerate much lower in-ward air temperatures associated with the high air-change rate. They also help to avoid the excessive energy consumption associated with the ordinary space-heating methods.

5.3.4 Maintaining healthy indoor air quality

With a higher air-change rate, the indoor air quality is more linked to the ambient air quality. The benefit is that the indoor air quality is less likely to be affected by the presence of common indoor pollutant sources, such as the off-gassing from common building materials.

5.3.5 Managing ambient air pollution

With the high air-change rate of untreated outdoor air, indoor air quality will be more affected by the ambient air pollution (Weschler & Shields, 2000; Ghiaus et al., 2005). In regions with severe ambient air pollution problems, the location of an infectious disease hospital should be chosen carefully. A hybrid (mixed-mode) ventilation design may be the only option. Solely relying on ordinary window openings will expose the occupants to a high ambient pollutants level.

5.3.6 External noise

As pointed out in CIBSE (2005), the presence of significant noise sources is one of the main barriers to using natural ventilation. However, this guideline recommends two solutions: one is to place the ventilation inlets on the sides of the building away from the principal noise sources; the other is to integrate acoustic baffles into the ventilation opening. However, this second solution will reduce the air-change rate, and is therefore best combined with hybrid (mixed-mode) ventilation where a mechanical fan can avoid the increased pressure loss over such a vent.

5.3.7 Selecting low-emission interior materials

A comprehensive understanding of air pollutant emissions from interior building materials has developed over the years (Levin, 1989; Li & Niu, 2007). Designers and contractors should be aware of the standards and regulations on building materials for indoor use. In particular, materials that can potentially release airborne respiratory-tract irritants should be avoided.

5.3.8 Humidity and mould growth

Condensation can occur on ceilings, walls, floors and beddings for many reasons. For example, in buildings with a heavy structure and that use natural ventilation, a sudden change of weather with warm, moist ambient air may induce condensation when the surface temperature is lower than the dew-point temperature of the moist incoming air (Niu, 2001). While the conditions are a discomfort and annoyance during the condensation period, mould may also grow — which is a health hazard.

When designing buildings with natural ventilation for a hot and humid climate, lightweight and insulated walls should be used. The surface temperature of a lightweight construction or a wall with internal insulation will respond rapidly to changes in air temperature, limiting the rise of surface and internal relative humidity when the sudden warm and humid air comes in contact with the wall (e.g. in the transient spring season).

For existing buildings with massive concrete or masonry walls, several retrofitting, operation and maintenance strategies may be needed if a natural ventilation strategy is to be adopted. The first option would involve the interior surface treatment, which can either be long term or short term.

5.3.9 Security and vector-borne disease spread

Large openings in natural ventilation without any protection increase the risk of security breaches and the spread of vector-borne diseases. Purpose-designed barred windows and semi-transparent mosquito meshes can be used in these situations.

5.3.10 High-rise considerations

Locating respiratory wards on the top floors may be desirable for high-rise buildings to minimize the possible re-entry of the exhausts into adjacent floors. This re-entry is caused by buoyancy as the exhaust air is normally warm and tends to flow upwards after leaving the wards (Wehrle et al., 1970).

5.3.11 Fire safety considerations

Designing a building with openings connecting rooms may conflict with fire-safety and smoke-control requirements. Naturally ventilated buildings may also be zoned to be in line with the compartmentalization requirements for smoke control. Ventilation openings may also be shut during a fire. The fire escape route also needs special attention, because natural ventilation design also has an impact on smoke flow pattern.

5.4 Designing for natural and hybrid ventilation systems

When developing the design concept for a naturally ventilated building for infection control, three basic steps are involved.

1. Specify the desired airflow pattern from the inlet openings, through the wards and other hospital spaces such as corridors, to the outlet openings. This is associated with the form (single corridor, central corridor, courtyard, etc.) and organization (relative location of the nursing station, offices, storage, etc.) of the building, which in turn depends on its intended use and site conditions, such as prevailing winds.
2. Identify the main available driving forces that enable the desired airflow pattern to be achieved. The effective strategies for infection control tend to be mostly wind driven, although the stack-driven strategy may also work if designed properly. A combined wind-driven and stack-driven flow needs to be considered where necessary and feasible. In some cases, hybrid (mixed-mode) ventilation may be used and these natural forces can be supplemented by fans. In a good design, the available dominating driving forces are in synergy with the intended flow pattern.
3. Size and locate the openings so that the required ventilation rates can be delivered under all operating regimes. This is, in itself, a three-step process. First, the ventilation rates need to be determined based on the infection control requirements as specified in Part 1 of this document. Second, the openings need to be sized and located to deliver these airflow rates under design conditions. Third, a control system needs to be designed to maintain the required flow rates under varying weather and occupancy conditions.

A general procedure for natural ventilation design includes several components.

- *Architectural design* — architects and engineers must initially set the global geometric configuration of the system (e.g. siting of the building and landscape configuration, overall building form, and approximate positions of fresh air inlets and air exhausts), considering both dominant and prevailing wind conditions, as well as unusual conditions by time of day and season.
- *System layout and component selection* — the designer will then lay out the airflow paths from inlet to outlet that will achieve the desired airflow objective (e.g. for the purpose of infection control and thermal comfort) and then select the types of airflow components (e.g. windows, doors, vents, solar chimneys) that will provide the desired control of airflow.
- *Opening (door, window, vent etc) size* — the designer will then size the components selected considering the ventilation requirements and relevant climatic conditions. Both the indoor and outdoor design conditions (or design criteria) need to be considered.
- *Design control strategy* — the designer must then develop a strategy for controlling ventilation flow to the design objectives when the operating conditions vary. At this stage, both hardware and software for control may need to be chosen to implement the control strategy if a high-tech natural ventilation strategy is used.
- *Detailed design drawing* — finally, the designer must develop detailed drawings so that the systems can be built.

5.4.1 Vent sizing

Vent sizing refers to the process of estimating the area of openings to achieve the required ventilation flow rates based on certain geometry, climate and other data of the building design. The sizing of openings is also a function of the opening distribution, which is a part of the ventilation strategy.

There are two methods for estimating the size of the vents required.

- *Direct methods* are derived for simple buildings where the ventilation flow rate is a simple function of the governing parameters. Allard (1998) discussed five of these methods.
- *Indirect methods* use network models to try different opening size combinations and identify the best one. One promising design method is the loop pressure equation-based method suggested by Axley (1998).

After the necessary ventilation flow rates in each zone of a building are estimated, these methods can be used to design the main flow paths and size ventilation openings to satisfy ventilation requirements in each zone. When designing large buildings, designers might also need to know different design options, how natural ventilation compares with mechanical systems, etc.

When a building is designed and operated with a configuration of openings and flow paths, the ventilation flow rate will mostly be determined by the available natural driving forces. At the design stage, it is important to harness the prevailing winds and to enhance and control stack (or buoyancy) forces in the building. This can be done by carefully positioning and sizing the openings, and by innovative use of devices to increase natural forces, such as wind towers and solar chimneys.

Transient high ventilation allowances

Allowing a transient ventilation rate that is much higher than the minimum ventilation rate specified in Part 1 is one of the benefits of natural ventilation. When the outdoor temperature is comfortable and the air is clean, it is effective to allow more outdoor air into the building. For some climates and buildings, a transient high ventilation rate can also be used for summer cooling. A transient high ventilation rate might also be needed when there are renovation activities in the building, which generate a high amount of pollutants in the air.

5.4.2 Three major design elements of natural ventilation

Designing natural ventilation requires more than just estimating vent and window sizes — it also requires innovative design and significant attention to detail. Priolo (1998) presented a comprehensive design guideline for natural ventilation. This section gives a brief overview of the three layers of the design process related to natural ventilation design:

- *site design* — building location, layout, building orientation, landscaping;
- *building design* — type of building, building function, building form, envelope, natural ventilation strategy, internal distribution of spaces and functions, thermal mass, heating, ventilation and air-conditioning if it exists; and
- *vent opening design* — position of openings, types of openings, sizing of openings, control strategy.

Site design

Site design involves integrating the buildings with the surrounding topography and buildings. For some situations, minor changes to the local site may be allowed, within the limits of environment and wildlife protection.

For natural ventilation, it is best to use the natural airflow patterns of the site to increase the potential of natural ventilation.

- If the building needs summer cooling and minimum winter ventilation, investigate the summer and winter prevailing wind directions, and locate the building to receive more summer winds and protection from winter winds.
- When several buildings are being built on one site, make sure each of the buildings is exposed to summer winds, but not to winter winds in cold climates.

As discussed in section 4.1, the driving wind pressure is not just the positive pressure at the windward openings, but also the negative pressures at the leeward openings. Building form and orientation should result in an increase in the negative pressures in the wakes of airflows. Aynsley, Melbourne & Vickery (1977) provide a useful explanation of downwind wakes caused by different building forms.

Vegetation also affects air movement around the buildings through wind sheltering, wind deflection, funnelling and air acceleration. Air quality and conditions are also changed when travelling beneath canopies of vegetation (e.g. trees).

Building design

For simple buildings, follow the guidance of Priolo (1998) on roof design, aspects ratios and the use of overhangs, wind walls and recessed spaces. For large and complex buildings, use computational fluid dynamics (e.g. Fluent, 2003) to investigate various design options for improving the natural ventilation potentials, and to avoid cold draughts. Take care to ensure pedestrian comfort at the outdoor ground level.

Internal space distribution is also important. For example, relatively "dirty" spaces should be located on the leeward side to avoid back flow of polluted air and odours into other spaces. Large windows for other living spaces in the windward side, such as the wards, can create a funnel effect to induce more incoming air. Interior partitions and furniture should not block the airflow.

For infection control, a single-row ward layout works better than a double-row layout with a central corridor in terms of natural ventilation and daylight. Large, open spaces should always have large windows in opposite walls. With the central corridor layout, natural ventilation may be improved by combining cross-ventilation with stack (or buoyancy) ventilation through corridor vents or through shafts in multistorey buildings.

For multistorey hospitals, stairwells and other shafts can work as exhaust ventilation systems to avoid warm air entering the upper-level apartments or offices. The outlet openings of the shafts should be located on the leeward side of the building, above the top floor level, with the inlet openings on the windward side of the building.

As the penetration depth of wind-driven natural ventilation is limited, the width of the building is limited (CIBSE, 2005). However, the use of wind towers may permit deeper buildings.

Vent opening design

In any design, the smallest opening area (the bottleneck) controls natural ventilation flow rate. Inlet and outlet openings should have as near equal dimensions as possible to maximize the airflow rate.

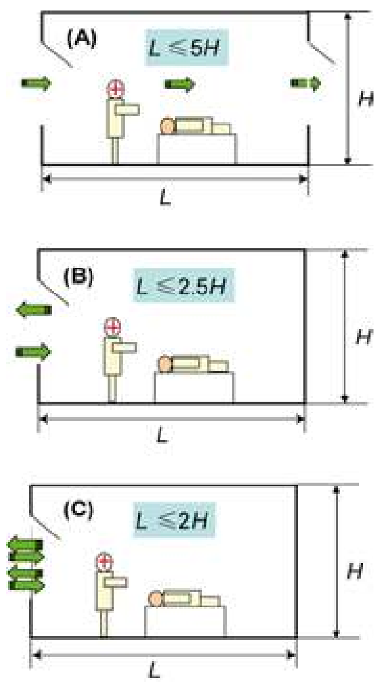
The position of openings needs to be considered with care, because of the possible conflict between cross and stack (or buoyancy) ventilation, human cooling or thermal mass cooling, etc.

Proper selection and design of openings such as windows, screens, louvres, solar chimneys, passive stacks, is also important. Proper sizing may be done using the vent sizing methods discussed earlier.

There are some other aspects to consider.

- *Furniture and internal portioning* — ventilation openings should not be blocked, and furniture layout and internal partitioning must not restrict the intended flow path and opening access.
- *Ward depth* — unlike mechanical ventilation, naturally ventilated buildings need to be narrow. The natural air currents may penetrate deeply into a building. The rules of thumb for the ward depth are available from CIBSE (2005) (see Figure 5.3).
- *Shading* — blinds, overhangs and projections (including deep window reveals) may be used. Self-shading by the building itself and remote shading (e.g. by another building or trees) may also work if properly considered. Retractable external blinds are desirable.
- *Daylight and glare control* — windows may be provided with a screen to avoid the direct sunlight. The shape and the position of the window openings are also important. The colour and the finishes of the surfaces must also be chosen properly for a comfortable level of lighting and glare control.

- *Heating and cold drafts* — during slightly cold weather, localized heating may be used to provide some thermal comfort. However, care should be taken if a greater indoor and outdoor air temperature difference is caused, because this can, in turn, increase the driving force. Natural ventilation may not be possible for ventilation control during very cold weather.
- *Cooling* — during hot and humid weather, local spot cooling or personalized cooling systems may be used (e.g. by using ceiling fans or desk fans).
- *Noise and acoustics* — external noise may be avoided by locating the windows and other ventilation openings away from the primary noise courses. Absorbent partitioning, ceiling banners, etc., may also be used to absorb noise.
- *Fire safety* — designing a building with openings that connect rooms may conflict with fire-safety and smoke-control requirements. Ventilation openings may need to be closed during a fine. Fortunately, naturally ventilated buildings can be designed to be in line with the compartmentalization requirements for smoke control. The fire escape route needs special attention, because natural ventilation design also has an impact on smoke flow pattern.
- *Security* — security risks may be created with opening windows, particularly on ground floors.



(A) Cross-ventilation. (B) Single-sided ventilation driven by buoyancy forces alone (i.e. stack (or buoyancy) ventilation, which is not effective for airborne infection control). (C) Single-sided ventilation (not effective for airborne infection control).

Figure 5.3 The rules of thumb for the depth of the ward for three different ventilation strategies

5.5 Types of natural ventilation systems

Natural ventilation systems are classified by their basic architectural design elements (corridors, courtyards, wind towers, chimneys, etc.). These building elements define the routes of airflow, as well as the basic natural ventilation strategy.

There are six basic types of natural ventilation systems:

- single-side corridor
- central corridor
- courtyard
- wind tower
- atrium and chimney
- hybrid (mixed-mode) ventilation.

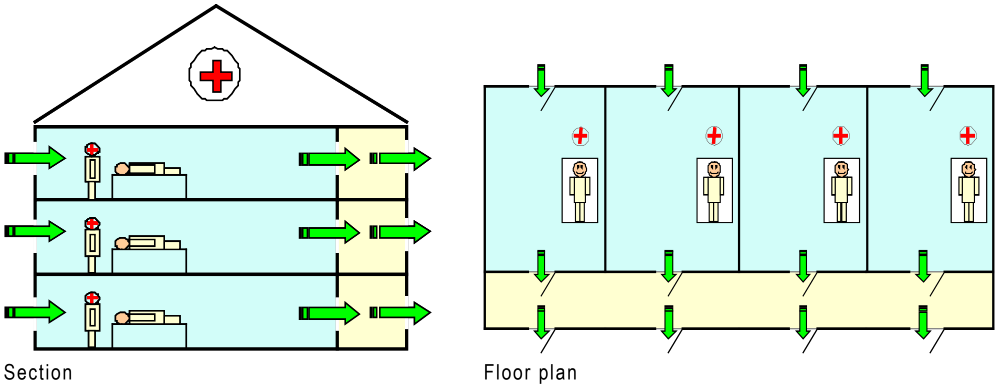
These systems are described in the following sections. It is possible to combine some of these systems to suit the local climate and particular hospital needs. Annexes F–I describe the natural ventilation systems used in four hospitals in different countries.

This guideline considers only simple natural ventilation systems, and designers will need to consider other aspects (e.g. control) when they are designing high-tech natural ventilation solutions.

5.5.1 Single-side corridor type

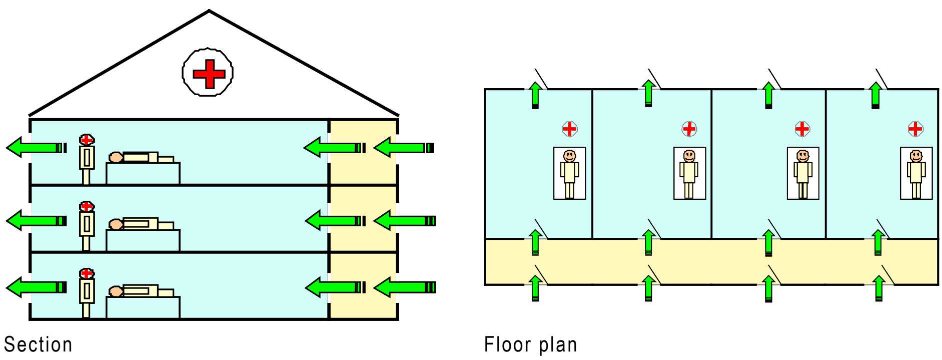
In the single-side corridor type of natural ventilation system, the corridor is on one side of the ward (see Figures 5.4 and 5.5). The airflow is a single directional flow either from the ward to the corridor or from the corridor to the ward, depending on the wind incident direction. This single directional flow can help to prevent cross-infection. The design of the windows is crucial for this type of design: it is better to position the windows in line with the ward door to create the path for cross-ventilation (Allard, 1998).

F Beer is credited with designing the first corridor hospital, where all the rooms were arranged alongside internal walkways. His hospital in Bern, built between 1718 and 1724, was the first of this type.



Note: This conceptual drawing should be used with care, and realistic limitations need to be considered.

Figure 5.4 Wind-driven natural ventilation in the single-side corridor type hospital with wind entering the ward



Note: This conceptual drawing should be used with care, and realistic limitations need to be considered.

Figure 5.5 Wind-driven natural ventilation in the single-side corridor type hospital with wind entering the corridor

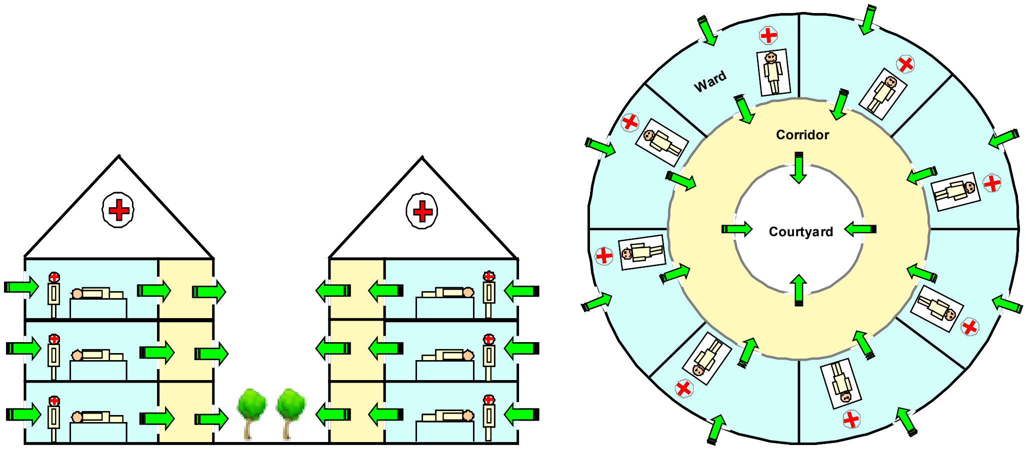
5.5.2 Central corridor type

The central corridor type of natural ventilation system is derived from the single-side corridor type by adding another series of wards on the other side of the corridor. The possible airflow path would be from one ward to the corridor, and then to the ward on the other side. When the wind is parallel to the windows, adding a wing wall helps to drive the outdoor air to enter the wards first, and exit from the central corridor. A central corridor type of floor layout would result in possibly contaminated air moving from the upstream ward to the downstream ward. At present, this guideline does not recommend this type of design.

5.5.3 Courtyard type

Courtyards are traditionally enclosed zones that can help to channel and direct the overall airflow and thus modify the microclimate around the buildings. Based on the relative position of wards and corridor to the courtyard, this type of natural ventilation system can be divided into the inner corridor and outer corridor subtypes (see Figures 5.6 and 5.7, respectively). This system can supply more ventilation than the others, as long as the courtyard is sufficiently large. The outer corridor type has an advantage over the inner type, because it can avoid cross-infection via connected corridors by delivering clean outdoor air into the corridor first.

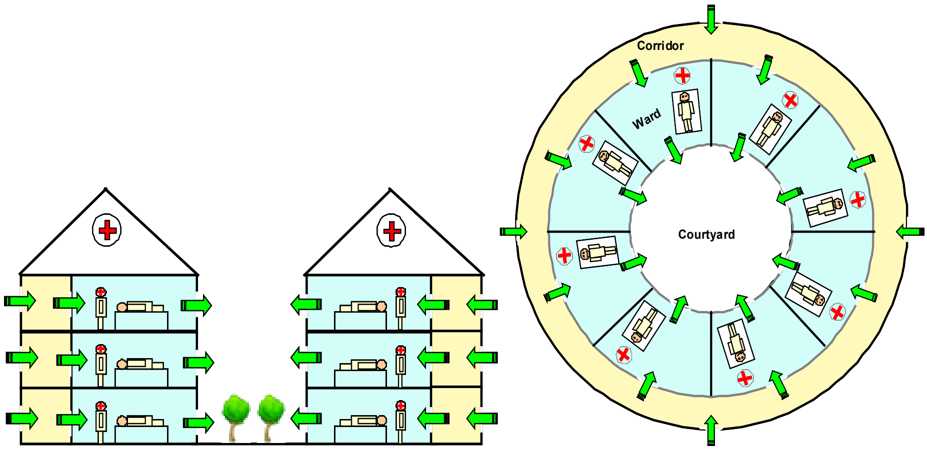
The first hospital of this type was Ospedale Maggiore, built in Milan in 1456, and designed by Antonio Averulino (better known as Filarete). The hospital is a symmetrical building with a large central courtyard; on both sides, the wings of the building delineate four smaller courtyards.



Section   Floor plan

Note: This conceptual drawing should be used with care, and realistic limitations need to be considered.

Figure 5.6 Combined wind and buoyancy-driven natural ventilation in the courtyard type (inner corridor) hospital



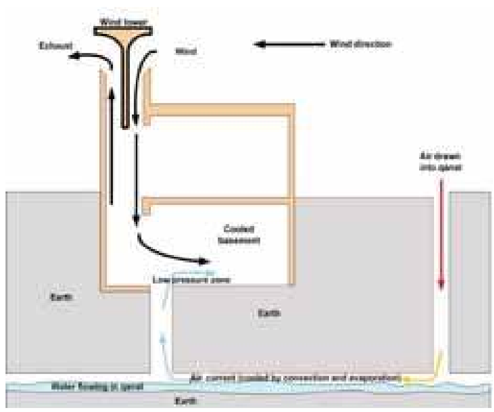
Section   Floor plan

Note: This conceptual drawing should be used with care, and realistic limitations need to be considered.

Figure 5.7 Combined wind and buoyancy-driven natural ventilation in the courtyard type (outer corridor) hospital

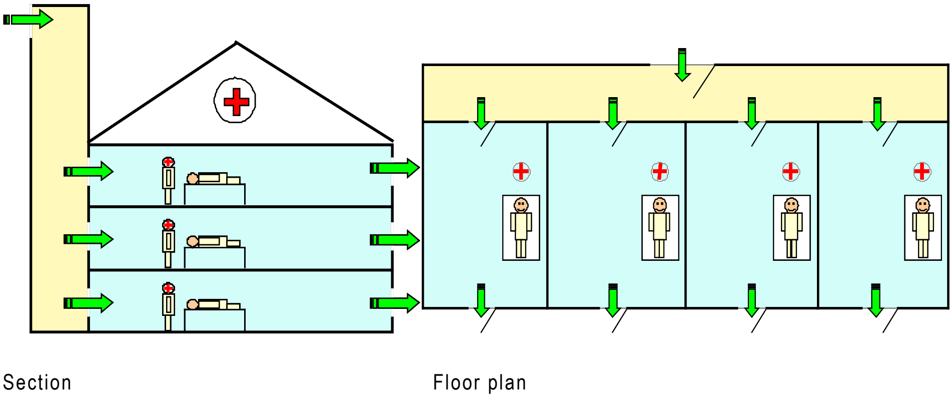
5.5.4 Wind tower type

A wind tower type of natural ventilation system can capture the wind at roof level and direct it down to the rest of the building (see Figures 5.8 and 5.9). Weatherproof louvres are installed to protect the interior of the building and volume control dampers are used to moderate flow. Stale air is extracted on the leeward side. The wind tower is normally divided into four quadrants, which can run the full length of the building and become air intakes or extractors depending on wind direction.



Note: This conceptual drawing should be used with care, and realistic limitations need to be considered.

Figure 5.8 Wind tower design

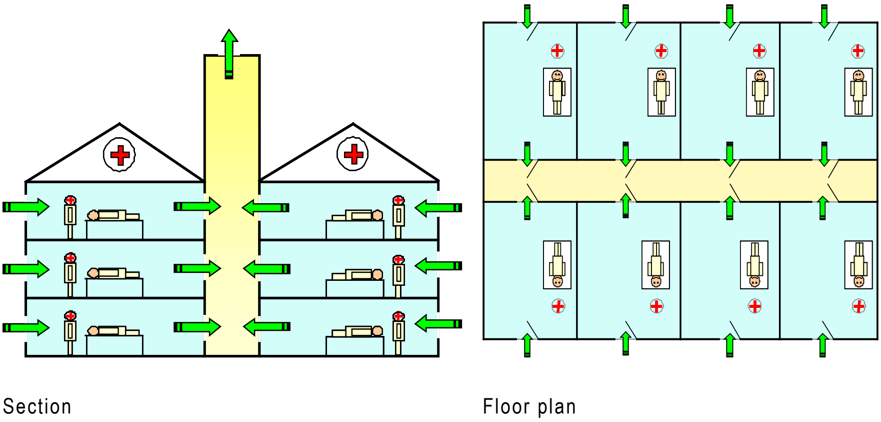


Note: This conceptual drawing should be used with care, and realistic limitations need to be considered.

Figure 5.9 Wind-driven natural ventilation in the wind tower type hospital

5.5.5 Atrium and chimney type

An atrium or chimney can help to increase the natural ventilation potential. An atrium or chimney type of natural ventilation system can be a side-atrium or chimney type, or a central atrium or chimney type, depending on the relative position of the wards, and the atrium or chimney (see Figure 5.10). Outdoor air is sucked into the wards through the windows by the stack (or buoyancy) effect. After diluting the contaminated air in the ward, the hot and polluted air converges in the atrium or chimney and discharges through the top openings. The applicability of this type of design will mainly rely on the height of the chimney, the indoor–outdoor temperature difference and its interaction with the background wind. This approach may be combined with motor-driven dampers and pressure sensors to control airflows and overcome some of the limitations of natural ventilation.



Note: This conceptual drawing should be used with care, and realistic limitations need to be considered.

Figure 5.10 Buoyancy-driven (including solar chimney) natural ventilation in the solar chimney type of hospital

5.5.6 Hybrid (mixed-mode) ventilation type

A limitation of natural ventilation is that it can sometimes depend too much on the outdoor climate. For example, if the outdoor wind speed is too small or the outdoor temperature is too high, the availability of natural ventilation will be reduced. To overcome this, hybrid (mixed-mode) ventilation can be used. In a simple hybrid (mixed-mode) ventilation system, mechanical and natural forces are combined in a two-mode system where the operating mode varies according to the season, and within individual days, reflecting the external environment and taking advantage of ambient conditions at any point of time.

The main hybrid (mixed-mode) ventilation principles are:

- switching between natural and mechanical ventilation
- fan-assisted natural ventilation
- concurrent use of natural and mechanical ventilation.

Each of the natural ventilation solutions discussed above (single-corridor, central corridor, courtyard, wind tower, and atrium and chimney) may be combined with mechanical fans to create a hybrid (mixed-mode) system. Of course, like all the systems that use natural or mechanical ventilation, design and control are critical.

5.6 Applicability of natural ventilation systems

Natural ventilation systems should be designed to take into account the local climate. There are four major climate types: hot and humid, hot and dry, moderate and cold.

Design of a natural ventilation system can also have one of three major objectives: to provide thermal comfort, to control airborne infection or indoor air quality, or to save energy.

When a ventilation type is evaluated against a climate type, both thermal comfort and infection control should be considered, but not energy-saving performance.

The performance is star-rated.

★	The performance in either thermal comfort or infection control is unsatisfactory. In terms of infection control, it means the magnitude of the ventilation rate.
★★	The performance is fair.
★★★	The performance is acceptable, but compromise may be needed in terms of thermal comfort.
★★★★	The performance is good in terms of both thermal comfort and airborne infection control.
★★★★★	The performance is very good (satisfactory) in terms of both thermal comfort and infection control.

Table 5.1 contains a comparison of the performance of different types of natural ventilation systems in the four major climate conditions.

Table 5.1 Potential applicability of natural ventilation solutions in ideal conditions (consensus of a WHO systematic review)

Climate	Natural ventilation					Hybrid (mixed-mode) ventilation	Mechanical ventilation
	Single-sided corridor	Stack (atrium/ chimney)	Courtyard		Wind tower		
			Outer corridor	Inner corridor			
Hot and humid	★★	★	★★	★★	★	★★★	★★★★
Hot and dry	★★★	★	★★★	★★★	★★★	★★★★	★★★★
Moderate	★★★	★★★	★★★	★★★	★★★	★★★★	★★★★
Cold	★	★★	★	★	★	★★	★★★★

Note: The actual achievement is not always up to the potential and care must be taken with all ventilation designs in the critical setting of health-care facilities with airborne infectious agents known or expected to be present.

5.7 Commissioning, operation and maintenance

The performance of a ventilation system depends crucially on design, operation and maintenance — collectively known as commissioning. These determine the performance and reliability of the ventilation system and are important whatever the level of technology used in the building's ventilation system. Proper construction and commissioning are needed to ensure the desired ventilation performance is achieved under different (climatic) circumstances, while proper operation and maintenance are needed to ensure the desired ventilation during the system's lifetime.

5.7.1 Commissioning

It is important that, even for a very low-tech system using grilles and vents, for example, the documentation describing the reasons for the design, how it works and how it should be maintained be handed over to the building manager or operator. For example, design and maintenance documentation describing why vents are of a certain size and in certain places will enhance the understanding of the system and help to ensure it is maintained properly.

The designers need to provide documentation to the personnel managing the building and its ventilation system:

- about the design strategy and expected operation of the natural or hybrid (mixed-mode) ventilation system;
- on the operation of the natural or hybrid (mixed-mode) system in day or night time, during different seasons, in extreme weather conditions, and when adapted for emergency conditions;
- for the patients and health-care workers explaining how the building works, is operated, and who has the right to open windows, etc;
- describing the operation and maintenance of the for the ventilation system, developed jointly with the commissioning personnel (i.e. an operating and maintenance manual); and
- explaining all the above (i.e. commissioning documentation).

It is desirable that the people using the system have the opportunity to provide feedback to the designers, however simple the system. Feedback and fine-tuning are essential to iron out potential problems in the system, and should continue for the first year of operation.

The commissioning process acts as a checking procedure to ensure that:

- the ventilation system is installed and operated as designed
- the system can be operated correctly and safely
- the system may be adjusted to satisfy the ventilation requirement at different climatic conditions
- ventilation rates under different weather conditions are appropriate.

This process should be maintained at least for the first year of operation.

5.7.2 Operation and maintenance

Operation and maintenance personnel should understand how the systems operate, and have some knowledge of infection control. Special attention is needed for the documentation and instructions for these personnel.

Operation personnel need training for the procedure to follow in special weather conditions, such as heavy rain, typhoons and heavy storms.

Patients are generally not permitted to operate the system unless instructed to do so (this includes opening windows).

Natural ventilation or hybrid (mixed-mode) ventilation usually has many distributed components, such as windows and fans. Detecting faults in these components can be time consuming.

It is crucial for any hospital designed for infection control to be reconsidered in terms of ventilation design when the occupancy patterns are changed.

Regular occupant surveys and checks will help to identify potential operational problems, as well as deal with complaints.

In naturally ventilated hospitals, the satisfaction of the patients and health-care workers may be improved if they understand how the system works.

5.8 Summary

Designing a naturally ventilated building for infection control follows three basic steps: selecting the desired airflow pattern, identifying the main driving forces, and sizing and locating openings. Although these steps are common to designing all such buildings, local conditions, such as the year-round climate and the impact this has on infection control, must also be taken into account.

At a more specific level, the main design elements of natural and hybrid (mixed-mode) ventilation systems are dictated by the specific components used. Aspects of different ventilation systems can be selected and combined as needed to suit the local climate and the requirements of each individual hospital.

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Annexes

Annex A Articles included in the systematic review on the association between ventilation and infection

The systematic review questions were defined by the World Health Organization Guideline Development Group, and the systematic review methodology was developed by the Technical Guideline Development Group and overseen by the External Steering Committee.

The systematic review was done by a team of research assistants (led by Prof Yuguo Li, University of Hong Kong), under the guidance of a librarian from the University of Hong Kong library. Search terms included keywords and medical subject headings (MeSH) relating to ventilation, infection and buildings. Databases searched included MEDLINE, EBM Reviews, ISI Web of Science, ScienceDirect, Engineering Village 2 and ISI ProceedingsSM. Google Scholar was also searched.

Set inclusion and exclusion criteria were used, and a review panel (comprising experts in medicine, health, engineering and architecture) oversaw the literature review process from the development of the search strategy to the critical appraisal of identified studies, data extraction and reporting. The External Steering Committee oversaw the final results and application of the results for the development of the guideline.

There were 13 661 articles searched using identified keywords as agreed in the systematic review protocol. Of these, 388 articles were retrieved and 65 were retained according to the inclusion and exclusion criteria, and distributed to a panel of sixteen experts from Europe, North America, Australia and Asia.

The 65 articles retrieved are listed below.

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Annex B Recommendation GRADE appraisal tables (GRADE system)

B.1 Explanation of the GRADE appraisal of recommendations

Several factors should be taken into account to appraise the strength of the recommendations, including the available scientific evidence, the balance of benefits versus harms and burdens, differences in values, and the balance of net benefits and costs.

The scientific evidence was assessed through the systematic review designed for the purpose of this guideline (see Annex A for details).

The overall ranking of the strength of the recommendations would consider each of the abovementioned factors as follows.

- The higher the quality of evidence, the more likely is a strong recommendation.
- The larger the difference between the desirable and undesirable consequences, the more likely is a strong recommendation warranted. The smaller the net benefit and the lower certainty for that benefit, the more likely is a weak recommendation warranted.
- The greater the variability in values and preferences, or uncertainty in values and preferences, the more likely is a weak recommendation warranted.
- The higher the costs of an intervention, that is, the more resources consumed, the less likely is a strong recommendation warranted.

B.1.1 Strong versus conditional recommendations

The definitions of strong and conditional recommendations are:

- **strong recommendation** — the panel is confident that the desirable effects of adherence to a recommendation outweigh the undesirable effects; and
- **conditional recommendation** — the panel concludes that the desirable effects of adherence to a recommendation probably outweigh the undesirable effects, but is not confident.

B.1.2 Implications of strong and conditional recommendations

The implications of a strong recommendation are:

- for patients — most people in your situation would want the recommended course of action and only a small proportion would not; request discussion if the intervention is not offered;
- for clinicians — most patients should receive the recommended course of action; and
- for policy makers — the recommendation can be adopted as a policy in most situations.

The implications of a conditional recommendation are:

- for patients — most people in your situation would want the recommended course of action, but many would not;
- for clinicians — you should recognize that different choices will be appropriate for different patients and that you must help each patient to arrive at a management decision consistent with his or her values and preferences; and
- for policy makers — policy making will require substantial debate and involvement of many stakeholders.

B.2 Recommendation appraisal tables

Recommendation 1:

To help prevent airborne infections, adequate ventilation in a health-care facility, in all patient-care areas, is necessary.

Population: Health-care settings

Intervention: Ventilation

Factor	Decision	Explanation
Quality of evidence	Moderate	There is moderate evidence available to suggest that insufficient ventilation is associated with an increased risk of infection (Gustafson et al., 1982; Bloch et al., 1985; Hutton et al., 1990; Calder et al., 1991).
Benefits or desired effects	Strong (benefits sometimes outweigh disadvantages)	Reduce the exposure to infectious droplet nuclei by patients and health-care workers. Improved indoor air quality for patients and health-care workers.
Disadvantages or undesired effects		There is a cost implication to install adequate ventilation in health-care facilities. Proper operation and maintenance procedures need to be followed.
Costs	May be low or high	Low cost is possible if simple natural ventilation is used and properly designed according to local climate. High initial cost is likely if full mechanical ventilation or high-tech natural ventilation or hybrid (mixed-mode) ventilation is used.
Feasibility	Conditional to climate	Mechanical ventilation and hybrid (mixed-mode) ventilation are feasible in all climates, but may be limited due to availability of resources. High-tech natural ventilation is feasible in most climates and if designed properly, simple natural ventilation is also feasible in resource-limited countries.
Overall ranking	**STRONG RECOMMENDATION**	
Research gap	There is a need to determine the ventilation rate requirements in health-care settings for infection control.	

Recommendation 2:

For natural ventilation, the following minimum hourly averaged ventilation rates should be provided:

- 160 l/s/patient (hourly average ventilation rate) for airborne precaution rooms (with a minimum of 80 l/s/patient) (note that this only applies to new health-care facilities and major renovations);
- 60 l/s/patient for general wards and outpatient departments; and
- 2.5 $l/s/m^3$ for corridors and other transient spaces without a fixed number of patients; however, when patient care is undertaken in corridors during emergency or other situations, the same ventilation rate requirements for airborne precaution rooms or general wards will apply.

The design must take into account fluctuations in ventilation rate.

When natural ventilation alone cannot satisfy the recommended ventilation requirements, alternative ventilation systems such as a hybrid (mixed-mode) natural ventilation system should be used, and then if that is not enough, mechanical ventilation should be used.

Population: Health-care settings

Intervention: Natural ventilation

Factor	Decision	Explanation
Quality of evidence	Low	There is no direct evidence available to suggest the direct impact of natural ventilation on disease transmission, though there is strong engineering evidence that natural ventilation can achieve a very high ventilation rate and it is suggested that a high ventilation rate can reduce airborne infection (Menzies et al., 2000).
Benefits or desired effects	Moderate (benefits sometimes outweigh disadvantages)	Suitable for mild or moderate climates. Lower capital, operational and maintenance costs. Capable of achieving very high ventilation rate. Large range of control of environment by occupants.
Disadvantages or undesired effects		Easily affected by outdoor climate. More difficult to predict, analyse and design to ensure airflow direction control. Reduces comfort level of occupants when hot, humid or cold. Inability to establish negative pressure in isolation areas, but may be provided by proper design; depends on situation.
Costs	May be low and high	Low cost if simple ventilation is used and properly designed with suitable climate. Can be higher if hybrid (mixed-mode) ventilation or high-tech natural ventilation is used.
Feasibility	Conditional to country settings	Natural ventilation is less feasible in extreme climates (extreme cold, hot, noisy, polluted).
Overall ranking	**CONDITIONAL RECOMMENDATION**	
Research gap	There is a need to determine the natural ventilation requirements in terms of variable ventilation rate and variable airflow direction for infection control in health-care settings.	

Recomendation 3:

When designing naturally ventilated health-care facilities, overall airflow should bring the air from the agent sources to areas where there is sufficient dilution, and preferably to the outdoors.

Population: Health-care settings

Intervention: Airflow control in natural ventilation

Factor	Decision	Explanation
Quality of evidence	Low	There is moderate evidence available to suggest that incorrect airflow direction is associated with an increased risk of infection (Gustafson et al., 1982; Bloch et al., 1985; Hutton et al., 1990; Calder et al., 1991).
Benefits or desired effects	Moderate (benefits sometimes outweigh disadvantages)	Possibly minimized transmission risks between rooms.
Disadvantages or undesired effects		More challenging in design and operation of the natural ventilation systems.
Costs	May be low and high	Low cost if simple natural ventilation is used and properly designed with suitable climate. Can be higher if a hybrid (mixed-mode) ventilation system or high-tech natural ventilation is used or additional engineering measures are used to control airflow direction.
Feasibility	Conditional to design and control	Natural ventilation is less feasible in providing airflow control and requires careful engineering and architectural design.
Overall ranking	**CONDITIONAL RECOMMENDATION**	
Research gap	There is a need to study engineering and architectural methods for airflow control in naturally ventilated buildings.	

Recommendation 4:

For spaces where aerosol-generating procedures associated with pathogen transmission are conducted, the natural ventilation requirement should, as a minimum, follow Recommendation 2. Should the agent be airborne, Recommendations 2 and 3 should be followed.

Population: Health-care settings

Intervention: Room ventilation for spaces with aerosol-generating procedures

Factor	Decision	Explanation
Quality of evidence	Very low	There is indirect evidence available to show that aerosol-generating procedures are associated with an increased risk of infection and ventilation may play a role.
Benefits or desired effects	Moderate (benefits sometimes outweigh disadvantages)	Possibly reduced infection risk.
Disadvantages or undesired effects		Reduces comfort level of occupants when hot, humid, or cold.
Costs	May be low and high	Low cost if simple natural ventilation is used. Can be higher if a hybrid (mixed-mode) ventilation system or high-tech natural ventilation is used.
Feasibility	Conditional to country settings	Natural ventilation is less feasible in extreme climates (extreme cold, hot, noisy, polluted).
Overall ranking	**CONDITIONAL RECOMMENDATION**	
Research gap	There is a need to determine the minimum ventilation requirements for natural ventilation in terms of variable ventilation rate and airflow direction control for aerosol-generating procedures.	

Annex C Respiratory droplets

According to Wells (1955), the vehicle for airborne respiratory disease transmission is the droplet nuclei, which are the dried-out residual of droplets possibly containing infectious pathogens.

C.1 Droplet generation and sizes

The term "droplet", as used in this context, consists mostly of water with various inclusions, depending on how it is generated.

Naturally produced droplets from humans (e.g. droplets produced by breathing, talking, sneezing, coughing) include various cells types (e.g. epithelial cells and cells of the immune system), physiological electrolytes contained in mucous and saliva (e.g. Na+, K+, Cl-), as well as, potentially, various infectious agents (e.g. bacteria, fungi and viruses).

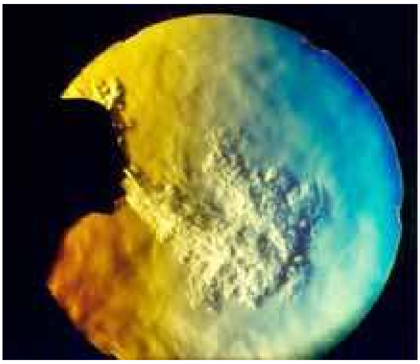
With artificially generated droplets in a health-care setting (e.g. suction of respiratory tract), the main constituent will also be sterile water, with various electrolytes (e.g. "normal" or physiological saline, including Na+, Cl-) and often the molecules of a drug (e.g. salbutamol for asthmatics).

Both these naturally and artificially generated droplets are likely to vary in both size and content. Droplets >5 µm tend to remain trapped in the upper respiratory tract (oropharynx — nose and throat areas), whereas droplets ≤5 µm have the potential to be inhaled into the lower respiratory tract (the bronchi and alveoli in the lungs).

Currently, the term droplet is often taken to refer to droplets >5 µm in diameter that fall rapidly to the ground under gravity, and therefore are transmitted only over a limited distance (e.g. ≤1 m). In contrast, the term droplet nuclei refers to droplets ≤5 µm in diameter that can remain suspended in air for significant periods of time, allowing them to be transmitted over distances >1 m (Stetzenbach, Buttner & Cruz, 2004; Wong & Leung, 2004). Other studies suggest slightly different definitions, with ranges for "large" droplets, "small" droplets and droplet nuclei being >60 µm in diameter, ≤60 µm in diameter and <10 µm in diameter, respectively (Tang et al., 2006; Xie et al., 2007). The concept is that the naturally and artificially produced aerosols will contain a range of droplet sizes, whose motion will depend significantly on various environmental factors, such as gravity, the direction and strength of local airflows, temperature and relative humidity (which will affect both the size and mass of the droplet due to evaporation).

There have been several studies on the number and size of droplets of saliva and other secretions from respiratory activities (Jennison, 1942; Duguid, 1945; Hamburger & Roberston, 1946; Loudon & Roberts, 1967; Papineni & Rosenthal, 1997; Fennelly et al., 2004) and excellent reviews have been written (Nicas, Nazaroff & Hubbard, 2005; Morawska, 2006). These studies and reviews note that the size of droplet nuclei due to sneezing, coughing and talking is likely to be a function of the generation process and the environmental conditions. The actual size distribution of droplets also depends on parameters, such as the exhaled air velocity, the viscosity of the fluid and the flow path (i.e. through the nose, the mouth or both) (Barker, Stevens & Bloomfield, 2001). There is also a great individual variability (Papineni & Rosenthal, 1997; Fennelly et al., 2004).

Humans can produce respiratory aerosols (droplets) by several means, including breathing, talking, coughing (Figure C.1, A), sneezing (Figure C.1, B) and even singing (Wong, 2003; Toth et al., 2004).



(A)

(B)

Source: Photographs reproduced with the kind permissions of (A) Prof Gary S Settles, Department of Mechanical and Nuclear Engineering, Pennsylvania State University, PA, USA; and (B) Prof Andrew Davidhazy, School of Photographic Arts and Sciences, Rochester Institute of Technology Rochester, NY, USA, respectively.

Figure C.1 (A) Schlieren image (visualization using light refraction caused by differences in air density) of a human cough, and (B) flash photo of a human sneeze

There is a natural physiological variation in the volume and composition of such aerosols generated between individuals and even within the same individual during any of these activities. An infection is likely to increase this variability, which itself may vary as the host immune system starts responding to the infection over time. For example, a patient with chickenpox will have no specific antibodies to the virus at the beginning of the infection, making the viral load much higher and thus potentially more transmissible during the acute, febrile, coughing, prodromal phase of the infection than later, when the specific antibody response starts to develop.

Relatively few studies have characterized the number, size and content of droplets generated by either natural or artificial means. Also, because of individual variation, studies on naturally generated droplets may be of limited use, and will not necessarily be relevant to so-called "super-spreaders" — infected individuals who manage to infect many others, generating many more secondary cases than is expected on average. This may be due to a number of reasons, including a poor host immune response to controlling the infection, concomitant diseases or other respiratory infections that increase the degree of shedding of the infectious agent, and environmental factors favourable to the survival of such agents (Bassetti, Bischoff & Sherertz, 2005).

Published data have suggested that sneezing may produce as many as 40 000 droplets between 0.5–12 µm in diameter (Cole & Cook, 1998; Tang et al., 2006) that may be expelled at speeds up to 100 m/s (Wells, 1955; Cole & Cook, 1998), whereas coughing may produce up to 3000 droplet nuclei, about the same number as talking for five minutes (Cole & Cook, 1998; Fitzgerald & Haas, 2005; Tang et al., 2006). Despite the variety in size, large droplets comprise most of the total volume of expelled respiratory droplets. Further data on the behaviour of droplet dispersion in naturally generated aerosols are needed.

Infectious aerosols are generated when they come into contact and mix with exhaled air that may carry infectious agents from patients' respiratory tracts. Several medical procedures generate aerosols, and some of these procedures may be associated with an increased risk of pathogen transmission. However, many of the most recent studies of these procedures have significant methodological flaws that preclude the use of their conclusions to draw recommendations. Overall, the risk associated with many of the aerosol-generating procedures is not yet well defined, and understanding the aerobiology of the aerosol-generating procedures may change with further studies. For the purpose of this guideline, the term aerosol-generating procedure associated with a documented increase in risk of pathogen transmission refers to the performance of the following procedures in acute respiratory disease patients:

- intubation and related procedures (e.g. manual ventilation, suctioning)
- cardiopulmonary resuscitation
- bronchoscopy
- surgery and autopsy.

C.2 Droplet evaporation

In the classic study of airborne transmission, Wells (1934) was able to identify the difference between disease transmission via large droplets and by airborne routes. Wells found that, under normal air conditions, droplets smaller than 100 µm in diameter would completely dry out before falling approximately 2 m to the ground. This finding allowed the establishment of the theory of droplets and droplet nuclei transmission depending on the size of the infected droplet. The Wells evaporation-falling curve of droplets (see Figure C.2) is important in understanding airborne transmission and transmission by large droplets. Wells' study also demonstrated that droplets could transform into droplet nuclei by evaporation.

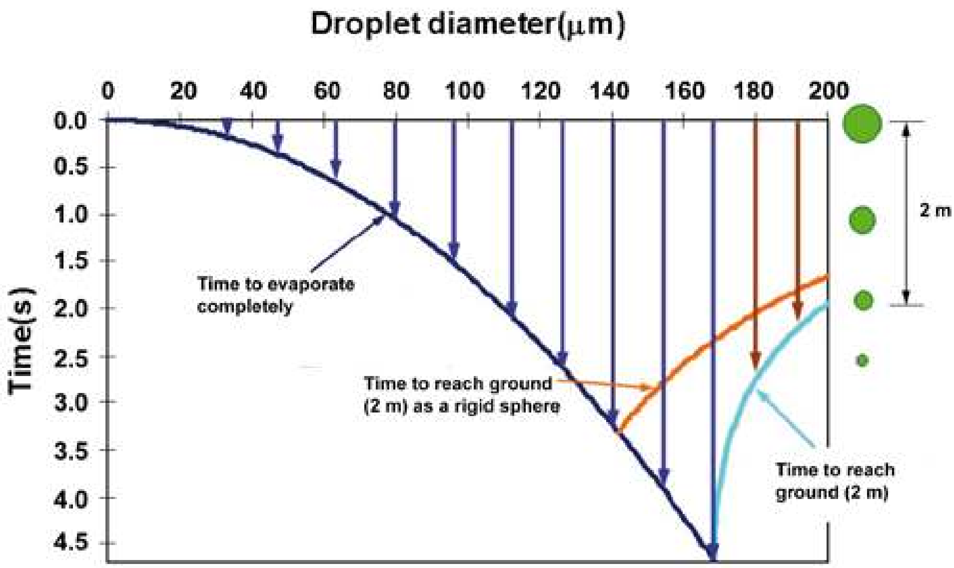
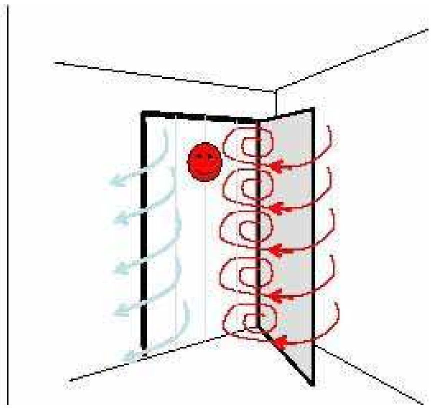


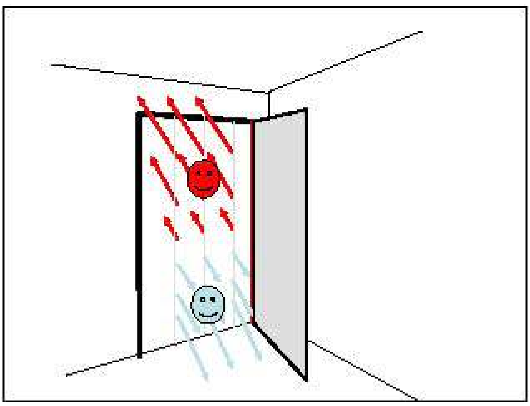
Figure C.2 The Wells evaporation-falling curve of droplets

C.3 Movement of air

Droplet nuclei floating on the air may be carried by the movement of air. Entrainment of air into neighbouring airspaces may occur during the most innocuous daily activities; for example, as a result of people walking, or the opening of a door between a room and the adjacent corridor or space (Hayden et al., 1998; Edge, Paterson & Settles, 2005; Tang et al., 2005, 2006). In addition, the air temperature (and therefore air density) differences across an open doorway will also cause air exchange to occur between the two areas, providing a second mechanism to allow air into other areas (Tang et al., 2005, 2006) (see Figure C.3).



(A) (B)



(C)

(A) Demonstration of how a walking person may entrain air into their wake (Tang et al., 2006).
(B) Demonstration of how opening a door may transport air from inside an isolation room to the outside, during the door-opening motion itself (Tang et al., 2005). (C) Demonstration of how an open door can allow air of different temperatures and densities to mix and exchange (Tang et al. 2005).

Figure C.3 Patterns of air exchange during daily activities

Even a patient simply sitting in or beside the bed will create air temperature differences from their body heat. A higher air temperature directly above the patient's head (or body, if lying down) will create convective air currents that may entrain potentially infectious air from neighbouring spaces into the higher temperature column rising air above the patient (Craven & Settles, 2006). Patients lying in bed, breathing or sleeping, may produce exhaled airflows that can reach the airspace of a patient in the neighbouring bed, and even further in the presence of certain types of ventilation systems (see below) (Qian et al., 2006). In the same way, other mechanical devices, including fans, televisions and medical equipment, may also disturb nearby airflows and disseminate air from nearby patients to the rest of the ward.

Annex D Basic concept of ventilation flow rate

The ventilation flow rate can be referred to as either an absolute ventilation flow rate in l/s or m^3/s, or an air-change rate relative to the volume of the space. In this guideline, the ventilation rate is referred to as the absolute amount of inflow air per unit time (litre per second or l/s, cubic meter per hour or m^3/hr) and the air-change rate as the relative amount of inflow air per unit time. For example, in an airborne infection isolation room, we need a 12 ACH air-change rate (CDC, 2005), while in an office, we need a 10 l/s per person ventilation rate.

The relationship between ventilation rate in l/s and air-change rate is:

Air-change rate = [ventilation rate (l/s) × 3600 (s/hr)] × 0.001 (m^3/s)]/[room volume (m^3)] (C.1)

or,

Ventilation rate (l/s) = air-change rate × room volume (m^3) × 1000 (l/m^3)/3600 (s/hr) (C.2)

The effect of ventilation rate on indoor air quality may be seen from its impact on the airborne pollutant concentration through examining the simple macroscopic governing equation of ventilation in a single room.

Consider a fully mixed room — meaning that the pollutant concentration is the same everywhere in the room. When there is a pollutant source in the room, the governing equation for the concentration can be written as:

$$V\frac{dc}{dt} = q(c_o - c) + \dot{V}_{pol} \qquad \text{(C.3)}$$

where:

V = volume of space (m^3)
c = concentration (% or kg/m^3)
q = ventilation rate (m^3/s)
c_o = supply air concentration (% or kg/m^3)
dc = change in concentration
dt = change in time

$\dot{V}_{pol}$ = pollutant generation rate in the room (m^3/s or kg/s).

Equation (C.3) is called the equation of ventilation, which shows the basic relationship between concentration, ventilation rate, initial indoor concentration, outdoor concentration and the pollutant generation rate. The general solution for equation (C.3) can be written as follows

$$c = (c_o + c_G)(1 - e^{-nt}) + c_I e^{-nt} \tag{C.4}$$

where:

$$c_G = \frac{\dot{V}_{pol}}{q} = \text{source concentration}$$

cI = initial concentration at time $t = 0$
n = air-change rate.

On the right-hand side of the solution (C.4), there are two parts. The first part shows how the concentration approaches its steady-state solution, and the second part shows how the initial concentration decays with time. When the time is sufficiently large, the second part will diminish while the pollutant concentration approaches the steady-state solution

$$c = c_o + \frac{\dot{V}_{pol}}{q} \tag{C.5}$$

The difference between the ventilation rate and air-change rate can be seen from the solutions (C.4) and (C.5). In (C.5), the steady-state concentration of a pollutant is determined by the pollutant generation rate and the ventilation rate (absolute ventilation flow rate), but not the air-change rate. Therefore, for the purpose of controlling long-term exposure to pollutants, we should specify the ventilation rate, not the air-change rate. In (B.4), assuming we consider the situation of concentration decay without a constant pollutant source (the first term = 0), the decay rate is governed by the air-change rate, not the ventilation rate. Therefore, for the purpose of reducing the pollutant concentration in a short time after a sudden release of a pollutant, the air-change rate is the most appropriate.

The above solution (C.5) can be re-written as the following relationship for the indoor and outdoor concentration of gaseous pollutants

$$\text{Indoor concentration} = \text{Outdoor concentration} + \frac{\text{Pollutant generation rate}}{\text{Ventilation flow rate}} \tag{C.6}$$

This is a useful relationship. We can easily find that:

- the higher the outdoor concentration, the higher the indoor concentration
- the higher the ventilation rate, the lower the indoor concentration
- the higher the generation rate, the higher the indoor concentration.

Equation (C.6) is derived from a simplified steady-state equation that ignores various removal processes, such as deposition on surfaces, transformation by collision with other particles, chemical processes and decay or loss of viability of organisms.

Ventilation systems can be classified according to:

- their driving forces — natural ventilation including infiltration, mechanical ventilation and hybrid (mixed-mode) ventilation;
- supply or exhaust — supply only mechanical ventilation, exhaust-only ventilation, balanced mechanical ventilation;
- integration with air-conditioning systems — fan coil and induction systems, constant air volume systems, variable air volume systems, single air duct systems, dual air duct systems; and
- air distribution strategies — mixing ventilation and displacement ventilation.

Annex E Rationale for determining the minimum ventilation rate requirements

The rationale for determining the minimum ventilation rate requirements is based on two main aspects.

First, we consider the effect of air-change rate on decay of droplet nuclei concentration. Table E.1 shows the calculated pollutant concentration decay with different ventilation rates in fully mixed isolation rooms, assuming the pollutant concentration in outdoor air is 0 and there is no source in the enclosed space according to the simple concentration decay equation. The table shows that there is 7-fold dilution within 10 minutes at 12 air changes per hour (ACH), 20-fold dilution within 10 minutes at 18 ACH and 54-fold dilution within 10 minutes at 24 ACH.

Table E.1 Decay of droplet nuclei concentration in an isolation room for different ventilation rates and duration of time

Time (minutes)	Ventilation rate (ACH) (%)			
	6	12	18	24
0	100.00	100.00	100.00	100.00
10	37.00	13.50	4.98	1.83
20	13.50	1.83	0.25	0.03
50	0.67	0.00	0.00	0.00
60	0.25	0.00	0.00	0.00

ACH, air changes per hour.

Second, we use mathematical modelling of infection risk using the Wells–Riley equation to estimate the effect of ventilation rate on infection probability for known airborne diseases. The Wells–Riley equation was developed for predicting the probability of airborne disease transmission.

We can calculate the infection risk in an enclosed room with different ventilation rates and quanta generations. The calculated results are shown in Table E.2 when we assume one infector entering an enclosed room with a dimension of 6 m × 6.7 m × 2.7 m over a period of one hour. The cross-infection risk of airborne-transmitted diseases decreases when the ventilation rate increases, especially for the low quanta-generation rate, while the actual reported average quanta-generation rate of different airborne diseases is low.

The benefits of using higher ventilation rates are also obvious. In clinical situations, where droplet nuclei are an important mode of disease transmission, the average quanta production rates in clinical patients not undergoing aerosol-generating procedures is usually <1 quanta/minute, and between 4–6 quanta/minute for bronchoscopy. With a quanta production rate of 10 quanta/minute, the estimated risk of infection with 15 minutes of exposure in a room with 12 ACH is 4%, and with 24 ACH is 2%, which illustrates the importance of adequate ventilation.

Table E.2 Infection risk with 15 minutes exposure with different ventilation rates and quanta generation for an infector entering an enclosed space with a dimension 6 m × 6.7 m × 2.7 m

Quanta generation (quanta/min)	Ventilation rate (air changes per hour) (%)							
	1	**3**	**6**	**12**	**15**	**18**	**24**	**30**
1	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.00
2	0.10	0.03	0.02	0.01	0.01	0.01	0.00	0.00
3	0.14	0.05	0.03	0.01	0.01	0.01	0.01	0.01
4	0.19	0.07	0.03	0.01	0.01	0.01	0.01	0.01
5	0.23	0.08	0.04	0.02	0.02	0.01	0.01	0.01
6	0.27	0.10	0.05	0.03	0.02	0.02	0.01	0.01
7	0.30	0.11	0.06	0.03	0.02	0.02	0.01	0.01
8	0.34	0.13	0.07	0.03	0.03	0.02	0.02	0.01
9	0.37	0.14	0.07	0.04	0.03	0.03	0.02	0.02
10	0.40	0.16	0.08	0.04	0.03	0.03	0.02	0.02
11	0.43	0.17	0.09	0.05	0.04	0.03	0.02	0.02
12	0.46	0.19	0.10	0.05	0.04	0.03	0.03	0.02
13	0.49	0.20	0.11	0.05	0.04	0.04	0.03	0.02
14	0.51	0.21	0.11	0.06	0.05	0.04	0.03	0.02
15	0.54	0.23	0.12	0.06	0.05	0.04	0.03	0.03
16	0.56	0.24	0.13	0.07	0.05	0.04	0.03	0.03
17	0.58	0.25	0.14	0.07	0.06	0.05	0.04	0.03
18	0.61	0.27	0.14	0.07	0.06	0.05	0.04	0.03
19	0.63	0.28	0.15	0.08	0.06	0.05	0.04	0.03
20	0.64	0.29	0.16	0.08	0.07	0.06	0.04	0.04

Annex F Natural ventilation example I: Hospital Nacional Dos de Mayo, Lima, Peru

Note: Inclusion of the example hospitals in Annexes F–I does not necessarily mean that this guideline considers the hospitals' designs to be effective. The examples are included because elements of their construction are of interest when considering design that improves natural ventilation. For an effective natural ventilation design, ventilation rates should be measured over one year, under variable climate and operating conditions. This has not been done in any of the examples included in these annexes.

F.1 Description and history of the hospital

Hospital Nacional Dos de Mayo is a government general hospital in Lima, Peru. It was founded in 1538, and was Peru's first hospital. In 1875, the hospital was moved to its current location in Barrios Altos, near the historic centre of Lima. The hospital has 646 beds, and offers services in all the major medical and surgical specialities, in addition to paediatrics and obstetrics. There are approximately 14 500 inpatients attended annually, 240 000 outpatient consultations and 50 000 patients seen in the emergency department. The hospital has 248 doctors and 912 other health-care workers. The hospital has a nationally renowned infectious diseases and tropical medicine service. The respiratory department inpatient wards are located upstairs above this service, and include beds for multidrug-resistant tuberculosis (TB). These buildings for infectious disease and tropical medicine were built in the 1950s at the northern end of the hospital, specifically for the isolation of TB patients, following many of the design principles of European TB sanatoria (see Figure F.1).

(A) The Hospital Nacional Dos de Mayo. (B) View of the building housing the infectious disease service

Figure F.1 Hospital Nacional Dos de Mayo

F.2 Principal architectural styles in the hospital

Many of the buildings that form the current hospital date from its inauguration in 1875, and exhibit the characteristics of Spanish colonial architecture. These include high ceilings (generally 4.2 m or higher), large windows, and skylights for light and ventilation. The general medical and surgical wards — large 'Nightingale' wards of 40 beds — are situated around a central garden where patients and staff can relax outside. The building housing the infectious diseases and respiratory wards, named Santa Rosa after the patron saint of Lima, is a two-storey building with high ceilings, large windows and balconies for TB patients to take the air (see Figure F.2). Part of the ground floor has been converted into mechanically ventilated negative-pressure isolation rooms for TB-HIV patients.

Substantial additions were made to the hospital in 1971 using modern building design and construction. These additions include the emergency department, paediatric and surgical departments, and laboratory and X-ray services. These buildings generally have small windows and low ceilings (approximately 2.9 m high).

F.3 Natural ventilation in wards built pre-1950

Ventilation was measured using a carbon dioxide tracer gas technique. The air changes per hour (ACH) quoted in Table F.1 are for the configuration of all windows and doors open, unless otherwise stated.

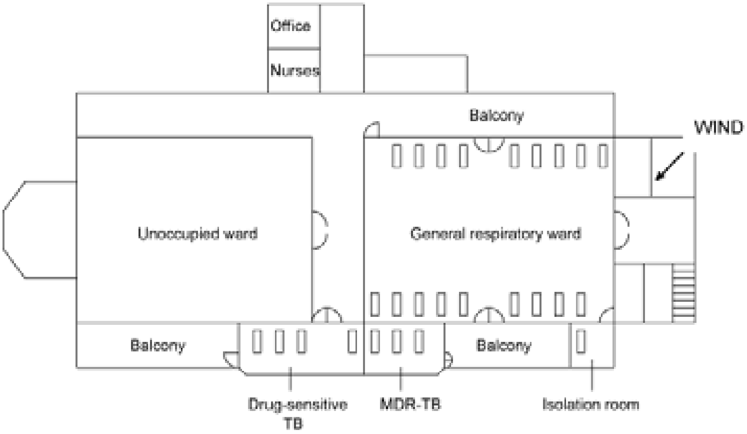
The respiratory wards are located on the first floor, well exposed to prevailing winds. Lima is situated on the coast, and winds come from the south-west off the Pacific Ocean. The general respiratory ward has 18 widely spaced beds, and room area of 166 m^2. The room has excellent cross-ventilation, with windows on the two long walls, and has four double doors.

Table F.1 Ward data and measured air changes per hour

Parameters	General respiratory ward	Drug-susceptible TB ward	MDR-TB ward	Isolation room	Procedures room
Floor area (m^2)	166	51	35	11.7	23
Ceiling height (m)	4.2	4.2	4.2	4.2	4.2
Total window area (m^2)	32.3	32.3	18.4	3.0	20.3
Openable window area (m^2)	12.5	22.0	12.3	3.0	19.6
Area of doors (m^2)	16.6 (n = 4)	9.2 (n = 2)	3.8 (n = 1)	2.0 (n = 1)	3.7
Mean ACH	25 (n = 26)	29 (n = 15)	33 (n = 42)	49 (n = 7)	51 (n = 7)

ACH, air changes per hour; MDR, multidrug resistant; TB, tuberculosis.

Note: The climatic conditions at the time of the measurement of ventilation rate were not available; therefore, the measured air change rates here are only indicative and short-term "snapshots". The accuracy of the measured ACH is not known.



(A) Floor plan of the respiratory wards

(B) General respiratory ward

(C) Drug-susceptible TB ward

(D) MDR-TB ward

(E) Location of the MDR-TB ward

MDR, multidrug resistant.

Figure F.2 Floor plan and photos of different wards in Hospital Nacional Dos de Mayo

The drug-susceptible TB ward has four beds, and is well ventilated due to the high ratio of window or door area to room volume, despite the ward being on the side of the building that is protected from prevailing winds. The façade of this room is seen on the first floor in Figure F.1.

The multidrug-resistant TB ward is adjacent to the drug-susceptible TB ward. Although still on the lee side of the building, it has better exposure to the prevailing winds. This ward has three beds for multidrug-resistant TB patients. Smoke testing consistently demonstrated airflow in through the door and out through the windows.

The isolation room is located off the main general respiratory ward (see Figure F.2, A). The door connects with the general respiratory ward, and three windows open to the outside. With the door closed, mean 23 ACH were measured with the three windows fully open ($n = 3$). Opening the door as well permitted cross-ventilation, and mean 49 ACH ($n = 7$) were measured. Smoke testing consistently demonstrated direction of airflow from the main ward, into the isolation room, and out the windows.

The procedures room (not shown) is currently disused owing to structural damage to this wing of the building. It is hexagonal in shape and has large windows on five sides, and large doors on the remaining wall for cross-ventilation. The room is also situated on the side of the building sheltered from the wind. Multiple measurements of ventilation were made with increasing numbers of windows and/or doors open.

F.4 Improvements to natural ventilation made through simple modifications

An example is given here to improve natural ventilation in a general outpatient waiting room (see Figure F.3). To measure the impact of the interventions, ACH were measured first in the original configuration (skylight re-sealed with plastic sheeting, removed panes of glass covered with plastic sheeting), following which the plastic sheeting was removed to measure ACH in the new configuration.

(A) (B)

(A) Photo of the general outpatient waiting room. (B) The ventilation rate increased from a mean of 6.5 ACH to 15 ACH with the opening of skylights in the general outpatient waiting room.

Figure F.3 Improving natural ventilation in the outpatient waiting room of the Hospital Nacional Dos de Mayo

The waiting area for general outpatients (including most medical specialties, surgery and psychiatry) is located in the large hall shown in the photograph. The consulting rooms lead off from both sides of this waiting hall. A front entrance leads out to the street, and doors at either end lead to other parts of the hospital, as seen in Figure F.4. Up to 300 patients share this room during consulting hours in the mornings and afternoons.

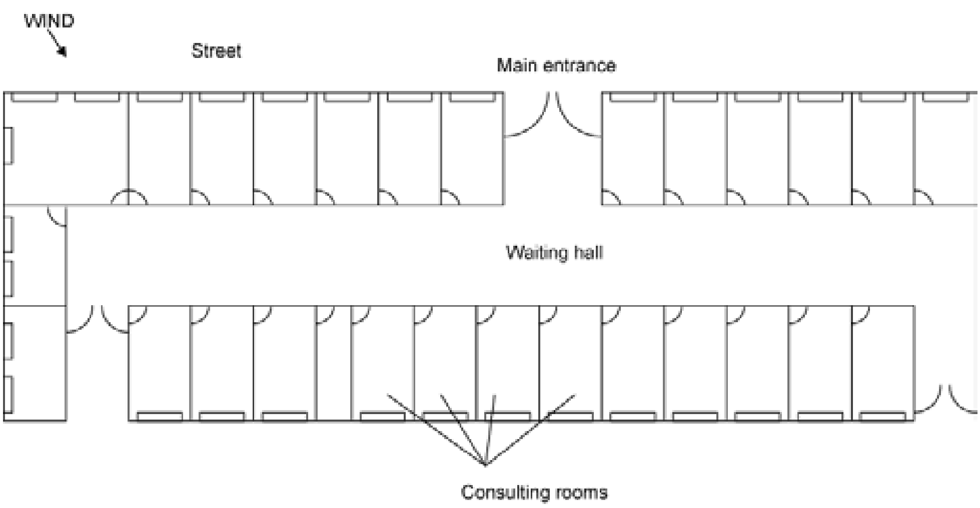


Figure F.4 Floor plan showing the waiting hall and consulting rooms

The roof of the outpatient waiting room originally had four sealed glass sections, two measuring 14 m × 2.4 m, the other two measuring 5 m × 2.4 m. These were raised on one-metre stilts to allow air to enter the waiting room through the roof. Ventilation was considerably improved with this simple intervention that cost approximately US$1000. Ventilation was originally a mean of 5.5 ACH with windows and doors open, which increased to a mean of 15 ACH with the opening of the skylights (n = 4).

Readers are reminded that the purpose of these examples is to provide case studies of naturally ventilated hospitals for infection control. Some of the infection-control design features in these examples (e.g. multi-bed wards, lack of alcohol-based hand sanitizers in the photos) mean that these examples may not be ideal.

Annex G Natural ventilation example II: Grantham Hospital, Hong Kong SAR, China

G.1 Description and history of the hospital

The tuberculosis (TB) wards in the Grantham Hospital are located on the seventh floor. Natural ventilation has been used in the TB wards since the hospital was built in 1957, and no central air-conditioning systems have been installed, although ceiling fans are used in summer (see Figures G.1 and G.2). The windows and doors are kept open all the time. The following is a description of the hospital in 1957:

> In designing a tuberculosis hospital airiness and spaciousness are a prime necessity, and it is for this reason that the main hospital building takes the form of a thin vertical slab and is kept well away from the administration building, so that there will be the maximum of through ventilation. It is oriented to catch the summer breezes, while being sheltered by the hills to the north from the cold winds in winter. It faces just east of south to give better shelter from the summer sun.

Figure G.1 Open wards and windows in the tuberculosis ward in Grantham Hospital

Figure G.2 A ceiling fan for summer cooling and a radiator for winter heating

G.2 Measuring natural ventilation rates

Two measurements of natural ventilation rates were taken on 9–10 November 2005 and 28 August 2008. During each measurement, four TB wards were vacated and simple thermal manikins were moved in to simulate thermal buoyancy flows of the inpatients. The heat generation of each thermal manikin was about 76 watts (W) corresponding to an adult at rest.

The decay method was used to measure the air-change rate. A tracer gas, sulfur hexafluoride (SF_6), was injected continually into the ward until its concentration become steady, then injection was stopped and the concentration decay measured. Two electrical fans were used to mix the air in the ward during the measurement. The injection of SF_6 was controlled by multi-gas sampler and doser type 1303 and the concentration of SF_6 was measured by the single-gas monitor 3425. Due to the difficulties in ensuring good mixing in the test room, the tracer gas decay was measured at two points in the room for each measurement, allowing two ventilation rates to be obtained. The ventilation rate for the ward is reported as the mean value.

G.3 Measured ventilation rates

Ventilation rates were measured in different situations, including when doors and windows were closed or open, and when the exhaust fans were turned on or off. In total, 20 tests were taken (see Table G.1, below).

The measured ventilation rate increased as the opening area of windows and doors increased. The mean measured ventilation rate was highest when all openings were fully open. When all openings were closed in the ward, the measured ventilation rate due to infiltration was only 0.71 in Test 15. When the openings connected to the corridor were fully open, the window to the outdoor was closed and exhaust fans were off, the ventilation rate was 8.7 air changes per hour (ACH) (Test 14).

The occurrence of a high ventilation rate depends on wind direction, wind speed and whether the two ventilation openings align with the prevailing wind direction. This explains the difference in measured ventilation rates in Tests 4 and 17 in the same ward; see Figure G.3. Figure G.3 shows the measured temperature, wind speed and direction from Hong Kong observatory during tests. Test 4 was done at 15:19 to 15:30 on 9 November 2005, when the wind speed and wind direction were 3.6 m/s and 150° respectively at 15:00, and 2.4 m/s and 170° respectively at 16:00. Test 17 was done at 17:42 to 18:04 on 28 August 2006, when the wind speed and direction were 4.1 m/s and 100° respectively at 17:00, and 4.8 m/s and 90° at 18:00. Despite the much higher wind speed during Test 17 compared with Test 4, the measured ventilation rate of Test 17 (18.5 ACH) was much lower than that of Test 4 (42.2 ACH). This was because of the wind direction. The angle between the wind direction and the tables and windows of Test 17 were less than 10°, while the angle of Test 4 was almost 75°. The effective wind speed flow to the windows was $3.0 \times \sin(75°) = 2.9$ m/s for Test 4, while the effective wind speed was less than $4.5 \times \sin(10°) = 0.78$ m/s. The results indicate the significance of wind speed and wind direction to the ventilation rate.

Table G.1 Measured ventilation rates in tuberculosis wards

Test	Date	Ward	Windows /doors to outdoor (% open)	Door to corridor (% open)	Fan	Room type	ACH
1[a]	9 Nov 2005	Cubicle 7; 6/F	100	100	off	2 beds	30.3
2			100	closed	off	2 beds	17.6
3			50	closed	off	2 beds	14.6
4		Cubicle 4; 6/F	100	100	off	2 beds	42.2
5			100	closed	off	2 beds	15.4
6			50	closed	off	2 beds	10.7
7			100	closed	on	2 beds	22.5
8[b]	10 Nov 2005	Cubicle 0; 2/F	100	100	off	2 beds	60.2
9			100	closed	off	2 beds	16.0
10			50	closed	off	2 beds	12.9
11[b]		Cubicle 7; 2/F	100	100	off	5 beds	69.0
12			100	closed	off	5 beds	31.6
13			50	closed	off	5 beds	23.5
14			closed	100	off	5 beds	8.70
15	28 Aug 2006	Cubicle 4; 6/F	closed	closed	off	2 beds	0.71
16			100	100	off	2 beds	14.0
17			100	100	off	2 beds	18.5
18			closed	closed	on	2 beds	12.6
19			100	100	on	2 beds	14.6
20			100	100	on	2 beds	29.2

ACH, air changes per hour.

[a] The window air-conditioner was on in the ward during the experiment.

[b] Tests 8 and 11: the ventilation rates were so high that the sampled data were inadequate.

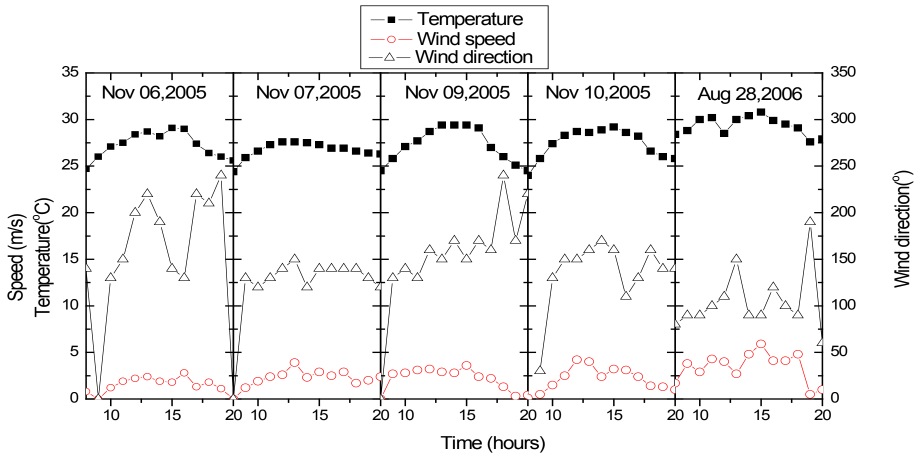


Figure G.3 Ambient air temperature, wind speed and wind direction measured by the Hong Kong Observatory at Wong Chuk Hang weather station, close to the Grantham Hospital

The results show that it is important to recognize the large dependence of ventilation rate and flow direction on wind speed and direction. Building designers should identify the dominant or average conditions and create a design to address them. This guideline is intended to be used in a wide range of climates and under a wide range of economic circumstances, as well as in an unlimited range of sites with varying topographic characteristics and other variable conditions. It is important that building designers, facility managers and people who control the openings into and out of critical spaces, potentially containing infectious agents, take these parameters into account.

Annex H Natural ventilation example III: Tuberculosis Control Unit, Tan Tock Seng Hospital, Singapore

The Tuberculosis Control Unit (TBCU) outpatient services comprise the Diagnostic Clinic where TB patients are evaluated and treated, and the Contact Clinic where TB contacts are screened and managed. The 20-bed TBCU ward (see Figure H.1) houses inpatients who are mostly long stayers with poor social or family support, and those under legal order for inpatient directly observed therapy. The ward is staffed by two to four nurses, and one health-care attendant per rotating shift (three shifts in 24 hours). The medical and nursing staff do not normally wear masks in the ward.

Figure H.1 **Two views of the single-storey tuberculosis inpatient ward; the perimeters are free from obstruction, allowing natural ventilation throughout the year**

The building has a long, sloping roof that overhangs the windows on each side; these windows are slatted and kept open. There are multiple axes for wind-driven airflow to ventilate the ward naturally. There are also numerous ceiling fans for cooling. The male and female patient areas are separate, with the health-care workers workstation located in between (see Figure H.2).

At any time, the ward has an occupancy rate of about 80%. The beds are spaced approximately 1.35 m apart, but patients are free to walk around the ward and to sit outside where there is a large, covered entrance area. The staff office area (not shown) is situated at the far end of the ward, opposite the main entrance and is separated from the main ward by incomplete partitions rather than doors. The back door can be opened to assist the flow of air along the length of the ward, and the slatted glass windows allow a cross-flow across the ward (see Figure H.3).

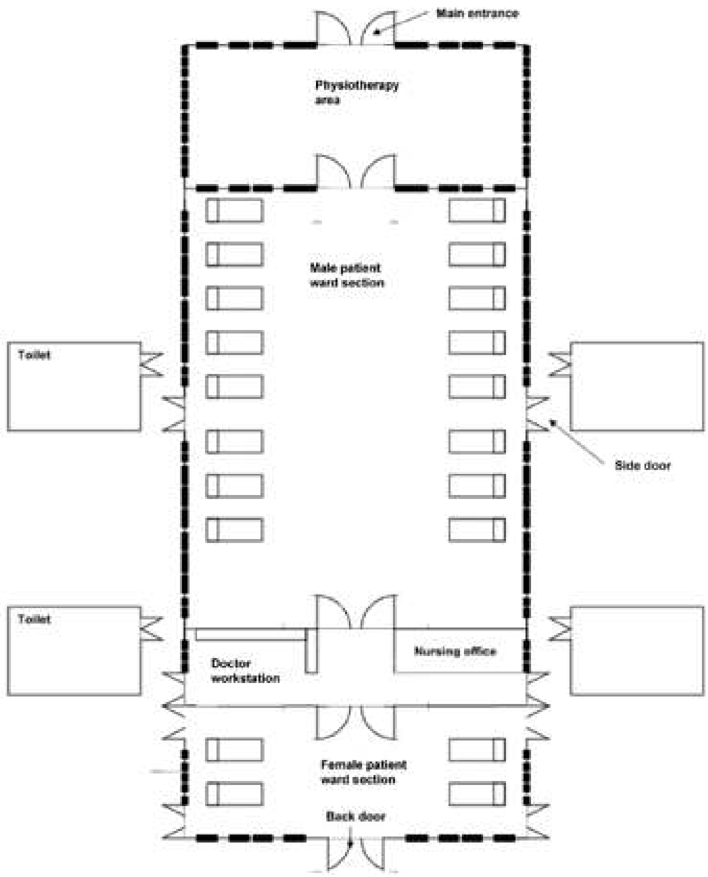


Figure H.2 Floor plan of tuberculosis unit inpatient ward

(A) (B)

(A) The side walls are of partial height so that there is a large gap between the top of the wall and the ceiling. (B) Ventilation is improved by the high ceiling and multiple ceiling fans.

Figure H.3 Inside the tuberculosis inpatient ward

Natural ventilation has been used in the Singapore TBCU for more than 50 years. Despite being situated near the downtown area of a modern, crowded island city, the environment is open, spacious and pleasant for the patients. The wind-assisted ventilation in both the outpatient clinic and inpatient ward allows for air exchange throughout potentially infectious patient areas, to maintain a healthier environment for both staff and patients.

No measured ventilation data are available for this facility.

Annex I Natural ventilation example IV: IOM Isolation Centre, Damak, Nepal

The International Organization for Migration (IOM) Holding Centre in Damak provides accommodation for migrants while they are undergoing IOM processing and health screening. The isolation units adjacent to the centre provide capacity to isolate any people who test positive for, or show signs of, infectious disease.

Both the compound (Figure I.1) and the individual buildings (Figure I.2) are designed to provide a secure and safe environment for those isolated and for those necessarily coming into contact with infected people through health-care treatment or otherwise. The design of the isolation units is expected to provide safe conditions for occupants in terms of the risk of airborne infection transmission, particularly for migrants who have been diagnosed with an infectious disease.

Figure I.1 The IOM Holding Centre in Damak

Figure I.2 Individual isolation unit (left), and the gap between the vertical wall and the roof for natural ventilation (right)

The units have three windows and a large, 0.8-m gap between the upper part of the wall and the eaves. There is a rotating "whirlybird" on the roof apex intended to increase ventilation rates and ensure an upwards movement of air. However, this has not been effective.

The units are designed for single occupancy and include a built-in shower. There are communal latrines in the compound.

The overall design is intended to maximize natural ventilation by providing a constant updraft with the intended airflow direction through the windows, to exit at the eaves and through the whirlybird.

The units are easy to build and could be built anywhere out of a range of locally available materials. Although the roof design provides all-year-round ventilation, it may also allow heavy rain to enter the unit via the gap between the wall and the roof.

The overhang of the roof should be increased to up to 1000 mm (from 450 mm) to let patients keep windows open during the rainy season, minimizing the penetration of heavy rain through the gap beneath the roof.

The IOM Construction Officer responsible for the design of these units intends to attach a polypropylene skirt of approximately one-metre depth around the roof edge. This will keep out slanting rain while not affecting greatly the ventilation of the building.

Given the substantial natural ventilation that large windows could provide (the existing windows seem to be too small), the whirlybird and the opening in the apex of the roof may not be necessary.

The limited area of this compound means that the nine units are relatively close to each other. Greater space between the units (achieved through a slightly larger compound) would help to create more air movement and therefore air exchange between the units. This may decrease the risk of any airborne infection between the units.

This document is the product of collaboration between WHO Water Sanitation and Health (WSH) and WHO Biorisk Reduction for Dangerous Pathogens (BDP), whose websites appear below:

http://www.who.int/water_sanitation_health/en/

http://www.who.int/csr/bioriskreduction/en/