Building and Environment 59 (2013) 66–75

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Modeling the impact of control measures on tuberculosis infection in senior care facilities

Chung-Min Liao*, Yi-Jun Lin, Yi-Hsien Cheng

Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei 10617, Taiwan, ROC

ARTICLE INFO

Article history:
Received 29 June 2012
Received in revised form
30 July 2012
Accepted 8 August 2012

Keywords:
Tuberculosis
Transmission
Senior care facilities
Control measures
Modeling
Indoor air quality

ABSTRACT

Tuberculosis (TB) is among the top ten causes of death worldwide. The impacts of potential control measures on TB infection in senior care facilities are poorly understood in Taiwan region. The purpose of this paper was to assess the impacts of potential control strategies for reducing the risk for TB infection among elderly in senior care facilities and to provide the suggestions for sound TB infection control measures that should be implemented in all senior care facilities with aged people suspected of having infectious TB. We proposed an integrated-level mathematical model, incorporating the TB transmission dynamics, the Wells–Riley mathematical equation, and the competing-risks model to quantify the potential spread of TB bacilli in senior care facilities. We found that individuals living in hospital-based nursing homes had much higher exposure to TB than those in long-term and domiciliary care facilities. We showed that the proposed combinations of engineering control measures (e.g., ventilation and ultraviolet germicidal irradiation) with personal protection (e.g., surgical mask) guarantee the provision of a reliable control strategy to decrease the transmission potential and spread rate of TB bacilli aerosols in senior care facilities in that the efficacies range from 45 to 90%. The introduction of appropriate TB transmission control measures may decrease TB annual incidence in senior care facilities by as much as 76–90% of tuberculin skin test (TST) conversion. Our study implicated that sound TB infection control measures, including diagnosis and prompt treatment of infectious cases should be prioritized.

1. Introduction

Tuberculosis (TB) is among the top ten causes of death worldwide and the number of new cases is continuous to grow. Approximately one-third of world's population is infected with TB bacilli with nearly 8.8 (range: 8.5–9.2) million new cases of TB in 2010 and an estimated 1.1 (range: 0.9–1.2) million deaths from TB in the same year [1]. Thus, TB is more prevalent in the world today than at any other time [2].

TB infection is caused by inhalation of *Mycobacterium tuberculosis* bacilli in a droplet nucleus form with a diameter less than 5 μm [3,4]. All TB outbreaks have been associated with cough-generating procedures [5], and other medical examination and treatment such as bronchoscopy [6], endotracheal intubation and suctioning [7], open abscess irrigation [8], and autopsy [9]. Emergence of strains resistant to multiple drugs has led to situations where treatment is no better than before the discovery of antibiotics [10]. Diagnosis of TB remains a major barrier to control of the disease because the standard method, the acid-fast smear using sputum, does not become positive until a few months after transmission occurs [11]. Culture-based techniques are more sensitive, but still take weeks to obtain results [12].

Recent recommendations to reduce TB infection risk in health care facilities are to use engineering control measures such as improved ventilation systems, use of ultraviolet germicidal irradiation (UVGI), recirculated high-efficiency particulate air (HEPA) filter, and adoption of N95 respirators [13–17]. Drug resistance emphasizes the urgency for implementing such measures to control the spread of *M. tuberculosis* aerosol, which would also benefit reduction of patient-to-patient transmission in health care facilities. The spread of TB in indoor environments is strongly influenced by the number of infected airborne droplet nuclei and the viability of the *M. tuberculosis* bacilli. Droplet nuclei settle slowly and becomes airborne lasted for several hours. Thus, it is recognized that TB outbreaks occurred under crowded living conditions with prolonged close exposure to an infectious person (http://www.sciencedaily.com/releases/1999/02/990201072734.htm).

In Taiwan the incidence and mortality rate of TB infection are 62.0–74.6 (per 100,000 population) and 3.3–5.7 (per 100,000 population) in the period 2002–2008, respectively [18]. The cluster

* Corresponding author. Tel.: +886 2 2363 4512; fax: +886 2 2363 6433.
E-mail address: cmliao@ntu.edu.tw (C.-M. Liao).

0360-1323/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2012.08.008

infections in senior care facilities were occasionally reported in Taiwan, there were 6, 5, and 6 reported cases in January, April, and June, respectively, in 2006. Tsai et al. [19] indicated that the annual TB incidence from senior care facilities was 810 (per 1000 population) in Taipei City during the period 2004–2006, which was almost 15.5 times higher than in the general population during the same time.

We adopted a simple well-developed TB transmission model [20,21] to investigate the population dynamics of TB in indoor environments. The TB epidemic model captures five-group dynamics of susceptible, latently infected, infectious TB, noninfectious TB, and recovered and is referred to as the SLTR model. These approaches provide a predictive ability to describe the potential transmission dynamics in an indoor environment. We employed the Wells–Riley mathematical model of airborne infection [22–24] to estimate the exposure concentrations in indoor environments where cases of inhalation of airborne infection occurred based on reported epidemiological data and epidemic curves, and basic reproduction number (R_0) and its variability in a shared indoor airspace.

Here a competing-risks theory [25–27] is employed to account for the impact of different enhanced measure efficacies from both engineering controls and respiratory protection on the airborne infection risk. The competing-risks model is a probabilistic model by which the dynamics of interplay among different enhanced engineering control-measure strategies can be described. The inclusion of competing risks in the model recognized the fact that an individual might gain substantial benefits in risk reduction of airborne infection from many different control measures including technological controls at the source (by surgical masking and treatment booths), environmental controls (by ventilation, air filtration and ultraviolet germicidal irradiation), and receptor controls (by respiratory protection via respirators) [13,28–30].

The impacts of potential control measures on TB infection in senior care facilities are poorly understood in Taiwan region. Moreover, research on the effects of TB control measures has evaluated largely independently of one another. In this paper, we proposed an integrated-level mathematical model, incorporating the SLTR transmission dynamics, the Wells–Riley mathematical equation, and the competing-risks model to quantify the potential spread of TB bacilli in senior care facilities in Taiwan region. Modeling the impact of the indoor air-based control measures of the combination of the potential engineering controls and public health interventions was assessed.

The purpose of this paper was twofold: (1) to assess the impacts of potential control strategies for reducing the risk of infection from airborne *M. tuberculosis* bacilli exposure among elderly in senior care facilities and (2) to provide the suggestions for sound TB infection control measures that should be implemented in all senior care facilities with aged people suspected of having infectious TB.

2. Materials and methods

2.1. Study data

A valuable dataset were obtained from the experiment based on Fennelly et al. [31]. These data represent the unique opportunity to examine the linkage between experimental aerosol TB concentrations and particle size distribution per infectious person. Fennelly et al. [31] first quantified the aerosol concentration and size distribution of emission characteristics of *M. tuberculosis* bacilli from TB patients by the Anderson sampler for culturing cough-generated aerosols and estimating the infectivity simultaneously.

Briefly, the subject was instructed to cough into the tubing for 5 min or for as long as was comfortable while the air samples were drawn from the chamber with both impactors and recorded the cough frequency. While the subject rested after the first session of coughing, the plates and reloaded with fresh plates were be removed and labeled. Three experimental tests were conducted including sputum smear grades, sputum culture, and culturable cough-generated aerosols for 16 subjects. Particle size distributions of culturable aerosols were collected by Anderson impactors during the first day of each subject. The size ranges were divided into 0.65–1.1, 1.1–2.1, 2.1–3.3, 3.3–4.7, 4.7–7.0, and >7.0 m. Based on the relationship between experimental aerosol TB concentrations and particle size distribution per infectious person, the average culturable TB aerosol concentration can be estimated. Here, the particle size diameters 5 μm were considered to define and quantify the infectious quantum generation rates of aerosol TB [3,4].

In this study, three different settings of senior care facilities were selected to be the study populations and indoor environments: (i) long-term care facilities, (ii) domiciliary care facilities, and (iii) hospital-based nursing homes. Here we used five major control measures including (i) general ventilation (GV), (ii) advanced ventilation (AV), (iii) surgical mask (M), (iv) UVGI, and (v) HEPA. The assigned combinations of control strategies include (i) GV + M, (ii) GV + M + UVGI, (iii) GV + M + HEPA, and (iv) GV + M + UVGI + HEPA.

2.2. Indoor TB transmission model

The essential features of the SLTR TB transmission model are depicted in Fig. 1. Briefly, (i) two certain types of TB were modeled: primary progressive TB (i.e., fast TB) and latently infected TB caused by endogenous reactivation or exogenous reinfection (i.e., slow TB), (ii) a case may be spontaneously cured at a cure rate and move into the recovered noninfection state R, and (iii) an individual in the recovered state may either relapse with equal probability into infectious or noninfectious TB or may never relapse and die of other causes at background mortality rate.

The system of ordinary differential equations corresponding to Fig. 1 can be described as follows [20],

$$\frac{dS(t)}{dt} = N\delta - (\lambda + \mu)S, \tag{1}$$

$$\frac{dL(t)}{dt} = (1 - p_n)\lambda S - (\nu + \mu)L, \tag{2}$$

$$\frac{dT_i(t)}{dt} = p_n p_f \lambda S + p_s \nu L + \omega R - (\mu + \mu_T + c)T_i, \tag{3}$$

$$\frac{dT_n(t)}{dt} = p_n(1 - p_f)\lambda S + (1 - p_s)\nu L + \omega R - (\mu + \mu_T + c)T_n, \tag{4}$$

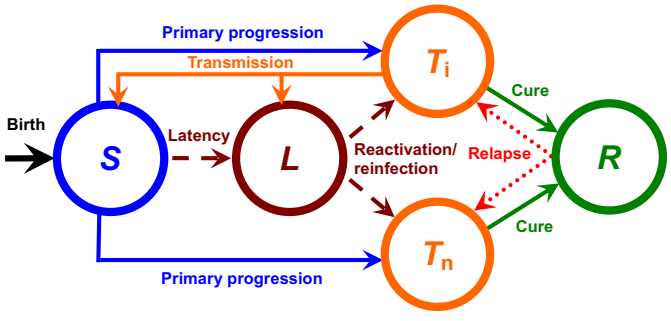

Fig. 1. Schematic of the susceptible-latently infected-active tuberculosis-recovered (SLTR) model describing TB population transmission dynamics in the present study.