Investigating the Cost-Benefit Analysis of Telemedicine Healthcare Consortium System with Evolutionary Gaming Theory

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Abstract. China faces a serious situation with insufficiently medical and health resources as well as the unreasonable resources distribution. In this paper, evolutionary game theory is employed to investigate the underlying model of the satellite hospital and patient in telemedicine-based Healthcare Consortium System. Its evolutionary process and results are analyzed for verification of the benefits brought by telemedicine. It can be concluded through the model simulation that both sides can get the most benefit when choosing telemedicine.

1. Introduction

It was reported that the United States spends the annual cost of medical services is the largest in developed countries, while China spends per capita annual medical expenses at only 0.27% of that in the United States [1], indicating that the medical resources in China are extremely scarce. The most importantly, the medical resources in China are of serious shortage and of uneven distribution. The urban part has a population of only 20 percent of the population but takes 80 percent of the country's medical and health resources, while the rural population is the opposite [2]. As a new mode of medical delivery system, telemedicine connects the central hospital and the satellite hospital through the Information and Communication Technology (ICT) network [3], so that the patients can get the treatment from the central hospital in the satellite hospital, and it can help to balance health care resource utilization and guide patient flow issues better. The difficulty of seeing a doctor especially an expert is greatly improved for the patients who are not dwelling in urban areas.

With a rapid development and application in health industry, Telemedicine technology has been widely used all over the world. Particularly, Healthcare Consortium System bonds central hospital and satellite hospitals as a group through telemedicine network, which encourage both stakeholders to be actively involved in the telemedicine system [4-6]. However, the costs and benefits for both of stakeholders have not been paid much attention to yet with regard to its systematic analysis [7, 8]. Since Telemedicine has played and will continue to play a significant role in the reformation of the China health care system, this article is designed to uses evolutionary game theory [9, 10] to analyze the benefits and costs introduced to the satellite hospitals in telemedicine-based Healthcare Consortium System.

2. Problem Statement

This paper is to investigate the game between satellite hospital and patient under the telemedicine system, so the two sides of the game are satellite hospital and patient respectively. Satellite hospitals choose whether or not to carry out telemedicine cooperation with the central hospital. Therefore, the satellite hospital's strategy set is {Consortium, no Consortium}, and patients choose whether to go to a satellite hospital for treatment. Therefore, the patient's strategy set is {choose, no choose}. Following application format of evolutionary gaming theory, it is supposed

that 1) satellite hospitals and patients in a telemedicine-based Healthcare Consortium System has limited rationality during the game process; and 2) the patient must have a medical treatment, when the patient does not choose the satellite hospital treatment, he will choose the central hospital for treatment.

Here is for the construction of income matrix. For hospitals, suppose that the ratio of satellite hospitals choose to cooperate with the central hospital with telemedicine is y (0 <y <1). The benefits of satellite hospital choose to cooperate with central hospital are π_1, the benefits of satellite hospitals do not cooperate with the central hospital are π_2, As patients can get more trust from telemedicine, so $\pi_1 > \pi_2$; the cost to be paid that satellite hospital cooperates with central hospital(advocacy costs, operating costs and other fixed costs) is C_1, the cost to be paid when not cooperating with the central hospital(hospital fixed costs) is $C_2 (C_1 > C_2)$, in addition regardless of the satellite hospital how to choose, the cost in doctor when patients choose satellite hospital(bonus and salary of doctor) is C_3; the financial support provided by the government when the satellite hospital cooperate with the central hospital is W_1, and the financial support provided by the government which does not cooperate with the central hospital is W_2, now China is strongly supporting and promoting telemedicine, so $W_1 > W_2$. For patients, suppose the ratio that patients choose to visit a satellite hospital is $x(0 < x < 1)$. When the satellite hospital cooperate with the central hospital, the utility that patients choose the satellite hospital is V_1, when the satellite hospital cooperate with the central hospital for telemedicine, the utility obtained by the patients choosing satellite hospitals was V_1. When the satellite hospital do not carry out the telemedicine cooperation with the central hospital, the utility obtained by the patients choosing satellite hospitals was $V_2 (V_1 > V_2)$; when the satellite hospital chooses to cooperate with the central hospital, the cost to be paid by the patient is P_1. When the satellite hospital does not choose to cooperate with the central hospital, the cost to be paid by the patient is P_2; the proportion of reimbursement of medical insurance in satellite hospital is σ, because the utility will reduce significantly when satellite hospitals do not cooperate with central hospitals, the patient will complain about the satellite hospital, and the cost is C_4, which result in the loss of the satellite hospital is L. Taking into account the patient must be medical treatment, this paper assumes that when the patient does not choose a satellite hospital for medical treatment, that is, choose the center of the hospital for medical treatment, the utility of the patient to the central hospital for treatment is V', the medical expense paid is P', and the reimbursement ratio of the central hospital is σ'. Additional costs paid such as transportation costs, time cost, and accommodation cost are E.

According to the above assumptions analysis: The actual expenses paid by patients when they choose to visit a satellite hospital are $P_1(1 - \sigma)$ and $P_2(1 - \sigma)$ respectively; when satellite hospital cooperate with central hospital, the patient's satisfaction with the satellite hospital increased, and the extra cost was saved, so the utility of the patient was $V_1 > (1 - \sigma)P_1$; when satellite hospitals do not cooperate with central hospitals, the patients are in doubt about the medical standards of satellite hospital doctors, so the patients may not be satisfied with the satellite hospital medical services, so the utility obtained by the patients is $V_2 < (1 - \sigma)P_2$.

Based on the above assumptions and analysis, we can get the return matrix of both sides of the game, as shown in Table 1.

Based on Table 1, the income matrix of patients is:

$$A = \begin{bmatrix} V_1 - (1-\sigma)P_1 & V_2 - (1-\sigma)P_2 - C_4 \\ V' - (1-\sigma')P' - E & V' - (1-\sigma')P' - E \end{bmatrix} \tag{1}$$

The income matrix of satellite hospital is:

$$B = \begin{bmatrix} \pi_1 - C_1 - C_3 + W_1 & \pi_2 - C_2 - C_3 + W_2 - L \\ -C_1 + W_1 & -C_2 + W_2 \end{bmatrix} \tag{2}$$

Table 1.   The income matrix of satellite hospitals and patients

		Satellite hospital	
		Consortium (y)	No Consortium $(1-y)$
Patients	Choose (x)	$V_1 - (1-\sigma)P_1,$ $\pi_1 - C_1 - C_3 + W_1$	$V_2 - (1-\sigma)P_2 - C_4,$ $\pi_2 - C_2 - C_3 + W_2 - L$
	No Choose $(1-x)$	$V' - (1-\sigma')P' - E,$ $-C_1 + W_1$	$V' - (1-\sigma')P' - E,$ $-C_2 + W_2$

The dynamic equation for constructing the imitator is:

$$F(x) = \frac{dx}{dt} = x(U_{11} - \bar{U}_1) = x(1-x)(U_{11} - U_{12})$$
$$= x(1-x)\{y[V_1 - V_2 - (1-\sigma)(P_1 - P_2) + C_4] - [V' - (1-\sigma')P' - E]\} \quad (3)$$

Similarly, the imitation of satellite hospitals dynamic equation is:

$$F(y) = \frac{dy}{dt} = y(U_{21} - \bar{U}_2) = y(1-y)[x(\pi_1 - \pi_2 + L) + W_1 - W_2 - (C_1 - C_2)] \quad (4)$$

The evolving behavior of the two sides in the process of game can be illustrated by the dynamic equation of imitators in both sides of the game. Let $F(x) = 0$, $F(y) = 0$, we can get five dynamic equilibrium point, respectively: $O(0,0)$, $A(0,1)$, $B(1,1)$, $C(1,0)$, $D(x^*, y^*)$, If and only if $0 < x^* < 1$ and $0 < y^* < 1$. Among them, there are:

$x^* = \frac{C_1 - C_2 - (W_1 - W_2)}{\pi_1 - \pi_2 + L}$ and $y^* = \frac{V' - (1-\sigma')P' - E - [V_2 - (1-\sigma)P_2 - C_4]}{V_1 - V_2 - (1-\sigma)(P_1 - P_2) + C_4}$.

According to the above assumptions and the actual situation, the benefits of patients will much than the cost paid when they see a doctor, otherwise the patient will not choose to see a doctor, and when satellite hospitals cooperate with central hospitals and patients choose satellite hospitals, because of the additional cost was saved, so the benefits of patients obtain are much than that they choose central hospitals, so $0 < y^* < 1$.

Among them, the formula (3) and (4) derived partial derivation:

$$\frac{\partial F(x)}{\partial x} = (1-2x)\{y[V_1 - V_2 - (1-\sigma)(P_1 - P_2) + C_4]$$
$$+ V_2 - (1-\sigma)P_2 - C_4 - [V' - (1-\sigma')P' - E]\}$$
$$\frac{\partial F(x)}{\partial y} = x(1-x)[V_1 - V_2 - (1-\sigma)(P_1 - P_2) + C_4]$$
$$\frac{\partial F(y)}{\partial x} = y(1-y)(\pi_1 - \pi_2 + L)$$
$$\frac{\partial F(y)}{\partial y} = (1-2y)[x(\pi_1 - \pi_2 + L) + W_1 - W_2 - (C_1 - C_2)]$$

The determinant of Jacobian matrix J is:

$$det(J) = |J| = \frac{\partial F(x)}{\partial x} \cdot \frac{\partial F(y)}{\partial y} - \frac{\partial F(x)}{\partial y} \cdot \frac{\partial F(y)}{\partial x}$$

The trace of the Jacobian matrix is:

$$tr(J) = \frac{\partial F(x)}{\partial x} + \frac{\partial F(y)}{\partial y} \qquad (5)$$

It should be pointed out that in the process of solving the model, we need to find out the evolutionary stability strategy of the game model to analyze the model. The evolutionary stability strategy has the corresponding criterion, when a certain equilibrium point of the game model makes the determinant of the Jacobian matrix positive and makes the trace of the Jacobian matrix to be negative, then this equilibrium point is the evolutionary stabilization strategy.

3. Model Analysis

According to the patient's imitator dynamic equation analysis, When $y = y^*$, $F(x)$ always is 0, so all x are stable. When $y > y^*$, $x^* = 1$ is the ESS equilibrium point; when $y < y^*$, $x^* = 0$ is the ESS equilibrium point.

From the above three cases are available, the patient's imitator dynamic phase diagram is shown in Fig. 1 (a-c).
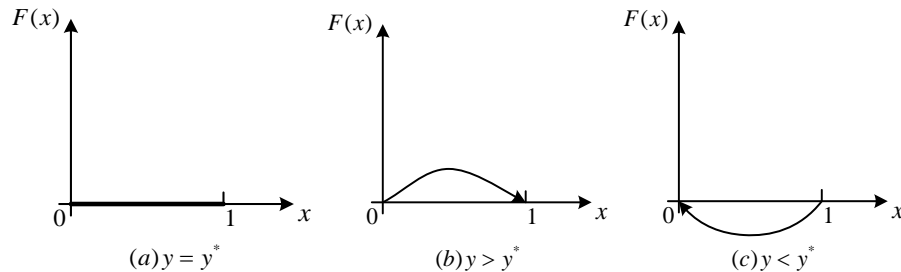

Fig. 1. The Imitator Dynamic Phase Diagram of Patients

Similarly, we can obtain what through the dynamic equation analysis of imitators in satellite hospital strategy is: when $x = x^*$, $F(y)$ is always, that is, all y are stable; when $x > x^*$, $y^* = 1$ is the ESS equilibrium point; when $x < x^*$, $y^* = 0$ is the ESS equilibrium point.

From the above three cases are available, the satellite hospital's imitator dynamic phase diagram is shown in Fig. 2 (a-c).
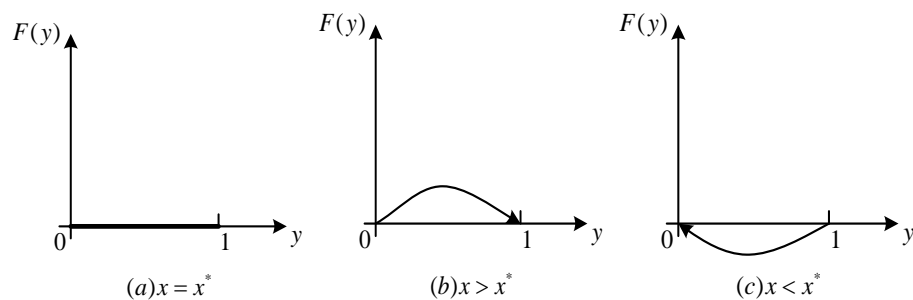

Fig. 2. The Imitator Dynamic Phase Diagram of Satellite hospitals

According to the different values of x^*, there are three cases for analysis. According to the analysis, when the value of x^* is different, the satellite hospital and the patient's game strategy choice will be different. The dynamic phase diagram of the imitator is shown in the same coordinate system to obtain the dynamic evolution diagram of interaction between ordinary hospitals and patients under different x^* values, as shown in Fig. 3 (a-c). It can be divided into three cases.
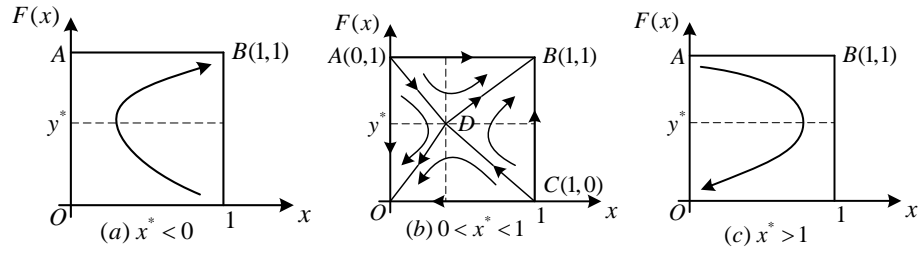
Fig.3. Dynamic Evolution of Satellite hospital-Patient Interaction

4. Simulation Analysis

The paper simulate the model on the case of $0 < x^* < 1$, analyzing the impact of the initial state of the system on the game process of satellite hospitals and patients in different situations by graphics. In this case, the initial parameters of the model are set as shown in Table 2.

Make the initial value of x、y is 0, loop step is 0.05, and running time at [0,10]. The $x - y$ chart of evolutionary game model of satellite hospital and patient running under the above conditions is shown in Fig 4. It shows that all the points of x and y converge to (0,0) or (1,1). That is, the final result of the evolution is that the satellite hospital chooses to cooperate with the central hospital and the patients choose to go to the satellite hospital for treatment or the satellite hospital does not choose to cooperate with the central hospital and patients do not choose to go to the satellite hospital. the system achieves a stable and balanced evolution at the (0,0) and (1,1).

Table 2. Parameters assignment

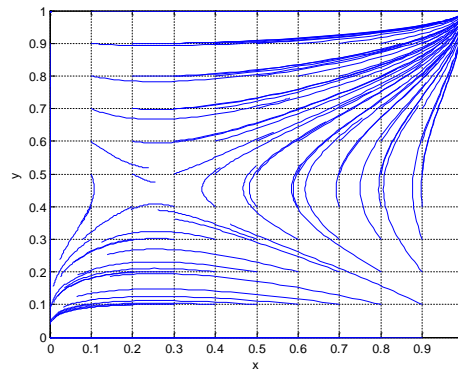| Factors	Assignment
W_1, W_2	700, 200(million)
C_1, C_2	700, 300(million)
π_1, π_2	400, 200(million)
P_1, P_2	1.2, 1
σ, σ'	0.4, 0.6
V_1, V_2	1, 0.2
L, E	2, 0.2
C_4, P', V'	1, 2, 1.2

Fig. 4. Evolution trend simulation diagram of $x - y$ based on case 2.

5. Conclusion

Based on the serious shortage of medical and health resources and the extremely uneven distribution in China, this paper investigates the benefits and costs introduced to the satellite hospitals and patients in telemedicine-based Healthcare Consortium System through evolutionary game. According to the analysis of the game between the two sides, it can be concluded that when the satellite hospital chose to cooperate with the central hospital for telemedicine, patients can receive maximum benefit from their visit. This paper uses $MATLAB$ to simulate the model, further illustrating that telemedicine technology can improve people's medical problems.

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