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A mathematical model of effects of environmental contamination and presence of volunteers on hospital infections in China

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ABSTRACT

Deterministic and stochastic mathematical models were formulated to investigate the roles that environmental contamination and the presence of volunteers played in the dynamics of hospital infections in China. Semi-stochastic simulation was used to estimate some of the parameters by fitting the observed data and investigating the impacts of interventions such as cleaning, hand hygiene and isolation of admitted MRSA (Methicillin-resistant *Staphylococcus aureus*) patients on mean prevalence of infection. The basic reproduction number was estimated to be 0.9753. Numerical simulations show that environmental contamination is a threat to hospital infection and free-living bacteria in the environment can promote transmission and initiate infection even if an infection has died out among HCWs (health-care workers) and patients. Sensitivity analysis indicates that a contaminated environment and volunteers contribute substantially to MRSA transmission in hospital infections, and hence effective control measures should be targeted. Hand hygiene of volunteers and cleaning are more effective in reducing the mean prevalence of colonized patients than isolation of newly admitted MRSA-positive patients and hand hygiene of HCWs. Hence volunteers, a cadre of semi-professional nurses, are beneficial to both disease control and supplementary treatment of HCWs if they are well trained. However, isolation of newly admitted MRSA-positive patients could be influential and dominant in reducing the prevalence of infection when the environment within a ward is sufficiently clean.

1. Introduction

Methicillin-resistant *Staphylococcus aureus* (MRSA) *has* posed a great threat to patients in hospitals especially in intensive-care units (ICUs) worldwide. Many studies have been published to show that transmission via the hands of health-care workers (HCWs) is an important determinant of spread and persistence in a MRSA-endemic within an ICU and hand hygiene is the most effective control measure (Austin et al., 1999; Cooper et al., 1999; Grundmann et al., 2002; Raboud et al., 2005; Sebille and Valleron, 1997; Sebille et al., 1997). However, much other evidence has been proposed to show that environmental contamination is also an important factor in the transmission of MRSA (Boyce et al., 1997; Boyce, 2007; Dancer, 2008, 2009; Weber and Rutala, 1997). Environmental contamination occurs in the rooms of 73% of infected patients and 69% of colonized patients (Boyce et al., 1997). People can contaminate their hands or gloves by touching such contaminated surfaces such as floors, bed tables, door handles and so on (Boyce et al., 1997; Dancer, 2009). John M. Boyce proposed in 1997 that the contaminated environmental surface may serve as a reservoir of MRSA in a hospital. Rampling et al. (2001) reported that strains of MRSA can survive and remain viable on dust particles or skin scales for many weeks or months. There is also evidence showing that low densities of MRSA can initiate infections (Dancer, 2008). Thus, MRSA can be spread between people and the environment so that environmental contamination may make an important contribution to hospital infection (Boyce, 2007). But little is known about the role of surface contamination in the transmission of MRSA and how to make a systematic and comprehensive assessment of an MRSA epidemic and its prevention. These problems provide the motivation for our study.

In China, due to a lack of professional nurses there is a special group of health-care workers called volunteers who take care of patients' daily lives, help them to transfer from home to hospital and report irregular results of patients to doctors, but do not undertake medical care. Usually, patients and volunteers are in a one to one ratio. Because of their lack of professional experience, volunteers have lower compliance rates for hand washing and they move in/out of the ward frequently. So the special care pattern of these volunteers and environmental contamination may play more important roles in hospital infections in China

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than elsewhere. Our purpose is to assess the contribution of volunteers and free-living bacteria in the contaminated environment to the transmission of MRSA in an intensive care unit.

Mathematical models have been widely used to analyse the transmission dynamics of hospital infection. Many papers have been published for nosocomial infection (Austin et al., 1999; Cooper et al., 1999; Grundmann et al., 2002; Raboud et al., 2005; Sebille and Valleron, 1997; Sebille et al., 1997). But most of them only considered direct transmission between HCWs and patients and neglected indirect transmission via free-living bacteria in the environment. To investigate the special care pattern in China and the threat of environmental contamination to disease transmission we established a mathematical model with volunteers and free-living bacteria in the environment within an emergency ward, including both direct and indirect transmission. A combination of analytical and numerical techniques was used to analyse the model and concentrate on the effects of free-living bacteria in the environment and volunteers on the transmission of MRSA. First a deterministic model was formulated for theoretical analysis and estimating the basic reproduction number, which is the threshold for invasion. Then, because of the small population in the ward, a stochastic version of the model was also examined to look at the inherent features that are not well described by the deterministic model.

2. Methods

2.1. Model description and assumptions

We initially extend the classic ward transmission model (Austin et al., 1999; Cooper et al., 1999) to include the dynamics of free-living bacteria in the environment within an emergency ward to consider the special care patterns in China. The transmissions between HCWs and patients or volunteers and their patients are modeled by direct transmission. Since the organism of MRSA can survive for long periods outside the host in suitable conditions, free-living infective bacteria in the environment result in another possible route of transmission. We also model this indirect transmission between HCWs/volunteers and contaminated environments via free-living environmental bacteria. So, our proposed model incorporates both direct transmission and indirect transmission. Let $H^S(H^I)$ be the number of susceptible (contaminated) health care workers; $P^S(P^C)$ be the number of susceptible (infectious) patients; W be the density of bacteria of the ward (ICU) including floors, door handles, bed tables, etc.; V be the number of volunteers. Hence the susceptible HCWs can be infected either by direct contact with infected patients (denoted by $\beta_1 H^S P^C$) or indirectly by transmission via free-living bacteria (denoted by $v_1 H^S W$). Note that free-living bacteria in the environment, although, can be alive for weeks or months, cannot reproduce themselves due to no proper conditions for reproduction. In such sense contaminated HCWs or volunteers cannot release bacteria but transfer them to other places where they touched. Hence, the bacteria shedding by colonized patients with rate of λ could be moved to everywhere in the environment through HCWs, volunteers and so on. So we assumed that the bacteria in the ward is uniformly distributed and then we treat the environment in the ward as one compartment. Free-living bacteria are cleared with a rate of μ due to sterilization of the hospital, and also are collected by HCWs and volunteers. We assumed that once patients become colonized they remain colonized for the duration of their stay in the ICU.

Note that here we only model the dynamics of HCWs, patients and environmental bacteria rather than the dynamics of volunteers. That is because the states (contaminated or uncontaminated) of volunteers are essentially the same as their corresponding patients. In other words, any volunteer caring for a colonized patient is always contaminated except during the transient time after washing their hands. And he/she will soon be contaminated by touching the free-living bacteria in the environment or his/her patient. Therefore, it is reasonable to assume that the dynamics of bacteria on the volunteers is similar to those of their cared for patients (i.e., $P^C(t)=V^C(t)$ and $P^S(t)=V^S(t)$), and so is not modeled. As a consequence, we model transmission from volunteer to patient implicitly due to ignoring dynamics of volunteers. We use $\beta_3 \xi V^S W$ to describe that volunteers are contaminated by the free-living bacteria and then quickly infect their corresponding cared patients, where β_3 denotes the transmission rate between patients and their corresponding volunteers and ξ is the indirect transmission rate between volunteers and environment via free-living bacteria. Denote $v_2=\beta_3\xi$, then $v_2 P^S W=\beta_3 \xi V^S W$, which describes transmission from volunteer to patient. Whereas, the transmission from HCWs to patients are explicitly modeled by $\beta_2 P^S H^C$ as usual way applied by many researchers (Austin et al., 1999; Cooper et al., 1999). That is because patients and HCWs are not one to one relationship, moreover, the states (contaminated or uncontaminated) of HCWs are not same as those of patients, compared to relationship between volunteers and their cared for patients.

Because there are no physical contacts among people except between HCWs and patients as well as volunteers and their corresponding patients, we assume there is no direct patient–patient, HCW–HCW, volunteer–volunteer or volunteer–HCW transmission. Also, in an ICU patients cannot move freely in the ward so it is reasonable to assume that there is no environment–patient transmission. On the basis of the diagram shown in Fig. 1 we formulate the model as follows:

$$\begin{cases} \dfrac{dH^S}{dt} = -(\beta_1 P^C + v_1 W)H^S + \gamma H^C \\ \dfrac{dH^C}{dt} = (\beta_1 P^C + v_1 W)H^S - \gamma H^C \\ \dfrac{dP^S}{dt} = (1-\overline{\phi})\Lambda - ((1-q)\overline{\beta}_2 H^C + (1-p)\overline{v}_2 W)P^S - d_1 P^S \\ \dfrac{dP^C}{dt} = (1-r)\overline{\phi}\Lambda + ((1-q)\overline{\beta}_2 H^C + (1-p)\overline{v}_2 W)P^S - d_2 P^C \\ \dfrac{dW}{dt} = \lambda P^C - (\mu + \xi V + v_1 H)W \end{cases} \tag{1}$$

where $H=H^S+H^C$ is a constant, and $V(t)=P(t)$ due to the one-to-one relationship between patients and their corresponding volunteers. Parameters p and q represent the hand hygiene compliance

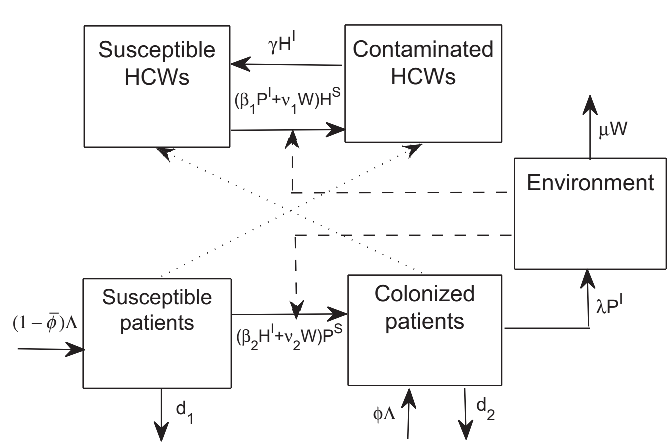

Fig. 1. A flow diagram for HCW–patient–volunteer MRSA transmission in an ICU showing the possible effect of hospital infection control measures.