REVIEW

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Tuberculosis Infection Control in Health-Care Facilities: Environmental Control and Personal Protection

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Transmission of tuberculosis (TB) is a recognized risk to patients and healthcare workers in healthcare settings. The literature review suggests that implementation of combination control measures reduces the risk of TB transmission. Guidelines suggest a three-level hierarchy of controls including administrative, environmental, and respiratory protection. Among environmental controls, installation of ventilation systems is a priority because ventilation reduces the number of infectious particles in the air. Natural ventilation is cost-effective but depends on climatic conditions. Supplemented intervention such as air-cleaning methods including high efficiency particulate air filtration and ultraviolet germicidal irradiation should be considered in areas where adequate ventilation is difficult to achieve. Personal protective equipment including particulate respirators provides additional benefit when administrative and environmental controls cannot assure protection.

Keywords: Tuberculosis; Infection Control; Environment, Controlled; Ventilation; Personal Protective Equipment

Introduction

Tuberculosis (TB) infection control remains a public health priority. TB outbreaks have long been reported in congregate settings including hospitals[1], prisons[2], and homeless shelters[3]. Nosocomial transmission of TB occurs in both developed and undeveloped countries, particularly in patients with human immunodeficiency virus[4,5].

The incidence of latent TB infection (LTBI) and TB disease among health care workers (HCWs) exceeds that among the general population. World Health Organization (WHO) reports have described a 5.7 times greater risk of LTBI and TB disease among HCWs than among the general population in low income settings, and 10 and 2 times higher, respectively, in high income settings[6].

TB infection control is a combination of measures designed to minimize the risk of TB transmission within populations. Guidelines suggest a three-level hierarchy of controls including administrative control, environmental control, and personal protection. Administrative control decreases TB exposure risk by rapid detection, isolation, and treatment of TB patients. Environmental control reduces the concentration of airborne infectious droplets nuclei. Personal respiratory protection includes the use of respiratory masks[6,7]. These strategies are synergistic in efficacy when combined. The synergistic combination of available nosocomial infection control strategies could prevent nearly half of extensively drug-resistant (XDR)-TB cases, even in a resource-limited setting[8].

This review provides an overview of environmental control and personal protection.

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Environmental Control

Environmental control is the second level of the TB control hierarchy. The purpose of environmental controls is to prevent spread TB by reducing the concentration of infectious airborne droplet nuclei. Primary environmental controls include infection source control and contaminated air removal using local exhaust ventilation (LEV) and general ventilation. Secondary environmental controls include airflow control for preventing contamination of air near the infection source and purification of the air using air-cleaning methods like high efficiency particulate air (HEPA) filtration or ultraviolet germicidal irradiation (UVGI)[6,7].

1. Local exhaust ventilation

LEV is a source-control technique used for capturing airborne contaminants before they disseminate into the general environment. Guidelines recommend the use of LEV for cough-inducing and aerosol-generating procedures. If LEV is not feasible, cough-inducing and aerosol-generating procedures should be performed in a room that meets the requirements for an airborne infection isolation room (AIIR)[7].

There are two basic types of local exhaust devices: complete enclosures (e.g., booths or tents) and partial enclosures (e.g., hoods). The former is the preferred type. Air from complete enclosures is HEPA-filtered and then can be exhausted outdoors or returned to the room. Complete enclosures should have sufficient airflow such that at least 99% of airborne particles can be removed during the interval between turnover of room air. Partial enclosures do not fully enclose the patient. Air is drawn across the patient's breathing zone and HEPA-filtered, then discharged back into the room or exhausted outdoors directly. The air velocity at the patient's breathing zone of partial enclosures should be kept above at least 200 feet per minute (FPM) to capture droplet nuclei[7,9].

2. General ventilation

1) Ventilation rates

The purpose of general ventilation is to dilute and remove contaminated air, and to control the direction and patterns of airflow in rooms. Ventilation rates are measured by air changes per hour (ACH). This is calculated by dividing room ventilation rate (m^3/hr) by the room volume (size, m^3). Ventilation rate for naturally ventilated spaces are difficult to calculate. Table 1 shows removal efficiencies of airborne contaminants according to ACHs[7].

A higher ventilation rate is able to provide a higher dilution of airborne pathogens and consequently reduces the risk of airborne infections. Previous studies investigated the effect of ventilation on TB infection control. In a modeling study performed in South Africa, improvements to natural ventilation could prevent average of 33% of XDR-TB cases (range, 8%–35% due to wind patterns)[8]. Another study including 17 hospitals in Canada showed that for non-isolation rooms, ventilation rates lower than two ACH were associated with higher tuberculin skin test (TST) conversion rates among HCWs[10]. American Institute of Architects guideline recommends minimum ventilation rates of two ACH in patient corridors, six ACH in patient rooms, and 12 ACH in AIIR, protective environment rooms, bronchoscopy rooms, and emergency department waiting areas[11].

Natural ventilation, such as keeping windows open on opposite sides of the room, could be more effective than mechanical ventilation. A study in Peru showed that natural ventilation achieved more than 17–40 ACH, while well functioning mechanical ventilation in isolation rooms achieved 12 ACH[12]. In contrast to negative-pressure mechanical ventilation, which is expensive to install and maintain and offers limited protection, natural ventilation may provide greater protection for little cost. However for natural ventilation control over direction of airflow is difficult and there is no easy-to-use tool for measuring ACH, because natural ventilation is climate dependent[6].

Table 1. ACH and removal efficiencies

ACH	Removal efficiency at 1 hour (%)	Minutes required for removal efficiency	
		99%	99.9%
2	86.5	138	207
4	98.2	69	104
6	99.75	46	69
12	99.9994	23	35
20	99.99999	14	21

ACH: air changes per hour.

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2) Control of airflow patterns in rooms

The two types of ventilation systems are single-pass ventilation systems and recirculation systems. In a single-pass air system, 100% of the supplied air is exhausted to the outside after passing through the room. This type is preferred because the system prevents contaminated air from being recirculated to other areas of the health-care setting. If recirculation of air is necessary, air-cleaning technologies can be used, that is, the air should be passed through HEPA filters and/or UVGI systems before being recirculated to the general ventilation system[7].

The general ventilation system should be designed and balanced so that air flows from clean to contaminated areas[7,13]. For control of the airflow direction, it is necessary to create a negative pressure in the area into which the air is desired to flow. Extractor fans can direct air flow from the clean to the contaminated area and then to the outside. In mechanical ventilation systems, the negative pressure can be achieved by creating a gradient between supply and extraction of air to achieve an exhaust flow higher than the supply flow. Control of total leakage area is critical to achieve and maintain the negative pressure. A negative pressure room must be well-sealed to prevent air from being pulled in through cracks and other gaps[7].

3) Monitoring negative pressure

Negative pressure must be monitored to ensure that air is always flowing from the corridor (or surrounding area) into the negative pressure room. The United States Centers for Disease Control and Prevention (CDC) Guidelines recommend the confirmation of negative pressure through the use of manometer measurements, smoke tubes, or other reliable indicators. Whenever used, all of the AIIR, sputum induction room and LEV devices should be checked for negative pressure daily[7]. The Korean regulations for management of government-designated isolation room recommend to install manometers to monitor pressure difference and the negative pressure controller in nurses' station[14].

3. Air-cleaning methods

Air-cleaning methods are considered an adjunct to other ventilation measures. They do not replace ventilation systems; rather, they should be considered as a complementary intervention. Such uses can increase the number of equivalent ACH in the room or area.

1) HEPA filtration

A HEPA filter is an air filter that removes ≥99.97% of particles ≥0.3 μm (including *Mycobacterium tuberculosis*–containing droplet nuclei) at a specified flow rate of air. A previous modeling study reported that supplementation of mechanical ventilation with HEPA filters could reduce XDR-TB incidence by a further 10%[8]. HEPA filters can be used as an additional safety measure to clean air from LEV devices or isolation rooms before exhausting it outdoors. In certain instances that recirculation of air is unavoidable, HEPA filters can be installed in the duct, or on the wall or ceiling of the room, or in portable air cleaners to remove infectious organisms from the air before it is returned to the general ventilation system.

2) Ultraviolet germicidal irradiation

UVGI is effective in killing or inactivating airborne *M. tuberculosis*. Typically, the optimal wavelength for UV germicidal radiation is 254 nm in the UV-C range. UVGI lamps can be placed in exhaust ducts, in upper-air irradiation systems, or in portable room air recirculation systems. This method can be used as a complementary option in healthcare facilities, for example emergency rooms, large waiting areas, and other enclosed spaces, where ventilation cannot be adequately protective and where extra protection is needed. However, this method does not provide fresh air and does not replace ventilation systems[6,7,9].

Several studies have shown that a well-designed UVGI upper room system can disinfect mycobacteria or surrogate test organisms in a test room that is equal to 10–20 equivalent air changes[15]. In an animal model study, upper-room UVGI could reduce TB transmission from 35% to 9.5% and TB disease from 8.6% to 3.6% in guinea pigs compared with the control group[16]. Similarly, another animal study performed under real hospital conditions demonstrated that the risk of TST conversion was 4.9 times higher in the control group compared with upper-room UVGI group[17]. A number of factors including UV fluence rate, ventilation, air mixing, relative humidity, photoreactivation, and temperature have been identified to affect the efficacy of UVGI systems[18]. The devices are potentially hazardous causing problems like dermatosis or photokeratitis if improperly designed or installed[19,20]. Therefore, as with any engineering control, a UVGI device needs proper design, installation, operation, and maintenance.

4. Negative pressure isolation room

A negative pressure isolation room (NPIR) is a single-occupancy patient-care room used to isolate persons with a suspected or confirmed airborne infectious disease. Some guidelines distinguish AIIR from NPIR to describe the purpose for and details of ventilation of the rooms. NPIRs should provide negative pressure in the room so that air should flow from corridors (cleaner areas) into isolation rooms (less clean areas) to prevent the spread of contaminants; and direct exhaust of air from the room to the outside of the building or recirculation of air through a HEPA filter before returning to circulation. Korean regulations for government-designated isolation room recommend airflow of ≥12 ACH when feasible, along with current CDC and WHO recommendation[14]. The

minimum negative pressure differential should be ≥2.5 Pa (0.01″ water gauge), maintaining the size of value as follows; bathroom≥isolation room≥anteroom>corridors. Results of air flow patterns should be monitored and documented daily[14]. Table 2 summarizes the comparison of regulations and guidelines for NPIRs.

Personal Protection

Although administrative and environmental controls minimize the number of areas where exposure to *M. tuberculosis* might occur, the exposure risk can still remain. Therefore, the purpose of personal protection is to further reduce the risk by using respiratory protective equipment when persons entering these areas[6,7]. Guidelines recommend the use of particulate respirators for HCWs when caring for confirmed or suspected TB, especially multidrug-resistant and XDR-TB patients, and during high-risk aerosol-generating procedures. Visitors should also wear particulate respirators when entering an enclosed space housing infectious patients[6,7]. A previous modeling study reported that respirator mask use could prevent 2% of XDR cases. If patients were provided with surgical masks, 5% of XDR infections could be averted[8].

1. Selection of respirators

The two types of respirators are powered air-purifying respirators (PAPRs) and non-PAPRs. Non-PAPRs that are certified by CDC/National Institute for Occupational Safety and Health (NIOSH) comprise nine classes of respirators including N (not resistant to oil) series, R (resistant to oil) series, and P (oil proof) series that have 95%, 99%, and 100% (99.7%) filtration efficiency, respectively, when challenged with 0.3 μm particles. PAPRs use a blower that draws air into the facepiece through filters and which are classified as high efficiency, and meet N100, R100, and P100 criteria. A tight-fitting or loose-fitting facepiece, helmet, or hood can be equipped with PAPRs[7]. For protection against TB, guidelines recommend particulate respirators that meet or exceed the N95 standards set by CDC/NIOSH or the FFP2 standards that are European Conformity (CE) certified. Either non-PAPRs with N95, N99, N100, R95, R99, R100, P95, P99, and P100 filters, or PAPRs with high efficiency filters can be used[6,7].

Respirators are available in a wide range of colors, shapes, sizes, and styles. The configurations are not standardized across models. Some N95 respirators have an exhalation valve on the front, which reduces exhalation resistance and makes it easier to breathe. Some styles will fit individuals better than

Table 2. Comparison of selected environmental controls for NPIRs of regulations and guidelines

	Korean regulation[14]	CDC[7]	ASHRAE[13]	AIA[11]
Room designation	NPIR	AIIR	AIIR	AIIR
Total ACH	Prefer ≥12 (minimum ≥6)	Prefer ≥12 (minimum ≥6)	>12	≥12
In-room HEPA recirculation allowed?	Yes	Yes	No	No
Total ACH can include HEPA recirculation?	Yes	Yes	No	No
Minimum outside ACH	2	Different among selected areas	2	2
Minimum room pressure differential	≥2.5 Pa	≥0.01" W.G.	≥0.01" W.G.	≥0.01" W.G.
Upper-air or in-duct UVGI allowed?	Not addressed	Yes, but not in lieu of ventilation	Not addressed	Yes, but not in lieu of ventilation
Anteroom required?	Yes	No	May be desirable	Noted as general option, required for protective environment isolation rooms for airborne infection isolation
Minimum anteroom ACH	Not addressed	10	10	10
Monitoring of negative pressure	Install manometers	Check daily while being used for isolation	Not addressed	Not addressed

Modified from Curry International Tuberculosis Center. Tuberculosis infection control: a practical manual for preventing TB, with permission of Curry International Tuberculosis Center[9].
NPIR: negative pressure isolation room; CDC: United States Centers for Disease Control and Prevention; ASHRAE: American Society of Heating, Refrigerating and Air Conditioning Engineers; AIA: American Institute of Architects; AIIR: airborne infection isolation room; HEPA: high efficiency particulate air; ACH: air changes per hour; HEPA: high efficiency particulate air; UVGI: ultraviolet germicidal irradiation.

others and certain styles may be more comfortable and have better fitting characteristics[21]. There does not appear to be a single best fitting respirator. Instead, studies demonstrate that fit testing programs can be designed to successfully fit nearly all workers with existing products[22]. Fit testing provides a means to determine which respirator model and size fits the wearer best as well as to confirm that the wearer can don the respirator properly. As long as the respirators exceed the NIOSH-approved N95 standards, have been fit tested, and are being used appropriately, then wearer can use them regardless of the model[21].

Some special circumstances should be considered for selection of respirators. For situations in which the risk for exposure to *M. tuberculosis* is especially high because of cough-inducing and aerosol-generating procedures (e.g., bronchoscopy), more protective respirators such as PAPRs should be considered[7,23,24]. PAPRs can also be useful for persons with facial hair or other conditions that prevent an adequate face to facepiece seal. On the other hand, when surgical procedures (or other procedures requiring a sterile field) are performed, respirators with exhalation valves or PAPRs should not be used because they do not protect the sterile field[7].

2. Fit testing

Two methods of fit testing are quantitative (QNFT) and qualitative fit testing (QLFT). Nowadays, the former serves as the gold standard. QNFT is an assessment of the adequacy of fit by numerically measuring the ratio of specific particles in the air inside and outside the breathing zone using an electronic device, which directly reflects the quantity of leakage. In contrast, the QLFT only measures the presence of leakage by an individual's response to a test agent such as isoamyl acetate or irritant smoke near the wearer's nose while wearing the respirator[25].

A given N95 respirator may fit only 0%–69% of wearers[26,27]. Other studies suggested a fit test passing rate of at least 90% of randomly selected wearers[28,29]. Training in respirator donning can improve passing a fit-test and result in an increase in protection[27,28,30].

The user must be fit tested in each respirator model before wearing a respirator. Fit testing should be performed during the initial respiratory–protection program training and periodically thereafter, based on the risk assessment of the setting and in accordance with applicable central or local government regulations[7].

3. Fit check

Aside from fit test, performing a fit check (user-seal check) on a respirator before each use is always necessary to minimize contaminant leakage into the facepiece. Because passing a fit test does not guarantee that an adequate fit will always be achieved, to go on achieving this, the wearer must perform the user fit check each time that he or she dons a respirator[31].

The fit checks for respirators are described in each user instruction from manufacturer. There are two types of fit checks; positive-pressure and negative-pressure checks. In each method, the wearer should cover the surface of the respirator and gently exhale or inhale. If the wearer feels air leaking around the face seal when exhaling or if the respirator is not drawn in toward the face when inhaling, the fit check was not successful. The respirator should be examined for any defects and readjusted. If the check is not successful despite of repeated attempts, new respirator should be tried[7].

Fit check is a simple, inexpensive, fast, and self-manageable test that can be conducted anytime and anywhere. However, this test is unable to serve as an effective alternative to QNFT because of its low sensitivity, accuracy, and predictive value[25,26,32,33]. Training wearers how to fit check increases the possibility that they will adjust respirators to proper fit[34].

Conclusion

Environmental control and personal protection are aspects that physicians could overlook when treating patients. But these aspects are indispensable to compose the TB control strategies.

The aim of environmental control is to reduce *M. tuberculosis* in the air people breathe, and the basic principle is that air should flow from more clean to more contaminated areas. Control of airflow direction can be achieved by creating a negative pressure, and properly designed ventilation systems are necessary. However, natural ventilation, such as open windows, can be sufficient to provide adequate ventilation, even if mechanical ventilation is not available. Any ventilation system should be monitored and maintained regularly. If ventilation is not sufficient, HEPA filter or UVGI can be used as complementary measures. Personal protection provides additional benefit in TB prevention. Wearers should select certificated respirators. In addition, implementation of both fit test and fit check can improve protective effect by increasing likelihood of achieving adequate fit.

Recognition of basic principles of TB infection control will be beneficial for both HCWs and patients to be protected from infection risks.

Conflicts of Interest

No potential conflict of interest relevant to this article was reported.

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