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Research Article

An *SIRS* Model for Assessing Impact of Media Coverage

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An *SIRS* model incorporating a general nonlinear contact function is formulated and analyzed. When the basic reproduction number $\mathscr{R}_0 < 1$, the disease-free equilibrium is locally asymptotically stable. There is a unique endemic equilibrium that is locally asymptotically stable if $\mathscr{R}_0 > 1$. Under some conditions, the endemic equilibrium is globally asymptotically stable. At last, we conduct numerical simulations to illustrate some results which shed light on the media report that may be the very effective method for infectious disease control.

1. Introduction

Media coverage has an enormous impact on the spread and control of infectious diseases [1–6]. The paper [7] considered that the evidence shows that, faced with lethal or novel pathogens, people will change their behavior to try to reduce their risk.

In [8], the authors studied the effect of media coverage on the spreading of disease by using the following model:

$$\begin{aligned} \frac{dS(t)}{dt} &= \Lambda - \mu S - \frac{(\beta_1 - \beta_2 f(I)) SI}{(S+I)} + \gamma I, \\ \frac{dI(t)}{dt} &= \frac{(\beta_1 - \beta_2 f(I)) SI}{(S+I)} - (\mu + \alpha + \gamma) I, \end{aligned} \tag{1}$$

where the authors proposed an *SIS* model with the general nonlinear contact function $\beta(I) = \beta_1 - \beta_2 f(I)$ and β_1 and β_2 are positive constants. Here, β_1 is the usual contact rate without considering the infective individuals and β_2 is the maximum reduced contact rate due to the presence of the infected individuals. Everyone cannot avoid contact with others in every case so it is assumed $\beta_1 > \beta_2$. When infective individuals appear in a region, people reduce their contact with others to avoid being infected when they are aware of the potential danger of being infected, and the more infective individuals being reported, the less contact the susceptible will make with others. Therefore, it is assumed that $f'(I) \geq 0$. The limited power of the infection due to contact is reflected by the saturating function $\lim_{I\to\infty} f(I) = 1$. In summary, the functional $f(I)$ satisfies $f(0) = 0$, $f'(I) \geq 0$, $\lim_{I\to\infty} f(I) = 1$.

In this paper, using the same contact function as [8], we study an *SIRS* model with media coverage. Let $S(t)$, $I(t)$, and $R(t)$ denote the number of susceptible individuals, infected individuals, and recovered individuals at time t, respectively. The ordinary differential equation with nonnegative initial conditions is as follows:

$$\begin{aligned} \frac{dS(t)}{dt} &= \Lambda - \mu S - (\beta_1 - \beta_2 f(I)) SI + \sigma R, \\ \frac{dI(t)}{dt} &= (\beta_1 - \beta_2 f(I)) SI - (\alpha + \mu + \lambda) I, \\ \frac{dR(t)}{dt} &= \lambda I - (\mu + \sigma) R. \end{aligned} \tag{2}$$

Here, all the variables and parameters of the model are nonnegative. Λ is the recruitment rate, μ represents the natural death rate, σ is the loss of constant immunity rate, α is the diseases induced constant death rate, and λ is constant recovery rate.

We have $dS/dt|_{S=0,R\geq 0} > 0$, $dI/dt|_{I=0} = 0$, $dR/dt|_{R=0,I\geq 0} \geq 0$, and $d(S+I+R)/dt|_{S+I+R=\Lambda/\mu} \leq 0$. So,

$$\Omega = \left\{ (S, I, R) \in \mathbb{R}_+^3 : S + I + R \leq \frac{\Lambda}{\mu} \right\} \tag{3}$$

is a positive invariant set of (2).

2. The Existence of the Equilibria

It is easy to see that model (2) always has a disease-free equilibrium $E_0 = (S_0, 0, 0)$, where $S_0 = \Lambda/\mu$. Let $x = (I, S, R)^\top$. Then model (2) can be written as

$$\frac{dx}{dt} = \mathscr{F}(x) - \mathscr{V}(x), \tag{4}$$

where

$$\mathscr{F}(x) = \begin{pmatrix} (\beta_1 - \beta_2 f(I)) SI \\ 0 \\ 0 \end{pmatrix},$$
$$\mathscr{V}(x) = \begin{pmatrix} (\alpha + \mu + \lambda) I \\ -\Lambda + \mu S + (\beta_1 + \beta_2 f(I)) SI - \sigma R \\ -\lambda I + (\mu + \sigma) R \end{pmatrix}. \tag{5}$$

According to Theorem 2 in [9], the basic reproduction number of model (2) is

$$\mathscr{R}_0 = \frac{\beta_1 S_0}{\alpha + \mu + \lambda} = \frac{\beta_1 \Lambda}{\mu(\alpha + \mu + \lambda)}. \tag{6}$$

In the following, the existence and uniqueness of the endemic equilibrium is established when $\mathscr{R}_0 > 1$. The components of the endemic equilibrium $E^*(S^*, I^*, R^*)$ satisfy

$$\begin{gathered} \Lambda - \mu S^* - (\beta_1 - \beta_2 f(I^*)) S^* I^* + \sigma R^* = 0, \\ (\beta_1 - \beta_2 f(I^*)) S^* - (\alpha + \mu + \lambda) = 0, \\ \lambda I^* - (\mu + \sigma) R^* = 0 \end{gathered} \tag{7}$$

which gives

$$R^* = \frac{\lambda I^*}{\mu + \sigma}, \tag{8}$$

$$S^* = \frac{\alpha + \mu + \lambda}{\beta_1 - \beta_2 f(I^*)}, \tag{9}$$

$$\Lambda - \mu R^* - \mu S^* - (\mu + \alpha) I^* = 0. \tag{10}$$

Substituting (8) and (9) into (10), we get $\phi(I^*) = 0$, where

$$\phi(I) = \Lambda - \frac{\mu\lambda I}{\mu + \sigma} - \frac{\mu(\alpha + \mu + \lambda)}{\beta_1 - \beta_2 f(I)} - (\alpha + \mu) I. \tag{11}$$

Hence, if an endemic equilibrium exists, its coordinate must be a root of $\phi(I) = 0$ in the interval $I \in (0, \Lambda/\mu)$.

Note that

$$\phi'(I) = -\frac{\mu\lambda}{\mu + \sigma} - \frac{\beta_2 \mu (\alpha + \mu + \lambda) f'(I)}{(\beta_1 - \beta_2 f(I))^2} - \alpha - \mu < 0. \tag{12}$$

Hence, $\phi(I)$ is monotonically decreasing for $I > 0$.

Besides,

$$\begin{gathered} \phi\left(\frac{\Lambda}{\mu}\right) = -\frac{\lambda\Lambda}{\mu + \sigma} - \frac{\mu(\alpha + \mu + \lambda)}{\beta_1 - \beta_2 f(\Lambda/\mu)} - \frac{(\alpha + \mu)\Lambda}{\mu} < 0, \\ \phi(0) = \frac{\mu(\alpha + \mu + \lambda)(\mathscr{R}_0 - 1)}{\beta_1}. \end{gathered} \tag{13}$$

Therefore, when $\mathscr{R}_0 > 1$, $\phi(0) > 0$, $\phi(I)$ has unique positive root I^* in the interval $I \in (0, \Lambda/\mu)$. S^* and R^* are uniquely determined by I^*. Therefore, model (2) has a unique endemic equilibrium $E^*(S^*, I^*, R^*)$ if $\mathscr{R}_0 > 1$. Otherwise, there is no endemic equilibrium.

3. Stability of the Disease-Free Equilibrium

Theorem 1. *The disease-free equilibrium E_0 is locally asymptotically stable for $\mathscr{R}_0 < 1$ and unstable for $\mathscr{R}_0 > 1$.*

Proof. The Jacobian matrix of system (2) at $X = E_0$ is

$$J(E_0) = \begin{pmatrix} -\mu & \dfrac{\beta_1 \Lambda}{\mu} & \sigma \\ 0 & \dfrac{\beta_1 \Lambda}{\mu} - (\alpha + \mu + \lambda) & 0 \\ 0 & \lambda & -(\mu + \sigma) \end{pmatrix}. \tag{14}$$

The eigenvalues of the matrix $J(E_0)$ are given by

$$\xi_1 = -\mu, \qquad \xi_2 = -(\mu + \sigma), \qquad \xi_3 = (\alpha + \mu + \lambda)(\mathscr{R}_0 - 1). \tag{15}$$

If $\mathscr{R}_0 < 1$, then $\xi_3 < 0$. Thus, using the Routh-Hurwitz criterion, all eigenvalues of $J(E_0)$ have negative real parts, and E_0 is locally asymptotically stable for system (2). □

4. Stability of the Endemic Equilibrium

Theorem 2. *If $\mathscr{R}_0 > 1$, $E^*(S^*, I^*, R^*)$ is locally asymptotically stable.*

Proof. Let

$$\begin{gathered} A = (\beta_1 - \beta_2 f(I^*)) I^* > 0, \\ B = \beta_2 f'(I^*) S^* I^* > 0. \end{gathered} \tag{16}$$

The Jacobian matrix at $E^*(S^*, I^*, R^*)$ is

$$J(E^*) = \begin{pmatrix} -\mu - A & B - (\alpha + \mu + \lambda) & \sigma \\ A & -B & 0 \\ 0 & \lambda & -(\mu + \sigma) \end{pmatrix}. \tag{17}$$

The characteristic polynomial of the matrix $J(E^*)$ is given by

$$\det(\delta I - J(E^*)) = a_0 \delta^3 + a_1 \delta^2 + a_2 \delta + a_3, \tag{18}$$

where

$$\begin{aligned} a_0 &= 1, \\ a_1 &= A + B + \sigma + 2\mu > 0, \\ a_2 &= 2B\mu + \mu\sigma + \mu^2 + B\sigma + A\sigma + A\alpha + A\lambda \\ &\quad + 2A\mu > 0, \end{aligned}$$

$$
\begin{aligned}
a_3 &= A\alpha\sigma + B\mu^2 + B\mu\sigma + A\mu\left(\mu + \sigma + \alpha + \lambda\right) > 0, \\
a_1 a_2 - a_3 &= \sigma(A + B)^2 + A\lambda\sigma + 5A\mu\sigma + A\mu\lambda \\
&\quad + 4B\mu\sigma + 5AB\mu + A\mu\alpha + 4B\mu^2 + 6A\mu^2 + 2 \\
&\quad \cdot B^2\mu + 3A^2\mu + \mu\sigma^2 + 3\sigma\mu^2 + B\sigma^2 + A\sigma^2 \\
&\quad + 2\mu^3 + AB\alpha + AB\lambda + \Phi^2\alpha + A^2\lambda > 0.
\end{aligned} \tag{19}
$$

Thus, using Routh-Hurwitz criterion, all eigenvalues of $J(E^*)$ have negative real parts which means $E^*(S^*, I^*, R^*)$ is locally asymptotically stable. □

Theorem 3. *If $\mathscr{R}_0 > 1$, $E^*(S^*, I^*, R^*)$ is globally asymptotically stable, provided that inequalities $\mu > \sigma$ and $\mu > \lambda$ hold true.*

In order to study the global stability of $E^*(S^*, I^*, R^*)$, we use the geometrical approach which is developed in the papers of Smith [10] and Li and Muldowney [11]. We obtain simple sufficient conditions that $E^*(S^*, I^*, R^*)$ is globally asymptotically stable when $\mathscr{R}_0 > 1$. At first, we give a brief outline of this geometrical approach.

Let $x \mapsto f(x) \in R^n$ be a C^1 function for x in an open set $D \in R^n$. Consider the differential equation

$$x' = f(x). \tag{20}$$

Denote by $x(t, x_0)$ the solution to (20) such that $x(0, x_0)$. We make the following two assumptions.

(i) There exists a compact absorbing set $K \subset D$.

(ii) Equation (20) has a unique equilibrium $\overline{x}$ in D.

The equilibrium $\overline{x}$ is said to be globally stable in D if it is locally stable and all trajectories in D converge to $\overline{x}$.

The following general global stability principle is established in [11].

Let $x \mapsto P(x)$ be an $\binom{n}{2} \times \binom{n}{2}$ matrix-valued function that is C^1 for $x \in D$. Assume that $P^{-1}(x)$ exists and is continuous for $x \in K$, the compact absorbing set. A quantity q is defined as

$$q = \limsup_{t \to \infty} \sup_{x \in K} \frac{1}{t} \int_0^t \overline{\mu}\left(Q\left(x\left(s, x_0\right)\right)\right) ds, \tag{21}$$

where

$$Q = P_f P^{-1} + P J^{[2]} P^{-1} \tag{22}$$

and $J^{[2]}$ is the second additive compound matrix of the Jacobian matrix J. The matrix P_f is obtained by replacing each entry p_{ij} of P by its derivative in the direction of f, $p_{ij} f$, and $\overline{\mu}(Q)$ is the Lozinskiĭ measure of Q with respect to a vector norm $|\cdot|$ in R^N (where $N = \binom{n}{2}$) defined by [12]

$$\overline{\mu}(Q) = \lim_{h \to 0^+} \frac{|I + hQ| - 1}{h}. \tag{23}$$

It is shown in [11] that, if D is simply connected, the condition $q < 0$ rules out the presence of any orbit that gives rise to a simple closed rectifiable curve that is invariant for (20), such as periodic orbits, homoclinic orbits, and heteroclinic cycles. As a consequence, the following global stability result is proved in Theorem 3.5 of [11].

Lemma 4. *Assume that D is simply connected and that the assumptions (i) and (ii) hold. Then, the unique equilibrium $\overline{x}$ of (20) is globally asymptotically stable in D if $q < 0$.*

We now apply Lemma 4 to prove Theorem 3.

Proof. The paper [13] showed that the existence of a compact set which is absorbing in the interior of Ω is equivalent to proving that (2) is uniformly persistent, which means that there exits $c > 0$ such that every solution $(S(t), I(t), R(t))$ of (2) with $(S(0), I(0), R(0))$ in the interior Ω satisfies

$$\liminf_{t \to \infty} |(S(t), I(t), R(t))| \geq c. \tag{24}$$

In fact, when $\mathscr{R}_0 > 1$, then E_0 is unstable. The instability of E_0, together with $E_0 \in \partial\Omega$, implies the uniform persistence [14]. Thus, (i) is verified. Moreover, as previously shown, E^* is the only equilibrium in the interior of Ω, so that (ii) is verified, too. Let $x = (S, I, R)$ and $f(x)$ denote the vector field of (2). The Jacobian matrix $J = \partial f / \partial x$ associated with a general solution $x(t)$ of (2) is

$$J = \begin{pmatrix} -\mu - \Phi & \Psi - (\alpha + \mu + \lambda) & \sigma \\ \Phi & -\Psi & 0 \\ 0 & \lambda & -(\mu + \sigma) \end{pmatrix}, \tag{25}$$

where

$$
\begin{aligned}
\Phi &= \left(\beta_1 - \beta_2 f(I)\right) I > 0, \\
\Psi &= \beta_2 f'(I) SI > 0,
\end{aligned} \tag{26}
$$

and its second additive compound matrix $J^{[2]}$ is

$$J^{[2]} = \begin{pmatrix} -\mu - \Phi - \Psi & 0 & -\sigma \\ \lambda & -\Phi - 2\mu - \sigma & \Psi - (\alpha + \mu + \lambda) \\ 0 & \Phi & -\Psi - \mu - \sigma \end{pmatrix}. \tag{27}$$

Set the function $P(x) = P(S, I, R) = \operatorname{diag}\{I/R, I/R, I/R\}$; then

$$P_f P^{-1} = \operatorname{diag}\left\{\frac{I'}{I} - \frac{R'}{R}, \frac{I'}{I} - \frac{R'}{R}, \frac{I'}{I} - \frac{R'}{R}\right\}, \tag{28}$$

and the matrix $Q = P_f P^{-1} + P J^{[2]} P^{-1}$ can be written in block form

$$Q = \begin{pmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{pmatrix}, \tag{29}$$

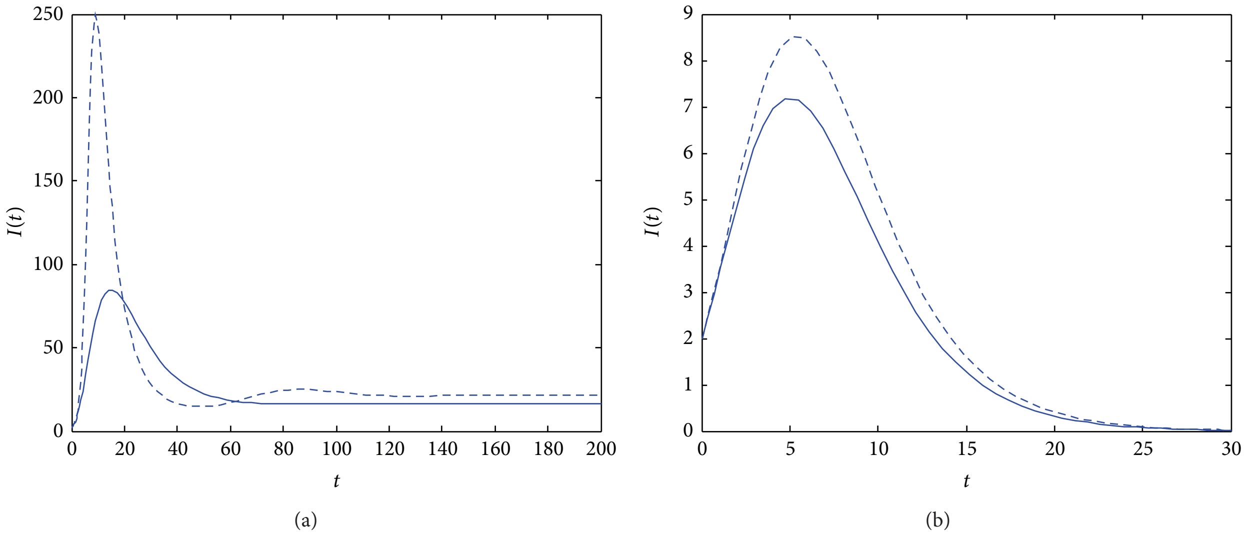

FIGURE 1: The tendency of the infected population varies. The solid line represents the case when $\beta_2 = 0.0018$, and the dashed line represents the case when $\beta_2 = 0$.

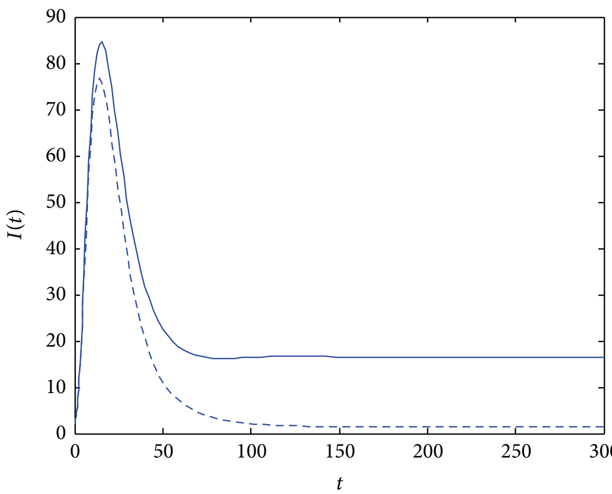

FIGURE 2: Variation of the number of infected under different Λ. The solid line represents the case when $\Lambda = 5$, and the dashed line represents the case when $\Lambda = 2$.

where

$$Q_{11} = -\frac{R'}{R} - \mu - \Phi - \Psi,$$

$$Q_{12} = (0, -\sigma),$$

$$Q_{21} = \begin{pmatrix} \lambda \\ 0 \end{pmatrix},$$

$$Q_{22} = \begin{pmatrix} \frac{I'}{I} - \frac{R'}{R} - \Phi - 2\mu - \sigma & \Psi - \alpha - \mu - \lambda \\ \Phi & \frac{I'}{I} - \frac{R'}{R} - \Psi - \mu - \sigma \end{pmatrix}. \tag{30}$$

The vector norm $|\cdot|$ in $R^3 \cong R^{\binom{3}{2}}$ is chosen as $|(u, v, w)| = \sup\{|u|, |v| + |w|\}$ and let $\mu(\cdot)$ be the Lozinskiĭ measure with respect to this norm. Following the method in [15], we have

$$\overline{\mu}(Q) \leq \sup\{g_1, g_2\}, \tag{31}$$

where

$$g_1 = \overline{\mu}_1(Q_{11}) + |Q_{12}|,$$
$$g_2 = \overline{\mu}_1(Q_{22}) + |Q_{21}|. \tag{32}$$

$|Q_{12}|$ and $|Q_{21}|$ being the matrix norm with respect to the l_1 vector norm. More specifically,

$$\overline{\mu}_1(Q_{11}) = -\frac{R'}{R} - \mu - \Phi - \Psi,$$
$$|Q_{12}| = \sigma,$$
$$|Q_{21}| = \lambda. \tag{33}$$

To calculate $\overline{\mu}_1(Q_{22})$, add the absolute value of the off-diagonal elements to the diagonal one in each column of Q_{22} and then take the maximum of two sums. We thus obtain

$$\overline{\mu}_1(Q_{22}) = \frac{I'}{I} - \frac{R'}{R} - 2\mu - \sigma. \tag{34}$$

Therefore, we have

$$g_1 = \overline{\mu}_1(Q_{11}) + |Q_{12}| = \sigma - \frac{R'}{R} - \mu - \Phi - \Psi,$$
$$g_2 = \overline{\mu}_1(Q_{22}) + |Q_{21}| = \lambda + \frac{I'}{I} - \frac{R'}{R} - 2\mu - \sigma. \tag{35}$$

This leads to

$$\overline{\mu}(Q) \leq \frac{I'}{I} - \mu + \max\{\sigma, \lambda\}. \tag{36}$$

Table 1: Parameters for the simulation.

Figure	Parameter values						
	Λ	μ	β_1	β_2	α	λ	σ
Figure 1(a)	5	0.02	0.002	0.0018, 0	0.1	0.05	0.01
Figure 1(b)	5	0.2	0.002	0.0018, 0	0.1	0.05	0.01
Figure 2	5, 2	0.02	0.002	0.0018	0.1	0.05	0.01
Figure 3	5	0.02	0.002	0.0018	0.1	0.05, 0.5	0.01

We can deduce that if

$$\begin{gathered} \mu > \sigma, \\ \mu > \lambda \end{gathered} \tag{37}$$

hold, then

$$\bar{\mu}(Q) \leq \frac{I'}{I} - d, \tag{38}$$

where

$$d = \min\{\mu - \sigma, \mu - \lambda\} > 0. \tag{39}$$

Along each solution $(S(t), I(t), R(t))$ of system (2) for which $(S(0), I(0), R(0)) \in \Omega$, we have

$$\begin{aligned} q &= \limsup_{t\to\infty} \sup_{x_0\in\Omega} \frac{1}{t} \int_0^t \bar{\mu}(Q(x(s, x_0)))\, ds \\ &\leq -\frac{d}{2} < 0. \end{aligned} \tag{40}$$

According to Lemma 4, if $\mathscr{R}_0 > 1$, then the endemic equilibrium $E^*(S^*, I^*, R^*)$ of system (2) is globally asymptotically stable in Ω. □

5. Simulation Study and Discussion

To complement the mathematical analysis carried out in the previous section, using the Runge-Kutta method, we now investigate some numerical properties of (2). Choose $f(I) = I/(b + I)$, $b > 0$, and b reflects the reactive velocity of people and media coverage to the disease. Related parameter values are listed in Table 1.

Figure 1(a) shows that, when $\mathscr{R}_0 = 2.941 > 1$, the number of infected individuals is asymptotically stable, and the media coverage is beneficial to decrease the number of infected individuals. Figure 1(b) shows that, when $\mathscr{R}_0 = 0.029 < 1$, the number of infected individuals tends to zero point, and the media coverage can quicken the extinction of infectious disease.

Furthermore, the analysis of the impact of related parameters on the infectious disease progression is fairly important. From the definition of $\mathscr{R}_0$, it can be seen that

$$\begin{aligned} \frac{\partial \mathscr{R}_0}{\partial \Lambda} &= \frac{\beta_1}{\mu(\alpha + \mu + \lambda)} > 0, \\ \frac{\partial \mathscr{R}_0}{\partial \lambda} &= -\frac{\beta_1 \Lambda}{\mu(\alpha + \mu + \lambda)^2} < 0. \end{aligned} \tag{41}$$

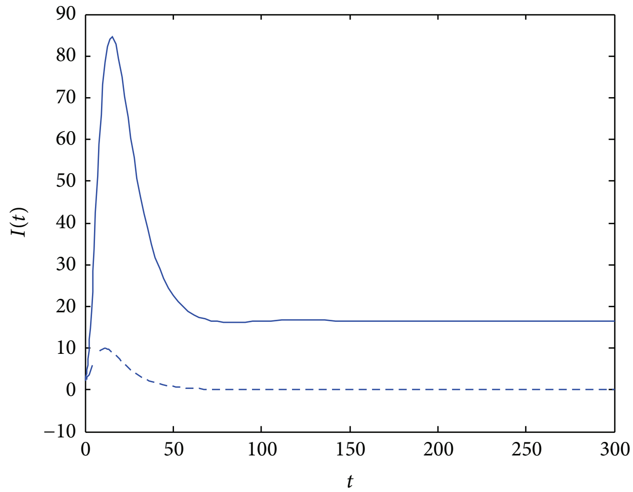

Figure 3: Variation of the number of infected under different λ. The solid line represents the case when $\lambda = 0.05$, and the dashed line represents the case when $\lambda = 0.5$.

Hence, $\mathscr{R}_0$ is an increasing function of Λ and is a decreasing function of λ. The mathematical results show that the basic reproduction number $\mathscr{R}_0$ satisfies a threshold property. When $\mathscr{R}_0 < 1$, it has been proved that the disease-free equilibrium E_0 is locally asymptotically stable, and the diseases will be eliminated from the community. And, when $\mathscr{R}_0 > 1$, the unique endemic equilibrium E^* is globally asymptotically stable, and the diseases persist. This shows that $\mathscr{R}_0$ reduces to a value less than unity by reducing Λ or increasing λ, so as to control the spread of infectious diseases.

From Figure 2, we can find that the number of infected individuals decreases as the recruitment rate (Λ) decreases. Organized measures such as limitation of travel, closure of public places, or isolation are beneficial to lessen the recruitment rate to control the spreading of infectious diseases. Figure 3 reveals that the number of infected individuals decreases as the recovery rate (λ) increases. So timely and effective treatment is regarded as one good method in managing infectious diseases.

Based on the obtained results, we can get that media coverage has an effective impact on the control and spread of infectious diseases. It is hoped that these control strategies we considered may offer some useful suggestions for authorities. In addition, we can generalize the current model by incorporating some control methods, such as isolation and treatment strategies. A more realistic model deserves to be considered.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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