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ARTICLE

A note on infectious disease, economic growth, and related government policy

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Abstract

Introducing susceptible-infected-recovered epidemiology dynamics with vaccines into an endogenous growth model, we investigate the impact of government infectious disease policy on macroeconomic performance. We find that any expenditure that improves health, whether to reduce the contact rate or increase the recovery rate or the vaccination rate, and regardless of whether it comes directly from the households or the government, has a positive impact on economic growth, but does not necessarily improve the welfare. The reason people's health has improved but their welfare has fallen is because government expenditures must be covered by taxes, which will reduce their disposable income and consumption.

Keywords: Economic growth; epidemiology; infectious diseases; welfare

1. Introduction

Along with domestic production capacity and human capital, many other factors potentially affect a country's economic performance, including medical quality, environmental sanitation, and the health of people, which all have an impact on a country's economics. However, even in highly developed countries with high-quality public health systems, diseases may still threaten the lives of people. Especially with globalization, the global transmission of people and goods has increased the spread of infectious disease, including COVID-19, which has recently affected human health and economics worldwide. The purpose of this paper is to investigate the impact of infectious disease and related government policies on macroeconomic performance.

Improving health around the world is an important social objective, with many existing studies investigating the effects of health on economic performance, but with mixed empirical results. For example, Acemoglu and Johnson (2007) found that there is no evidence that the large increase in life expectancy has actually raised per capita income. This result contrasts with Weil (2007), which revealed that the effect of health on income is economically significant. Related discussions are also found in Ashraf et al. (2008) and Bloom et al. (2014). Regardless, from an economic or humanitarian perspective, improving human health is an important policy issue for governments. Accordingly, this paper discusses how governments can best assist when an infectious disease epidemic arises.

On the one hand, the government could improve the health of people by increasing investment in activities or setting regulations that lower the prevalence of infectious diseases. On the other hand, they could provide better therapy that attenuates infection. The former includes research and development (R&D) into vaccines, the production of personal epidemical prevention

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equipment (such as masks, gowns, disposable gloves, and eye protection equipment), and social distancing restrictions, such as closing the city and lockdowns, among others. The latter includes the upgrading of medical equipment, the expansion of hospital wards, and the invention of therapeutic drugs. Especially under the economics of the COVID-19 pandemic, these government expenditures are actually being incurred and are affecting the spread of infectious diseases. Note that Gersovitz and Hammer (2004) and Gersovitz and Hammer (2005) discuss the externalities arising from infectious disease prevention and therapy.

Many studies have constructed theoretical models to explore the relationship between disease and economic development. For example, Chakraborty et al. (2010) incorporated disease behavior and prevention in a growth model and found that infectious disease can generate an unconventional growth trap. Similarly, Aksan and Chakraborty (2014) constructed a three-period overlapping generations model with epidemiological transitions that could qualitatively and quantitatively account for demographic and disease transitions in sub-Saharan Africa. However, neither study considered the impact of epidemiological dynamics, which incorporates whether healthy people are infected and whether infected people can recover, nor did they discuss government policy relating to infectious disease. For its part, our paper explores these critical issues.

Different infectious diseases have dissimilar transmission mechanisms, including the susceptible-infectious-susceptible (*SIS*) epidemiology model, in which there is no subsequent immunity conferred to the disease upon recovery, and the susceptible-infected-recovered (*SIR)* epidemiology model, in which we can remove a group of people from the susceptible-infectious interaction by recovery with immunity and vaccination. For other diseases with similar transmission paths, see Goenka et al. (2014, p. 35). In this paper, we extend the *SIR* epidemiology model with vaccines as we investigate the impact of different government policies for dealing with infectious disease that include vaccines. Many extant studies have introduced *SIS* dynamics into the growth model. For example, Goenka and Liu (2012) focused on the impact of diseases on endogenous labor productivity and Goenka et al. (2014) used health capital to internalize both the contact and the recovery rates. However, neither study was able to discuss the endogenous growth rate and human capital accumulation we investigate in our model. In addition, in our paper, whether people become infected and whether they can recover is subject to their own health expenditures and government policies.

Although Goenka and Liu (2020) used the *SIS* epidemiology model and also discussed the endogenous growth rate, Goenka and Liu (2012), Goenka et al. (2014), and Goenka and Liu (2020) each set the contact and recovery rates in the *SIS* model irrelevant to the government policy. However, different government medical expenditures will affect the dynamics of infectious diseases by affecting the contact, vaccination, and recovery rates. Besides, they ignored the fact that some people may be removed from the susceptible-infectious interaction by recovery with immunity and vaccination. Therefore, we extend the *SIR* epidemiology dynamics with vaccines and set the contact, vaccination, and recovery rates that depend on government medical policies and household medical expenditure.

In this paper, we incorporate the *SIR* epidemiology dynamics with vaccines into a two-sector endogenous growth model and investigate the impact of government medical policies and household medical expenditure that affect the prevention and therapy of infectious diseases on macroeconomic performance. The contribution of this paper is that this paper models real-world government-related medical expenditures, which will affect the contact, vaccination, and recovery rates, and investigates the impact of specific government medical policies, which is not discussed in the existing literature.

The structure of the paper is as follows. Section 2 constructs a benchmark growth model including epidemiology dynamics and proves the existence of the long-run equilibrium. This section also provides some comparative statics analysis. Section 3 analyzes numerically the impact of government policies related to disease relief. Section 4 provides some brief concluding remarks.

2. The model

This section forms the basic analytical framework, which extends the Lucas (1988) endogenous growth model to include *SIR* epidemiology dynamics with vaccines. We populate the economy in this model with a continuum of representative households of mass one, a continuum of representative firms also of mass one, and a fiscal authority.

2.1 The revised SIR epidemiology model

We first briefly introduce the *SIR* epidemiology model with vaccines and then describe the modifications made in this analysis. The epidemiology dynamic model divides the population into a number of categories according to the epidemiological situation. Different diseases have different transmission mechanisms. Details of the epidemiological models are available in Hethcote (2008). In this paper, people face three epidemiological situations, the first is healthy and susceptible to the disease, referred to as S, the second is infected and capable of transmitting the disease, referred to as I, and the third is removed from the susceptible-infectious interaction by recovery through immunity, vaccination, or death, referred to as R. If the total population is N, then $S+I+R=N$.

People are born healthy with birth rate b, where p proportion is vaccinated and thus removed from the susceptible-infectious interaction, and the remainder remains susceptible to the disease. In addition, the death rate is d. Susceptible people have a probability I/N of encountering infected people with contact rate α. That is, the number of new infected cases per unit of time is $\alpha(I/N)S$. Infected people have a chance γ of recovering; thus, the total number of individuals recovering from the disease at each time period is γI. We take COVID-19 as an example where there are still very few people who have been vaccinated or have been infected, recovered, and then infected again. We set σ as the relapse rate of the disease. Therefore, according to Hethcote (2008), the *SIR* epidemiology model with vaccines yields the following system of differential equations:

$$\begin{aligned}
\dot{S} &= bN(1-p) - \alpha(I/N)S - dS, \\
\dot{I} &= \alpha(I/N)S - \gamma I - dI + \sigma R, \\
\dot{R} &= bNp + \gamma I - dR - \sigma R, \\
N &= S + I + R, \\
S, I &\geq 0; S(0), I(0) > 0, R(0) \geq 0 \ \text{ given.}
\end{aligned}$$

Defining $s \equiv S/N$, $r \equiv R/N$, and $s+r$ as the fraction of healthy people, we derive the following dynamic equation:

$$\dot{s} = b(1-p-s) - \alpha(I/N)s, \tag{1}$$

$$\dot{r} = b(p-r) + \gamma(1-s-r) - \sigma r. \tag{2}$$

Note that $I/N = 1-s-r$ in equilibrium. However, we take it as given by households that people cannot control what epidemiological conditions they encounter.

In this analysis, we revise the above *SIR* epidemiology model to one where the public can influence their health through increasing medical expenditure. In addition, the government can influence people's health through medical and vaccine R&D or purchase expenditure and through setting regulations like closing the city, wearing masks, and social distancing policies. We set that the recovery rate follows the following function:

$$\gamma = 1 - \phi_1 \exp\left(-\frac{G_1}{\bar{y}}\right) - \phi_2 \exp\left(-\frac{m}{\bar{y}}\right), \tag{3a}$$

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where G_1 is the government's expenditure on R&D or purchase of medicines to treat disease, m is household health expenditure, $\bar{y}$ is the economywide average gross domestic product (GDP) per capita, also taken as given by households, and $0 < \phi_1, \phi_2, \phi_1 + \phi_2 < 1$. Note that if neither the government nor the people spend money on disease treatment, then $\gamma = 1 - \phi_1 - \phi_2 \in (0, 1)$. In addition, $\partial\gamma/\partial G_1 > 0$, $\partial\gamma/\partial m > 0$ $\partial^2\gamma/\partial G_1^2 < 0$, and $\partial^2\gamma/\partial m^2 < 0$. That is, the more money the government or the public spends on disease treatment, the higher the recovery rate, but the degree of impact will decrease.

Moreover, the government can set regulations like closing cities and social distancing policies or buying masks and forcing people to wear masks to reduce the chances of them being infected by contact with infected people. The contact rate can be rewritten as follows:

$$\alpha = \bar{\alpha} \exp\left(-\frac{G_2}{\bar{y}}\right), \tag{3b}$$

where G_2 is the government's expenditure on related regulation setting to reduce the contact rate. Note that the closure of the city or related social distancing requires police enforcement, and it also costs money to buy or manufacture masks and other protective products. Overall, the more the government spends on related regulations, the lower the contact rate, that is, $\partial\alpha/\partial G_2 < 0$. If the government does not set any regulations, the contact rate is a constant, $\bar{\alpha} \in (0, 1)$.

Furthermore, the government can develop or buy vaccines to eliminate susceptible-infectious interactions. The vaccination rate can be rewritten as follows:

$$p = 1 - \phi_3 \exp\left(-\frac{G_3}{\bar{y}}\right), \tag{3c}$$

where G_3 is the government's expenditure on R&D or the purchase of vaccines and related administrative expenses, and $0 < \phi_3 \leq 1$. Once again, the more the government spends on vaccine development or purchase, the higher the vaccination rate, but the degree of impact will decrease.

Note that the only effect on the contact, recovery, and vaccination rates in this analysis is the flow expenditures. This is because the expenditures related to regulation setting and the related administrative expenses are government consumer expenditures, which are originally flows. As for the government's expenditure on the development or purchase of medicines to treat disease and vaccines, it is not that the government directly manufactures drugs or vaccines, instead, it supports domestic manufacturers to produce drugs and vaccines or suppliers to buy drugs and vaccines directly from manufacturers (domestic or foreign). Therefore, these expenditures are close to the government's consumption expenditure, so they are flows. We focus on the impact of these government expenditures on the contact, recovery, and vaccination rates, and how they affect people's health, economic growth, and welfare. Not all countries have their own medicines and vaccines, and most countries import them from foreign manufacturers. Even if a country does produce its own medicines and vaccines, it is performed by private enterprises but not public enterprises, and the government only purchases medicines and vaccines from these manufacturers.

Moreover, in the setting of this paper, the contact, recovery, and vaccination rate values are all between zero and one. To start, the vaccination rate is originally between zero and one in the design of *SIR* epidemiology dynamics with vaccines and the actual situation. Concerning the contact and recovery rates, and taking COVID-19 as an example, Toda (2020) used the fact that the majority of patients with COVID-19 experience only mild symptoms resembling the common cold or influenza, which takes about 10 days to recover from, and thus set the recovery rate at 0.1. They also estimated the contact rates in 30 countries, which are between zero and one (the value of β in Table 1 in Toda, 2020). Therefore, the model setting is consistent with the actual data.

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2.2 Households

A member of the representative household is endowed with one unit of time. Only healthy people can engage in production and accumulate human capital. At any instant in time, the household devotes a fraction of time u to improving its skills and the remaining fraction of time $1-u$ to goods production. We denote k and h as physical and human capital per capita, respectively.

A household's human capital accumulates via a learning activity, as follows:

$$\dot{h} = B(s+r)uh - (b-d)h, \tag{4}$$

where $B > 0$ measures the efficiency of the process of human capital accumulation. The accumulation function of human capital is based on the setting in Lucas (1988).

We use w and r^k to denote the wage and rental rates, respectively. At any point in time, the representative household's flow budget constraint is:

$$\dot{k} = w(s+r)(1-u)h + r^k k + \pi - c - (b-d)k - m(1-s-r) - T, \tag{5}$$

where π is the firm's profits, given that households own the shares of the firm, and T is the lump-sum taxes. Note that when people are infected, they not only cannot work or accumulate human capital but must also bear any medical expenses. The budget constraint indicates that unspent income is used to accumulate physical capital. To simplify the model, we assume that the depreciation rates of both physical and human capital are zero.

The household's lifetime utility is represented as:

$$U = \int_{t=0}^{\infty} u(c) e^{-(\bar{\rho}-b+d)t} dt, \tag{6}$$

where $u(c) = \frac{c^{1-\sigma}-1}{1-\sigma}$, c is consumption, and $\bar{\rho} > 0$ is the time preference rate. To simplify the analysis, we define $\rho = \bar{\rho} - b + d$. In (6), we use a conventional constant relative risk aversion utility function with a constant intertemporal elasticity of substitution, $1/\sigma$, for consumption.

The representative household's problem is to maximize lifetime utility (6) by choosing between consumption, medical expenditure, and investment in the goods and education sectors, subject to the constraints (1), (2), (4), and (5), along with (3a)–(3c), taking as given the factor prices, w and r^k, government policies, and the initial levels of health, human, and physical capital, $s(0)$, $r(0)$ $h(0)$, and $k(0)$. Let λ_s, λ_r, λ_h, and λ_k denote the Lagrangian multipliers associated with (1), (2), (4), and (5), respectively. The necessary conditions are as follows:

$$c^{-\sigma} = \lambda_k, \tag{7a}$$

$$\lambda_h B = \lambda_k w, \tag{7b}$$

$$\lambda_r \phi_2 e^{-\frac{m}{\bar{y}}} \frac{1}{\bar{y}} = \lambda_k, \tag{7c}$$

$$\frac{\dot{\lambda}_s}{\lambda_s} = \rho + b + \bar{\alpha} e^{-\frac{G_2}{\bar{y}}}(1-s-r) + \frac{\lambda_r}{\lambda_s}\left[1 - \phi_1 e^{-\frac{G_1}{\bar{y}}} - \phi_2 e^{-\frac{m}{\bar{y}}} - \phi_2 e^{-\frac{m}{\bar{y}}}\left(\frac{wh}{\bar{y}} + \frac{m}{\bar{y}}\right)\right], \tag{7d}$$

$$\frac{\dot{\lambda}_r}{\lambda_r} = \rho + b + 1 - \phi_1 e^{-\frac{G_1}{\bar{y}}} - \phi_2 e^{-\frac{m}{\bar{y}}} + \sigma - \phi_2 e^{-\frac{m}{\bar{y}}}\left(\frac{wh}{\bar{y}} + \frac{m}{\bar{y}}\right), \tag{7e}$$

$$\frac{\dot{\lambda}_h}{\lambda_h} = \rho - B(s+r) + b - d, \tag{7f}$$

$$\frac{\dot{\lambda}_k}{\lambda_k} = \rho - r^k + b - d. \tag{7g}$$

Note that (7d)–(7g) have been rewritten by using (7a)–(7c). We also have the following transversality conditions: $\lim_{t\to\infty} e^{-\rho t}\lambda_k(t)k(t) = 0$, $\lim_{t\to\infty} e^{-\rho t}\lambda_h(t)h(t) = 0$, $\lim_{t\to\infty} e^{-\rho t}\lambda_s(t)s(t) = 0$, and $\lim_{t\to\infty} e^{-\rho t}\lambda_r(t)r(t) = 0$.

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2.3 Firms

The representative firm produces a single final good Y by renting physical capital and employing labor under the following production technology: $Y = AK^{\beta}[(s+r)(1-u)hN]^{1-\beta}$, where $A > 0$ is productivity and $\beta \in (0, 1)$ is the capital share. Defining $k \equiv K/N$ as capital per capita and $y \equiv Y/N$ as GDP per capita, we can rewrite the production function as follows: $y = Ak^{\beta}[(s+r)(1-u)h]^{1-\beta}$.

The firm's objective is to choose inputs to maximize the following profits:

$$\pi = y - w(s+r)(1-u)h - r^k k. \tag{8}$$

The first-order conditions are as follows:

$$\beta\frac{y}{k} = \beta Ak^{\beta-1}[(s+r)(1-u)h]^{1-\beta} = r^k, \tag{9a}$$

$$(1-\beta)\frac{y}{(s+r)(1-u)h} = (1-\beta)Ak^{\beta}[(s+r)(1-u)h]^{-\beta} = w. \tag{9b}$$

2.4 Government

We assume that the government levies lump-sum taxes to finance all expenditure on R&D and the purchases of medicines to treat disease and vaccines to increase the vaccination rate, in addition to related regulations to reduce the contact rate, and follows the following balanced budget constraint:

$$T = G_1 + G_2 + G_3. \tag{10}$$

For consistency with a perpetual growth setup, we assume that government expenditures on related medical policies are functions of economywide average GDP per capita, that is, $G_1 = g_1\bar{y}$, $G_2 = g_2\bar{y}$, and $G_3 = g_3\bar{y}$, with $0 < g_1, g_2, g_3, g_1 + g_2 + g_3 < 1$, respectively.

2.5 Equilibrium

An equilibrium consists of the time paths of the households' choices, the firms' choices, and prices, such that (1) households optimize, (2) firms optimize, (3) the government's budget balances, and (4) all markets clear.

In equilibrium, $\bar{y} = y$ and $I/N = 1 - s - r$. By using (3a)–(3c), we can rewrite (1) and (2) as follows, respectively:

$$\dot{s} = b(\phi_3 e^{-g_3} - s) - \bar{\alpha} e^{-g_2}(1-s-r)s. \tag{11a}$$

$$\dot{r} = b(1 - \phi_3 e^{-g_3} - r) + \left(1 - \phi_1 e^{-g_1} - \phi_2 e^{-\frac{m}{y}}\right)(1-s-r) - \sigma r. \tag{11b}$$

By combining (5), (8), and (10), along with (9a) and (9b), we can derive the aggregate goods market clearing constraint as follows:

$$\frac{\dot{k}}{k} = (1 - g_1 - g_2 - g_3)A\left[(s+r)(1-u)\left(\frac{h}{k}\right)\right]^{1-\beta} - \frac{c}{k} - \frac{m}{k}(1-s-r) - (b-d). \tag{11c}$$

Moreover, combining (7a) and (7g) along with (9a) yields:

$$\frac{\dot{c}}{c} = \beta A\left[(s+r)(1-u)\left(\frac{h}{k}\right)\right]^{1-\beta} - \bar{\rho}. \tag{11d}$$

Note that the combination of (7a) and (7c) shows that if $\sigma \neq 1$, then the shadow price of r, that is, λ_r, will keep increasing or decreasing. However, the value of r is between 0 and 1. That is, the value of λ_r is bounded and only achieved under $\sigma = 1$. In the following analysis, we have given that $\sigma = 1$.

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Further, using (7b), (7f), and (7g), along with (9a) and (9b), we can obtain the following relationship:

$$\dot{u} = \frac{1-u}{\beta}\left\{\beta A\left[(s+r)(1-u)\left(\frac{h}{k}\right)\right]^{1-\beta} - B(s+r) + \frac{\beta}{s+r}(\dot{s}+\dot{r}) + \beta\left(\frac{\dot{h}}{h} - \frac{\dot{k}}{k}\right)\right\}. \tag{11e}$$

Finally, using (7c), (7e), and (7g), along with (9a) and (9b), we can derive the following relationship:

$$\frac{\dot{m}}{m} = \frac{\dot{k}}{k} + \frac{y}{m}\left\{\rho + b + 1 - \phi_1 e^{-g_1} - \phi_2 e^{-\frac{m}{y}}\left[1 + \frac{1-\beta}{(s+r)(1-u)} + \frac{m}{y}\right] + \sigma + \left(\frac{m}{y} - 1\right)\left[\frac{1-\beta}{s+r}(\dot{s}+\dot{r}) - \frac{1-\beta}{1-u}\dot{u} + (1-\beta)\left(\frac{\dot{h}}{h} - \frac{\dot{k}}{k}\right)\right] + \frac{\dot{c}}{c} - \frac{\dot{k}}{k}\right\}. \tag{11f}$$

In addition, $\dot{h}/h = B(s+r)u - (b-d)$. (11a)–(11f) show that all the dynamic equations are functions of u, s, r, c/k, h/k, and m/k. To analyze the equilibrium, we transform the perpetually growing variables of consumption, human capital, household medical expenditure, and physical capital into the ratios c/k, h/k, and m/k. Denote $z \equiv c/k$, $q \equiv h/k$, and $x \equiv m/k$. We can derive the time paths of u, s, r, z, q, and x using the dynamic equations of (11a)–(11f) and $\dot{h}/h$.

2.6 The balanced growth path

Now, we analyze the existence of the balanced growth path (BGP). A long-run equilibrium is a BGP along which the household's fractions of time devoted to learning u, and the household's healthy situation s and r are all constant, and consumption c, human capital h, household medical expenditure m, and physical capital k all grow at the same rate, denoted by Λ. Note that (11a)–(11f) show that c, h, m, and k have the same growth rate in the long run.

In the long run, by using $\dot{s}/s = \dot{r}/r = \dot{u}/u = \dot{z}/z = \dot{q}/q = \dot{x}/x = 0$, we can derive the following relationships along the BGP:

$$r = 1 - s - \frac{be^{g_2}}{\bar{\alpha}}\left(\frac{\phi_3 e^{-g_3}}{s} - 1\right), \tag{12a}$$

$$u = 1 - \frac{\rho}{B(s+r)}, \tag{12b}$$

$$q = \left[\frac{B}{\beta A}(s+r)^{\beta}(1-u)^{\beta-1}\right]^{\left(\frac{1}{1-\beta}\right)}, \tag{12c}$$

$$\rho + b + 1 - \phi_1 e^{-g_1} + \sigma = \phi_2 e^{-\frac{m}{y}}\left[\frac{(1-\beta)B}{\rho} + \frac{m}{y} + 1\right], \tag{12d}$$

$$x = \frac{m}{y}\frac{B(s+r)}{\beta}, \tag{12e}$$

$$z = (1 - g_1 - g_2 - g_3)\frac{B(s+r)}{\beta} - (1-s-r)x - B(s+r)u, \tag{12f}$$

$$\frac{be^{g_2}}{\bar{\alpha}}\left(\frac{\phi_3 e^{-g_3}}{s} - 1\right)\left(b + 1 - \phi_1 e^{-g_1} - \phi_2 e^{-\frac{m}{y}} + \sigma\right) = (b+\sigma)(1-s) - b(1-\phi_3 e^{-g_3}). \tag{12g}$$

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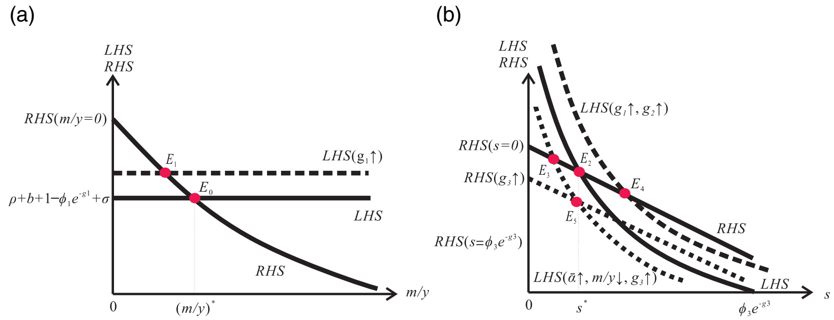

Figure 1. The balanced growth path and comparative statics.

The left-hand side (LHS) of (12d) is a positive constant, and the right-hand side (RHS) of (12d) is decreasing in m/y from $\phi_2[(1-\beta)B/\rho+1]$ when $m/y=0$ to zero when m/y goes to infinity. Note that $d(RHS)/d(m/y)=-\phi_2 e^{-m/y}[(1-\beta)B/\rho+m/y]<0$. That is, there exists a positive constant value of m/y under the condition where $\phi_2[(1-\beta)B/\rho+1]>\rho+b+1-\phi_1 e^{-g_1}+\sigma$, that is, $RHS(m/y=0)>LHS(m/y=0)$. See Figure 1A (solid line, point E_0). Intuitively, $RHS(m/y=0)>LHS(m/y=0)$ implies that the benefit of increasing the recovery rate when the household increases medical expenditures under $m/y=0$ for household welfare is greater than zero, so the household has an incentive to increase medical expenditures. Thus, we obtain positive medical expenditure.

As m/y is a positive constant according to (12d), (12a)–(12c) and (12e)–(12f) imply that r, u, q, x, and z are functions of s. The fraction of healthy people is also a function of s, which is $s+r=1-(be^{g_2}/\bar{\alpha})(\phi_3 e^{-g_3}/s-1)$, and is increasing in s. We can derive the long-run level of s by using (12g). The LHS of (12g) is decreasing in s from infinity when $s=0$ to 0 when $s=\phi_3 e^{-g_3}$. The RHS of (12g) is also decreasing in s from a positive constant $b\phi_3 e^{-g_3}+\sigma$ when $s=0$ to $\sigma(1-\phi_3 e^{-g_3})>0$ when $s=\phi_3 e^{-g_3}$. That is, the LHS of (12g) and the RHS of (12g) must intersect. Thus, there exists a unique long-run value of s, where $0<s<\phi_3 e^{-g_3}<1$. See Figure 1B (solid line, point E_2). Then, the unique long-run levels of r, u, q, x, and z can be derived from (12a)–(12c) and (12e)–(12f).

It is worth noting that the long-run growth rate of the economy is $\Lambda=\dot{y}/y=\dot{h}/h=\dot{k}/k=\dot{m}/m=\dot{c}/c=B(s+r)u-(b-d)$, and the learning time (u) is increasing in the household's health situation ($s+r$) according to (12b). That is, an improvement in people's health will contribute to economic growth. In addition, it may also have a positive effect on people's welfare, which is affected by the economic growth rate and the ratio of consumption to physical capital (z).

2.7 Comparative statics analysis

We now analyze the relative comparative statics and explore the corresponding economic implications. We focus on the impact of the spread of infectious disease and the related government policies. First, we confirm the impact of the coefficient affecting the contact rate, that is, a higher $\bar{\alpha}$. An increase in $\bar{\alpha}$ decreases the level of the LHS of (12g). Therefore, the long-run level of s must decrease (see point E_3 in Figure 1B), as does the fraction of healthy people, that is, $s+r$ also decreases. This result is not surprising because an increase in the contact rate means that people are easily infected. Therefore, the proportion of healthy people will decline. Because there are fewer healthy people and fewer people can then work, people are less likely to receive education. That is, the household's learning time (u), the ratio of human capital to physical capital (q), and the ratio of GDP to physical capital (y/k) all decline. Note that $y/k=B(s+r)/\beta$ in the long run. Because people accumulate less human capital, the economic growth rate also declines. In

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addition, the ratio of consumption to physical capital (z) may decrease. Therefore, the household's welfare may also decline.

Next, we check the impact of the government policies relating to people's health. An increase in government expenditure on the development or purchase of medicines to treat diseases, that is, a higher g_1, increases the level of the LHS of (12d) and the long-run level of m/y decreases (see point E_1 in Figure 1A). In contrast, a lower level of m/y decreases the level of the LHS of (12g), while a higher g_1 by itself increases the level of the LHS of (12g). Thus, the impact of g_1 on the long-run level of s is uncertain. Intuitively, when government medical expenditure increases, people do not need to spend too much money on medical expenditure, so the long-run level of m/y decreases. Therefore, the impact of a higher g_1 on the recovery rate is uncertain due to a higher g_1 and a lower m/y, as is their impact on the proportion of healthy people and economic growth. Moreover, from this example, we can also know that any factor that can increase m/y has a positive impact on the health of people and can increase economic growth.

Regarding an increase in the government expenditure on setting regulations to reduce the contact rate, that is, a higher g_2, this increases the level of the LHS of (12g). Therefore, the long-run level of s must increase (see point E_4 in Figure 1B), as does the proportion of healthy people, $s + r$. Intuitively, the health of the people improves if the government attempts to stop the spread of infectious disease. Thus, u, q, y/k, and the economic growth rate increase. This means that the advanced prevention of infectious disease by the government, such as setting regulations like closing the city, wearing masks, and social distancing policies, is helpful to the economy. However, there are two effects on the level of z. Increased output will help people consume, but increased taxes will reduce their disposable income, and they will then reduce consumption. If the former effect dominates, people's welfare increases, whereas if the latter effect dominates, economic growth does not imply that people will feel any happier.

As for an increase in the government expenditure on the development or purchase of vaccines, that is, a higher g_3, this decreases the levels of both the LHS and RHS of (12g). Therefore, the impact of g_3 on the long-run level of s is uncertain (see point E_5 in Figure 1B), However, the development or purchase of vaccines helps reduce the likelihood of people being infected. A higher g_3 has a direct positive impact on the proportion of healthy people. That is, $s + r$, u, q, y/k, and the economic growth rate may increase under a higher g_3.

3. Numerical analysis

3.1 Calibration

To quantify the results, we calibrate the two-sector endogenous growth model along the BGP to reproduce the key features of the US economy at annual frequencies. We use data for the period 2000–2016. By using the Penn World Table data (Version 9.1), we can calculate that the ratio of human to physical capital in the USA during 2000–2016 was 1.1202.[1] Thus, we initially set $q = 1.1202$. In addition, we set the capital share in the production function of final goods at 0.36 according to Kydland and Prescott (1982); therefore, $\beta = 0.36$. Kydland and Prescott (1991) used 4% as the annual rate of time preference; thus, we set $\bar{\rho} = 4\%$.

According to the Organization for Economic Co-operation and Development's (OECD) statistics, the average GDP growth rate in the USA during 2000–2016 was 2.0222%.[2] Thus, we set the initial $\Lambda = 2.0222\%$. In addition, the OECD health status dataset shows that the death rate and the percentages of bad and very bad health to the total population over 15 years old in the USA during 2000–2016 were 0.8841% and 2.8412%, respectively. Assuming that the latter percentage is the proportion of unhealthy people, we initially set $s + r = 1 - 2.8412\% = 0.9716$ and $d = 0.8841\%$, respectively. In addition, the OECD historical population dataset shows that the population growth rate in the USA during 2000–2016 was 0.8656%. Hence, we estimate the birth rate as $b = 1.7497\%$.

Table 1. Macroeconomic performance under different government expenditures

s	r	$s+r$	x	u	q	z	Λ	U
(A) *Benchmark model*								
0.2760	0.6956	0.9716	0.0118	0.4795	1.1202	0.0966	2.0222%	−53.9833
(B) *Higher government expenditure on medicine development or purchase,* $g_1 = 0.1$								
0.2766	0.6952	0.9717	0.0096	0.4796	1.1205	0.0938	2.0230%	−54.9241
(C) *Higher government expenditure on regulation setting,* $g_2 = 0.1$								
0.2790	0.6928	0.9718	0.0118	0.4796	1.1206	0.0937	2.0234%	−54.9390
(D) *Higher government expenditure on vaccine development or purchase,* $g_3 = 0.1$								
0.2715	0.7001	0.9717	0.0118	0.4796	1.1204	0.0937	2.0226%	−54.9508
(E) *Social planner's allocation,* $g_1, g_2, g_3 < 0.001\%$								
0.2772	0.6919	0.9691	0.0221	0.4782	1.1229	0.1381	2.0067%	−42.7311

Assume that the contact rate is $\alpha = 0.5$. As for the vaccination rate, we take flu vaccination coverage as an example. According to the US Center for Disease Control and Prevention, the flu vaccination coverage among children 6 months through to 17 years in the USA during 2016–2017 was 59% and among adults over 18 years was 43.3%. That is, we set $p = 0.5$. Therefore, the discount rate, the proportions of the S and R categories, learning time, the efficiency of human capital accumulation, the ratio of GDP to physical capital, and the efficiency of the production function are calibrated at $\rho = 0.0313$, $s = 0.2760$, $r = 0.6956$, $u = 0.4795$, $y/k = 0.1673$, $B = 0.0620$, and $A = 0.2407$, respectively.

Furthermore, the OECD dataset shows that the percentage of total expenditure on health to GDP and the percentage of government/compulsory expenditure on health to GDP in the USA during 2000–2016 were 0.1532 and 0.0826, respectively. Assume that the latter percentage is g_1 and $g_1 = g_2 = g_3$; hence, we set $g_1 = g_2 = g_3 = 0.0826$. Besides, we can calculate the percentage of household expenditure on health of GDP as $m/y = 0.0705$. Therefore, we can calibrate the ratios of household medical expenditure and consumption to physical capital at $x = 0.0118$, and $z = 0.0966$, respectively. Thus, we can calibrate the recovery rate and related coefficients of the recovery, contact, and vaccination rates at $\gamma = 0.3653$, $\phi_1 = 0.3446$, $\phi_2 = 0.3407$, $\phi_3 = 0.5431$, and $\bar{\alpha} = 0.5431$, respectively. Finally, by assuming that $k(0) = 1$, the household's welfare can be derived as $U = -53.9833$. We summarize the related macroeconomic variables in Table 1 (case A).

3.2 The effects of government policies

We now check the effects of government policies related to dealing with infectious disease. First, we discuss the impact of government expenditure on the development or purchase of medicines to treat disease, that is, an increase in g_1. The results are shown in Figure 2(A). Note that we change one policy at a time. To save space, we only discuss the impact of government policies on people's health, economic growth, and welfare in Figure 2, and the impact on the other macroeconomic variables is presented in Table 2. Consistent with the theoretical inference, as the government spends more money on improving people's health, people do not need to spend too much money on medical expenses. That is, the medical expenditure of the household (x) decreases, while the overall health of the people has improved. Accordingly, the proportion of healthy people ($s + r$) increases. Therefore, more healthy people can invest in production and accumulate human capital. Hence, the learning time (u) increases, along with the economic growth rate (Λ). However, a higher g_1 implies that the households must pay more taxes. Thus, their disposable income and consumption decline. We obtain that household welfare declines. Thus, economic growth does not necessarily guarantee that people will feel happier.

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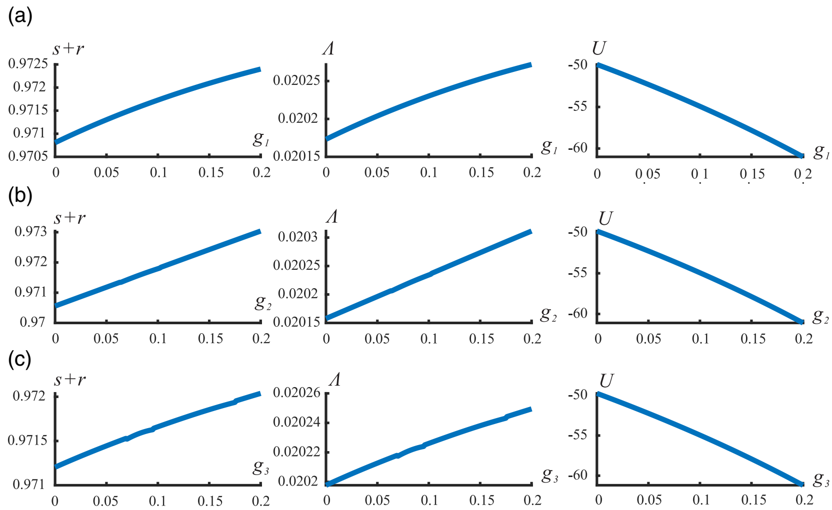

Figure 2. The long-run effects of an increase in g_1, g_2, or g_3.

Regarding the impact of the government expenditure on setting regulations to reduce the contact rate, or the impact of the government expenditure on the development or purchase of vaccines to increase the vaccination rate, that is, an increase in g_2 or g_3, the results are shown in Figure 2(B) and (C), respectively. A higher g_2 reduces the contact rate; therefore, s increases and r decreases. This is because fewer people are infected and then recover. However, a higher g_3 increases the vaccination rate, which removes more people from the susceptible-infectious interaction. Therefore, r increases and s decreases under a higher g_3. Regardless, the increase in g_2 or g_3 is good for people's health, economic growth, and other health-related variables. However, as the households must pay more taxes to cover higher government expenditures, household welfare declines due to lower disposable income and consumption by the household.

To understand more clearly the impact of the three government expenditures on the economy, we separately increase these by the same amount (from 0.0826 to 0.1) and observe the comparative statics results. The results are in Table 1 (cases B, C, and D). Although all three government policies can improve people's health, the degree of impact differs. Obviously, prevention beforehand like setting regulations is more beneficial to people's health than remedial effort afterwards. This result is not surprising because it is more efficient to prevent infection at the beginning than to treat people when they are sick. However, the interesting thing is that setting regulations like quarantining people to avoid infection, forcing people to wear masks, or maintaining social distancing is more effective than vaccination. Note that this result is robust as we obtain the same conclusion when we change the other parameters in Table 2 slightly.

We obtain that the proportion of healthy people and the economic growth rate are highest under an increase in g_2. That is, if the government budget is limited, the government should spend more on the setting of regulations, such as using their public power to close the city, force people to wear masks, and maintain social distancing. However, when faced with unknown infectious diseases, the government also needs to invest in the development or purchase of therapeutic drugs and vaccines because it cannot completely prevent people from being infected. Note that by comparing the damage to welfare caused by these three types of government expenditures, we obtain that g_1 involves less damage to the welfare of the people. This is because the government's medical expenditures can replace the people's medical expenditures, and the people can save some money to then consume.

Table 2. Comparative static analysis in the long run

	s	r	$s+r$	x	u	q	z	Λ	U
g_1	+	−	+	−	+	+	−	+	−
g_2	+	−	+	+	+	+	−	+	−
g_3	−	+	+	+	+	+	−	+	−
$\bar{\alpha}$	−	+	−	−	−	−	−	−	−
ϕ_1	−	+	−	+	−	−	−	−	−
ϕ_2	+	−	+	+	+	+	−	+	−
ϕ_3	+	−	−	−	−	−	−	−	−
B	+	−	+	+	+	+	+	+	+
b	+	−	+	+	+	+	−	+	−
d	−	+	−	−	−	−	+	−	+
σ	−	+−	−	−	−	−	−	−	−

Note: + and − indicate that the effects of changing the parameters on the related variables are monotonically increasing and decreasing, respectively. +− indicates that the impact in terms of changing the parameter values on related variables is first rising and then falling.

Here we also analyze the social planner's allocation. The social planner's problem is to maximize the household's lifetime utility, (6) subject to the household's human capital accumulation function, (4) the aggregate goods market clearing constraint, (11c) and two dynamic equations of people's health situation (11a)–(11b). Using the same parameter settings as in the benchmark model (Table 1, case A), we can derive the social planner's allocation, which is shown in Table 1 (case E). We found that the first-best government policies related to dealing with infectious diseases are very small and close to zero, where $g_1, g_2, g_3 < 0.001\%$. As the government's health expenditure needs to be covered by taxation, the results of numerical analysis show that the negative effect of taxation on welfare is greater than the positive effect of people becoming healthier. That is, the optimal values of g_1, g_2, and g_3 are close to zero.

With less help in terms of the government's health expenditure, people must increase their medical expenditures, but the proportion of healthy people is still declining (based on comparing case E with case A in Table 1). However, since there is no additional burden on government expenditures (taxes), people can spend more, and so household welfare increases. Notwithstanding that these policies are good for welfare, this does not mean that they are good for economic growth. We find that the economic growth rate is lower under the social planner's allocation. Note that the social planner seeks to maximize the household welfare, and not to maximize the economic growth rate.

3.3 Other comparative static analysis

We now investigate the effects of different parameter values relating to infectious diseases. To conserve space, we list all comparative static results in Table 2. The intuitions of an increase in $\bar{\alpha}$, g_1, g_2, and g_3 are the same as those in Section 3.2 and Figure 2, respectively. The results are also consistent with the theoretical inference. Regarding all other comparative statics results, if a parameter has a positive effect on people's health, then it will also have a positive effect on economic growth. However, if a parameter has a negative effect on people's health, then it will have the opposite result. However, factors that are good for people's health and economic growth are not necessarily good for household welfare and depends on whether these factors can increase household consumption.

Regarding the coefficients that affect the recovery rate, given an increase in ϕ_1 reduces the recovery rate, its impact is like that under a decrease in g_1 except for that on z and welfare. As

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people must spend more money on medical expenses to prevent the recovery rate from falling too much, that is, x increases, they spend less on consumption. Therefore, welfare declines, that is, both z and U decrease. In addition, an increase in ϕ_2 has two effects. First, it reduces the recovery rate, which results in fewer healthy people. Second, it induces people to increase health expenditure as $\partial\gamma/\partial m$ is increasing in ϕ_2 and helps people to recover. Our model shows that the latter effect dominates. Therefore, public health is increasing in ϕ_2. The impact on macroeconomic performance is the same as an increase in g_1.

As for the coefficient that affects the vaccination rate, a higher ϕ_3 reduces the vaccination rate; therefore, r decreases and s increases. As there are now more susceptible people that may be infected, the proportion of healthy people declines. Because there are fewer healthy people and fewer people can work, people are less likely to receive education. That is, the household's learning time (u) and the ratio of human capital to physical capital (q) all decline. Because people accumulate less human capital, the economic growth rate also declines. In addition, the ratio of consumption to physical capital (z) also decreases, as does the household's welfare.

Moreover, as birth and death rates also affect people's health according to the *SIR* epidemiology model with vaccines, we also confirm the impact of changing b and d. These results are very intuitive. Because people are born healthy, when the birth rate increases, the proportion of healthy people will increase, but it will have the opposite effect when the death rate increases. More healthy people suggests that more people can work; therefore, people are more likely to receive education. That is, the household's learning time (u) and the ratio of human capital to physical capital (q) all increase. Because people accumulate more human capital, the economic growth rate also increases. However, more people imply less consumption per capita. Hence, welfare is declining. Intuitively, the impact of a higher d is like that of a lower b.

Furthermore, we further check the impact of the higher efficiency of human capital accumulation. Intuitively, a higher B increases people's incentive to accumulate more human capital. Therefore, learning time, human capital accumulation, output, and economic growth all increase. When people's income increases, they will pay more attention to health and expenditure on health will increase; thus, the proportion of healthy people will also increase. As the people's production capacity increases, consumption can also increase with the increase in output, as does household welfare.

Finally, we discuss the impact of a higher relapse rate. Intuitively, a higher σ is not good for people's health, and the proportion of healthy people declines. The subsequent impact is similar to a higher $\bar{\alpha}$ where the household's learning time (u), the ratio of human capital to physical capital (q), the economic growth rate, the ratio of consumption to physical capital (z) all decline, as does the household's welfare.

4. Concluding remarks

This paper constructs an endogenous growth model including infectious disease and explores the impact of related government policies on macroeconomic performance. The policies include expenditures for infectious disease treatment, for regulation setting, and for vaccine development and purchase. Our results show that the government's advance prevention of infectious disease, such as setting regulations like quarantining people to avoid infection, forcing people to wear masks, or maintaining social distancing, is more helpful to the economy than medical assistance following infection and is even more helpful to the economy than vaccines. Moreover, while all three types of government expenditure exert a positive impact on economic growth, they do not necessarily improve people's welfare.

In this paper, we did not analyze heterogeneity among households or firms. Moreover, it would be interesting to examine the implications for the impact across generations in this framework. In addition, the various epidemiology models for different infectious diseases have diverse dynamics and may have distinctive impacts on people's health, economic growth, and welfare. Besides, other than dealing with people's health, the government also must address economic problems relating to infectious disease, such as recessions. Furthermore, we focus on the disease endemic case with positive economic growth, which is also the actual situation. However, there are many interesting corner solutions. For example, there could be a disease-free case. In this situation, if everyone is healthy, then our model will return to the Lucas (1988) endogenous growth model. The other case is that where the infectious disease is so serious that no one can accumulate human capital, there is no economic growth. Discussing the related government policy or foreign aid in that poverty trap is also an interesting issue. We defer these analyses to future research.

Notes

1 The data are from https://www.rug.nl/ggdc/productivity/pwt/.

2 The data are from http://stats.oecd.org/

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