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Research article

Study on the evolutionary strategy of upward patient transfer in the loose medical consortia

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Abstract: Medical institutions in loose medical consortia tend to have poor cooperation due to fragmented interests. We aim to explore any issues associated with patient upward transfer in a loose medical consortium system consisting of two tertiary hospitals with both cooperative and competitive relationships. A two-sided evolutionary game model was constructed to assess the stability of equilibrium strategy combinations in the process of interaction between game players under different cost-sharing scenarios and different degrees of penalties when running patient upward transfer between super triple-A hospitals (STH) and general triple-A hospitals (GTH). We found that a hospital's stabilization strategy was related to its revenue status. When a hospital has high/low revenues, it will treat patients negatively/positively, regardless of the strategy chosen by the other hospital. When the hospital has a medium revenue, the strategy choice will be related to the delay cost, delay cost sharing coefficient, government penalty and the strategic choice of the other hospital. Delay cost-sharing coefficient is an important internal factor affecting the cooperation in a medical consortium for patient upward transfer. External interventions, such as government penalty mechanisms, can improve the cooperation between hospitals when hospitals have moderate revenue.

Keywords: loose medical consortia; evolutionary game; triple-A hospital; delay cost

1. Introduction

As per capita life expectancy has increased around the world, the demand for health care has increased significantly. However, the fundamental conflict between limited resources and unlimited demand has put tremendous pressure on healthcare providers. To improve the quality and efficiency of healthcare services, the United States, the United Kingdom, Japan and other countries have taken different measures to restructure and reorganize their healthcare delivery systems since the 1970s, resulting in a more efficient and robust health care model called integrated health care [1]. The World Health Organization (2016) [2] defines integrated health care as a continuum of health promotion, disease prevention, diagnosis, treatment, disease management, rehabilitation and palliative care services, coordinated at different levels and locations within and outside the health sector, according to the whole life course of a person.

Chinese medical institutions are divided into three levels according to the scale of development, staffing, technical level and service capacity of the hospital [3]. There is no established gatekeeper system in China and patients are free to select hospitals for medical services. Even though the positioning of tertiary hospitals is to provide medical services for patients with complicated diseases, many patients with mild diseases are keen to seek medical services in tertiary hospitals but not in lower-level hospitals, resulting in more people in tertiary hospitals and fewer people in community hospitals. According to the data reported in the 2022 China Health and Family Planning Development Bulletin [4], only 8% of China's healthcare institutions are tertiary public hospitals, but these institutions provide 66% of healthcare services such as inpatient services. In order to alleviate the mismatch between patient flow and hospital level, Chinese healthcare reformers proposed an integrated healthcare model in 2015, called medical consortia, which is an integration of medical resources to form a medical alliance with a regional tertiary hospital and several lower level hospitals such as secondary and community hospitals.

Medical consortia can be classified by two types, loose and tight, depending on the degree of cooperation. Loose medical consortia are formed mainly through the signing of cooperation agreements on technical cooperation. Hospitals in the loose medical consortia have a weaker cooperation than the tight medical consortia. Thus, the loose medical consortia often encounter problems for compartmentalization of interests, poorer stability, unsustainability and more barriers for patient referrals [5]. Thus, we explored the issues associated with the patient upward transfer in a loose medical consortium consisting of two tertiary hospitals with both cooperative and competitive relationships. The delay cost is incorporated into the evolutionary game model to explore the effect of delay cost-sharing coefficients and government penalties on the evolutionary trajectory of the medical consortia. By constructing a two-sided evolutionary game model for super triple-A hospitals (STH) and general triple-A hospitals (GTH) in a loose medical consortium, we solved and analyzed the stability of equilibrium strategy combinations in the process of interaction between game players under different cost-sharing scenarios and different degrees of penalties. It should be noted that the STHs in this study has a higher level than GTHs. Although they form a loose alliance and GTH have a certain local reputation, GTH still relies on the medical technical support from STH, especially when treating patients with complicated diseases. Figure 1 illustrates the classification standards for Chinese hospitals and the key issues that will be explored in this study.

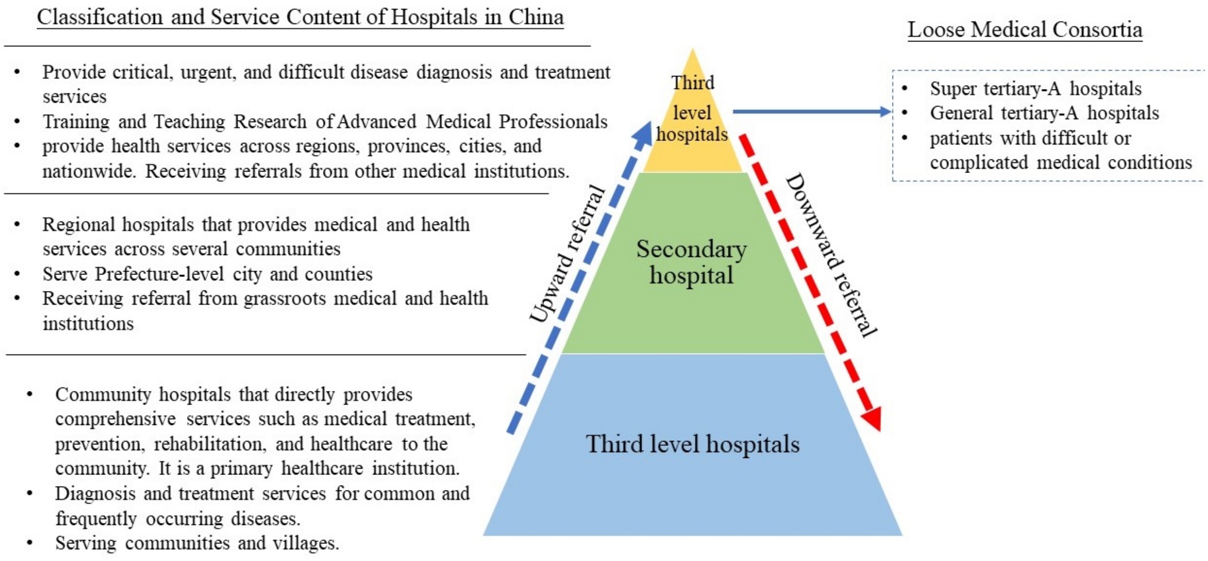

Figure 1. Criteria for classifying hospitals in China and the issue of loose medical consortia.

This study is relevant to the current literature from two perspectives. First, the integrated health care model is a popular research area in various countries around the world. Since the introduction of integrated health care, the United States, Canada and other countries have conducted a series of studies. Early studies into integrated health care focused primarily on qualitative analysis, such as the definition of integrated health care services [6], measurement methods [7], strategic changes [8] and summaries of practical experiences or cases [9]. Some research has been conducted using questionnaires or metrological methods to study specific aspects of an integrated healthcare system, such as different groups' perceptions of integrated healthcare [10,11], patients' healthcare service quality [12], inter-hospital information synergy [13] and family physicians [14]. Some research has been conducted into the best way to promote the integrated health care with emerging technologies and approaches [15]. For example, Burns et al. [16], used social networks to study relationship coordination and integrated health care and analyze integrated health care at three levels of analysis: micro, meso and macro.

Second, the evolutionary game approach is a very useful mathematical model that can simulate complex biological and social systems and help with better understanding and predicting their behaviors. This approach can use evolutionary game theory to explore dynamics of strategy (Cooperation or Defection) change under various competing systems in different situations of dilemma game [17]. In recent years, evolutionary game theory has been recognized as an effective tool for analyzing complex interactions among social agents and has been applied to many social issues [18,19], such as industrial pollution [20], supply chain energy conservation and emission reduction [21], agricultural supply chain finance [22], construction waste recycling behavior [23], livestock pollution control [24] and electronic product waste recycling [25]. The main topics of literature related to evolutionary games and medical problems include the multi-subject evolution of sudden public events [26], medical data sharing [27], doctor-patient disputes [28] and other aspects of geriatric health and collaboration [29].

The main contributions of this article are as follows.

1) From a research perspective, this study fills the current evidence gap regarding cooperation in the upward referral of patients in the context of loose medical consortia. In recent years, although the

issues arising from the evolution between different subjects within an integrated healthcare system has caused a certain attention, the past research mainly focused on tightly-knit medical consortia that consists different core hospitals. Xu et al. [30] constructed an evolutionary game model involving urban tertiary hospitals and rural hospitals and verified the impact of different values through numerical simulations, proving that the urban-rural cooperation mechanism is effective. The majority of subjects in current evolutionary game models for medical clusters are tertiary and community hospitals [31]. Instead, this study focused on the issue of patient referrals from tertiary and community hospitals, which have different positioning and complementary relationships and make cooperation more likely. There are lack of studies using evolutionary game models to simulate the behavioral strategies of hospitals in loose alliances that face the dilemma of poor cooperation.

2) The simulation in this study is more micro. The two hospitals studied in our study have unequal positions in a loose alliance and they cooperate as well as compete. The current literature on the application of evolutionary games to healthcare consortia can be classified as two main categories. One category focuses on the referral of patients in the same hospital but assess the evolutionary relationship between the hospital and other subjects such as patients and the government [32]. For example, Tao et al. [33] integrated prospect theory into the promotion of the hierarchical diagnosis and treatment system, constructing a three-party evolutionary game model containing local health departments, medical institutions, and patients, and concluded that the amount and duration of financial subsidies had strong impact on the evolution of the game system. The other category focuses on issues within the healthcare consortium other than referral of patients, such as information sharing [34].

3) From the practice level, this paper explores a two-party evolutionary game model of hospitals with competitive nature based on the context of loose healthcare consortiums in China's national context, which is a fusion of theory and practice. The conclusions of the model should eventually be fed back to the practice level. This paper analyzes how key elements such as different costs, affect the strategic choices of the game's subjects, proposes internal and external constraints on the negative behaviors of loose healthcare associations and thus provides evidence in favor of policy recommendations to facilitate the transition from loose to close healthcare associations.

The remainder of this paper is structured as follows. In Section 2, we describe the background of the research and builds the evolutionary game model. In Section 3, we solve the model and analyze the stability of the strategy portfolio. In Section 4, we simulate the model, analyze the effect of different parameters on the results and present the managerial insights of the study. In Section 5, a conclusion is drawn.

2. Materials construction

Based on the actual development situation of loose medical consortia in China, combined with evolutionary game theory, a detailed description of the problem and research hypotheses are presented below and followed by the constructed evolutionary game model.

2.1. Problem description

In a loose medical consortium, GTH and STH operate independently, admitting and treating their patients. In this work, we consider the problem of patient referral from two hospitals of the same level with competing relationships. The logical framework diagram of this paper is shown in Figure 2.

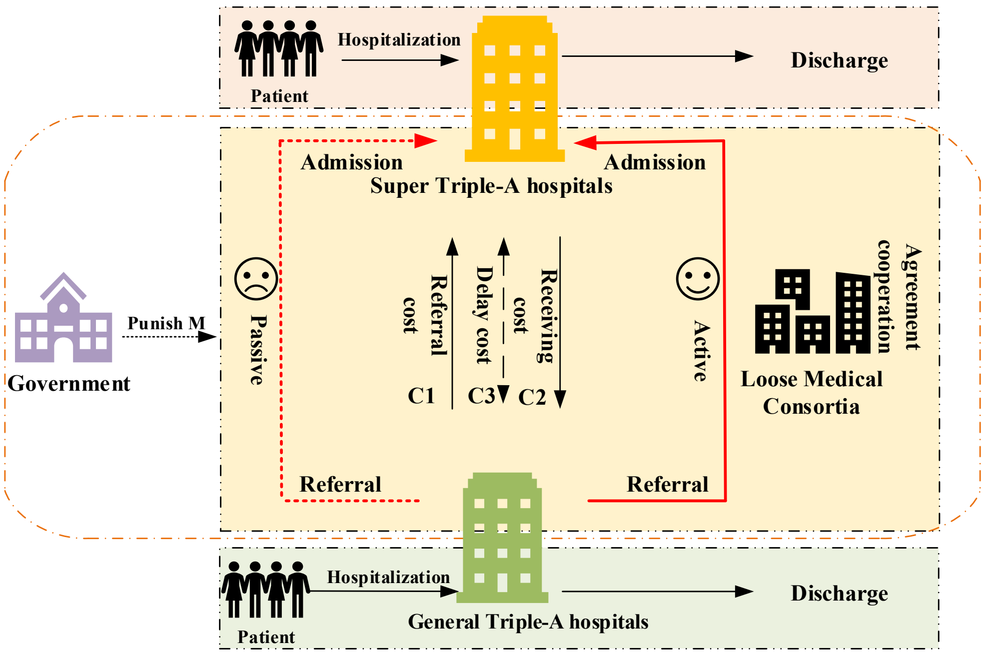

Figure 2. Logic diagram of patient up-transfer in a medical consortium.

It is assumed that when a patient is eligible for referral and a GTH refers a patient up to an STH, referral costs will be incurred (e.g., communication costs incurred by the hospital for referral procedures). Admission costs are incurred when STH actively receives patients (e.g., dual transfer green lanes, coordination costs). If the two hospitals don't agree with the referral/acceptance, there would be an additional gain for both hospitals (STH and GTH). Specifically, when the GTH passively refers a patient, the patient will stay longer at the GTH for treatment and consume more medical services. When an STH passively accepts a patient, the hospital does not need to vacate a vacant bed for the patient. At the same time, GTH will not worry about the potential overspending of medical insurance funds by accepting the referral patients. There are also referral delay costs due to the negative treatment of patients. Usually, the referral delay costs include the doctor-patient conflict caused by delayed patient treatment due to complex referral procedures, the cost due to a lack of nursing beds, insufficient sharing of patient information between hospitals for patient referrals, etc. The government will implement a penalty mechanism for hospitals that negatively cooperate.

2.2. Assumptions

In this section, the following hypotheses are used.

Hypothesis 1: Two participants, a GTH and an STH, are selected in this model. There are two strategies, active referral or passive referral, for upward referral of patients from the GTH, corresponding to probabilities of x and $1-x$, respectively. There are two behavioral strategies for STH, active admission and passive admission, corresponding to probabilities of y and $1-y$, respectively. Both participants are finite and rational and adjust their strategic choices in response to events to maximize their benefits.

Hypothesis 2: When both hospitals actively deal with referred patients, each has a base benefit, R_1 and R_2. When the GTH refers patients passively, patients continue to treatment and additional benefits, S_1, are generated. When an STH passively accepts patients, it does not need to spare beds for them, nor does it need to worry about overspending on medical insurance funds. Thus, additional benefits, S_2, are generated.

Hypothesis 3: When both hospitals treat patients passively, the government will punish the defaulting hospital with a penalty of M.

Hypothesis 4: Because the two hospitals are members of the medical consortium, the patient referral process should fully reflect the community attributes of the consortium. Therefore, this model introduces a cost-sharing factor α, where $\alpha \in (0, 1)$, assuming that both hospitals share the delay cost when both hospitals treat referrals negatively.

Without loss of generality, the fixed cost of referral or non-referral in both types of hospitals is set as 0. This study only considered the additional referral costs incurred by referring patients to the STH and GTH. This processing method is often used in evolutionary game research and does not impact the equilibrium results of the game. C_1 denotes the referral cost of actively referring patients from the GTH and the referral cost of actively admitting patients from the STH is C_2. The delay cost incurred by either hospital treating the referred patient passively is set to C_3.

The parameters used in this paper are shown in Table 1.

Table 1. Parameter symbols and their meanings.

Parameters	Description
R_1	Base revenue of GTH
R_2	Base revenue of STH
S_1	Additional revenue when GTH refers patients passively
S_2	Additional revenue when STH admits patients passively
M	Government penalties for hospitals that do not fulfill their alliance contracts
C_1	Referral costs for patients referred from GTH
C_2	The admission cost of patients received by STH
C_3	Delay costs incurred by either participant for passive treatment of referred patients
α	Delay cost-sharing factor

2.3. *Model construction*

Based on the above assumptions and parameter settings, the payoff matrix of the two-sided evolutionary game between the GTH and STH constructed in this study is shown in Table 2. The payoffs under different strategy choices are explained as follows:

(I) When the strategy of the GTH and STH is (active referral, active admission), the revenues of the GTH and STH are $R_1 - C_1$ and $R_2 - C_2$, respectively.

(II) When the strategy of the GTH and STH is (active referral, passive admission), super tertiary hospitals are penalized by the government with M and bear the delay cost C_3 alone, but receive an additional benefit S_2, at which point the revenue of the GTH is $R_1 - C_1$ and the revenue of the STH is $R_2 - C_2 - C_3 - M + S_2$.

(III) When the strategy of the GTH and STH is (passive referral, active admission), this scenario is similar to case (II), where the GTH is fined M by the government and it alone bears the delay cost C_3, as well as gaining additional revenue, S_1. The benefits for the GTH and STH are $R_1 - C_1 - C_3 - M + S_1$ and $R_2 - C_2$, respectively.

(IV) When the strategy of the GTH and STH is (passive referral, passive admission), both hospitals are fined M by the government. Both hospitals share the delay cost C_3 based on the coefficient α. At this point the benefit to the GTH is $R_1 - C_1 - \alpha C_3 - M + S_1$ and the benefit to the STH is $R_2 - C_2 - (1-\alpha)C_3 - M + S_2$.

Table 2. The payoff matrix.

		STH Active admission y	Passive admission $(1-y)$
GTH	Active referral x	$R_1 - C_1$, $R_2 - C_2$	$R_1 - C_1$, $R_2 - C_2 - C_3 - M + S_2$
	Passive referral $(1-x)$	$R_1 - C_1 - C_3 - M + S_1$, $R_2 - C_2$	$R_1 - C_1 - \alpha C_3 - M + S_1$, $R_2 - C_2 - (1-\alpha)C_3 - M + S_2$

3. Equilibrium analysis

Based on the Malthusian dynamic equation, the equilibrium results of the previously constructed evolutionary game model will be calculated and theoretical analysis will be conducted under different scenarios.

3.1. Analysis of evolutionarily stable strategies

Based on the above assumptions and the benefits matrix, the expected benefits of active and passive referrals for the GTH and the average expected benefits are G_1, G_2 and $\overline{G}$, respectively, as shown below:

$$G_1 = y(R_1 - C_1) + (1-y)(R_1 - C_1) = R_1 - C_1 \tag{1}$$

$$\begin{aligned} G_2 &= y(R_1 - C_1 - C_3 - M + S_1) + (1-y)(R_1 - C_1 - \alpha C_3 - M + S_1) \\ &= R_1 - C_1 - \alpha C_3 - M + S_1 - y(1-\alpha)C_3 \end{aligned} \tag{2}$$

$$\overline{G} = xG_1 + (1-x)G_2 = R_1 - C_1 + (1-x)[-\alpha C_3 - M + S_1 - y(1-\alpha)C_3] \tag{3}$$

Similarly, the expected benefits of active and passive admission of patients for the STH and the average expected benefits are E_1, E_2 and $\overline{E}$, respectively, which are shown below:

$$E_1 = x(R_2 - C_2) + (1-x)(R_2 - C_2) = R_2 - C_2 \tag{4}$$

$$\begin{aligned} E_2 &= x(R_2 - C_2 - C_3 - M + S_2) + (1-x)[R_2 - C_2 - (1-\alpha)C_3 - M + S_2] \\ &= R_2 - C_2 - C_3 - M + S_2 + (1-x)\alpha C_3 \end{aligned} \tag{5}$$

$$\overline{E} = yE_1 + (1-y)E_2 = R_2 - C_2 + (1-y)[S_2 - M - C_3 + (1-x)\alpha C_3] \tag{6}$$

According to the relevant principles of evolutionary games [35], the replication dynamics equation of the evolutionary game systems of GTH and STH can be found as shown in Eq (7):

$$\begin{cases} F(x) = \frac{dx}{dt} = x(G_1 - \overline{G}) = x(1-x)[yC_3(1-\alpha) + \alpha C_3 + M - S_1] \\ F(y) = \frac{dy}{dt} = y(E_1 - \overline{E}) = y(1-y)[x\alpha C_3 + (1-\alpha)C_3 + M - S_2] \end{cases} \tag{7}$$

The derivatives for $F(x)$ and $F(y)$ are as follows:

$$\begin{cases} \frac{dF(x)}{dx} = (1-2x)[yC_3(1-\alpha) + \alpha C_3 + M - S_1] \\ \frac{dF(y)}{dy} = (1-2y)[x\alpha C_3 + (1-\alpha)C_3 + M - S_2] \end{cases} \tag{8}$$

Equation (8) shows that the evolutionary gaming system has five equilibrium points on a plane $M = \{(x,y)|0 \le x, y \le 1\}$: (0,0), (0,1), (1,0), (1,1) and ($-\frac{(1-\alpha)C_3+M-S_2}{\alpha C_3}, -\frac{\alpha C_3+M-S_1}{C_3(1-\alpha)}$) (later abbreviated as (x^*, y^*). When $0 \le -\frac{(1-\alpha)C_3+M-S_2}{\alpha C_3} \le 1$ and $0 \le -\frac{\alpha C_3+M-S_1}{C_3(1-\alpha)} \le 1$hold, (x^*, y^*) is also equilibrium point.

According to Friedman (1991) [36], the stability of the equilibrium point of an evolving system can be obtained by the local stability of the Jacobian matrix. The system Jacobi matrix J can be obtained from Eq (7), as shown in Eq (9):

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)[yC_3(1-\alpha) + \alpha C_3 + M - S_1] & x(1-x)(1-\alpha)C_3 \\ y(1-y)\alpha C_3 & (1-2y)[x\alpha C_3 + (1-\alpha)C_3 + M - S_2] \end{bmatrix} \tag{9}$$

When the determinant $(detJ)$ and trace $(traceJ)$ of the Jacobian matrix of the equilibrium point satisfy $detJ > 0$ and $traceJ < 0$, this is the local equilibrium point (LEP) in the dynamic process of system evolution, which is called an evolutionarily stability strategy (ESS).

The stable strategy of the evolutionary game must have the anti-disturbance ability in a stable state, satisfying $\frac{dF(x)}{dx} < 0$ and$\frac{dF(y)}{dy} < 0$. The specific values of the five LEP in the $Jacobi$ matrix of $detJ$ and $traceJ$ are shown in Table 3:

Table 3. The $detJ$ and $traceJ$ at each LEP.

LEP	$detJ$	$traceJ$
(0,0)	$(M + \alpha C_3 - S_1)[M + (1-\alpha)C_3 - S_2]$	$2M + C_3 - S_1 - S_2$
(0,1)	$-(M + C_3 - S_1)[M + (1-\alpha)C_3 - S_2]$	$\alpha C_3 - S_1 + S_2$
(1,0)	$-(M + \alpha C_3 - S_1)(M + C_3 - S_2)$	$(1-\alpha)C_3 + S_1 - S_2$
(1,1)	$(M + C_3 - S_1)(M + C_3 - S_2)$	$-2M - 2C_3 + S_1 + S_2$
(x^*, y^*)	$-\frac{(M + C_3 - S_1)(M + C_3 - S_2)(M + \alpha C_3 - S_1)[M + (1-\alpha)C_3 - S_2]}{{C_3}^2\alpha(1-\alpha)}$	0

3.2. Stability analysis of strategy portfolios

A total of nine scenarios were generated with different values of the parameters, as shown in Table 4. There are four equilibrium points for each scenario and we analyzed the stability of the evolutionary equilibrium point of the game system of GTH and STH for each scenario.

Table 4. The evolutionary stability of each LEP.

Scenarios	LEP	$detJ$	$traceJ$	State
Scenarios 1:	(0,0)	+	–	ESS
$S_1 > M + C_3$	(0,1)	–	Uncertain	Saddle point
$S_2 > M + C_3$	(1,0)	–	Uncertain	Saddle point
	(1,1)	+	+	Unstable
Scenarios 2:	(0,0)	+	–	ESS
$S_1 > M + C_3$	(0,1)	–	Uncertain	Saddle point
$(1-\alpha)C_3 + M < S_2 < C_3 + M$	(1,0)	+	+	Unstable
	(1,1)	–	Uncertain	Saddle point
Scenarios 3:	(0,0)	–	Uncertain	Saddle point
$S_1 > M + C_3$	(0,1)	+	–	ESS
$S_2 < (1-\alpha)C_3 + M$	(1,0)	+	+	Unstable
	(1,1)	–	Uncertain	Saddle point
Scenarios 4:	(0,0)	+	–	ESS
$\alpha C_3 + M < S_1 < C_3 + M$	(0,1)	+	+	Unstable
$S_2 > C_3 + M$	(1,0)	–	Uncertain	Saddle point
	(1,1)	–	Uncertain	Saddle point
Scenarios 5:	(0,0)	+	–	ESS
$\alpha C_3 + M < S_1 < C_3 + M$	(0,1)	+	+	Unstable
$(1-\alpha)C_3 + M < S_2 < C_3 + M$	(1,0)	+	+	Unstable
	(1,1)	+	–	ESS
Scenarios 6:	(0,0)	–	Uncertain	Saddle point
$\alpha C_3 + M < S_1 < C_3 + M$	(0,1)	–	Uncertain	Saddle point
$S_2 < (1-\alpha)C_3 + M$	(1,0)	+	+	Unstable
	(1,1)	+	–	ESS
Scenarios 7:	(0,0)	–	Uncertain	Saddle point
$S_1 < \alpha C_3 + M$	(0,1)	+	+	Unstable
$S_2 > C_3 + M$	(1,0)	+	–	ESS
	(1,1)	–	Uncertain	Saddle point
Scenarios 8:	(0,0)	–	Uncertain	Saddle point
$S_1 < \alpha C_3 + M$	(0,1)	+	+	Unstable
$(1-\alpha)C_3 + M < S_2 < C_3 + M$	(1,0)	–	Uncertain	Saddle point
	(1,1)	+	–	ESS
Scenarios 9:	(0,0)	+	+	Unstable
$S_1 < \alpha C_3 + M$	(0,1)	–	Uncertain	Saddle point
$S_2 < (1-\alpha)C_3 + M$	(1,0)	–	Uncertain	Saddle point
	(1,1)	+	–	ESS

Scenario 1: $S_1 > M + C_3$, $S_2 > M + C_3$ (high revenue, high revenue)

In Scenario 1, the stable point of the dynamic evolution system is (0,0), that is, the ESS of GTH and STH are passive referral and passive admission. For GTH, the additional benefit generated when referring patients negatively is greater than the sum of the delay cost and the penalty given by the government, which is a high benefit at this point, so GTHs are more inclined to choose to refer patients negatively. By the same token, the additional benefit to STHs when accepting patients passively is greater than the sum of penalties and the delay cost, so GTHs are also more likely to choose to admit patients passively.

Scenarios 2: $S_1 > M + C_3$, $(1-\alpha)C_3 + M < S_2 < C_3 + M$ (high revenue, medium revenue)

In Scenario 2, the stable point of the dynamic evolutionary system is (0,0). The ESS of the GTH and STH is passive referral and passive admission. For GTHs, the additional benefit generated when referring patients negatively is greater than the sum of the delay cost and the penalty given by the government. For the STHs, the additional benefit when they receive patients negatively is less than the sum of the penalty given by the government and the delay cost, but greater than the sum of the penalty and the delay cost sharing with the GTH, which is a medium-benefit state.

Scenarios 3: $S_1 > M + C_3$, $S_2 < (1-\alpha)C_3 + M$ (high revenue, low revenue)

In Scenario 3, the stable point of the dynamically evolving system is (0,1). The ESS of GTH and STH is passive referral and active admission. The GTH remains in a high revenue state, so it is more inclined to choose negatively referred patients. In contrast, the additional benefit of admitting patients negatively for the STH is less than the sum of the penalty given by the government and the delay cost-shared with the GTH, which leaves the GTH in a low-benefit situation, so the STH is more likely to choose positive patient admission.

Scenario 4: $\alpha C_3 + M < S_1 < C_3 + M$, $S_2 > C_3 + M$ (medium revenue, high revenue)

In Scenario 4, the stable point of the dynamic evolution system is (0,0). The ESS of the GTH and STH are passive referral and passive admission. For the GTH, the benefit is medium at this point. The gain is between the sum of the penalty and the delay cost and the sum of the penalty and the shared delay cost. The STH is more likely to choose to admit patients negatively because the additional benefit to the STH when it negatively receives patients is greater than the sum of the penalty given by the government and the delay cost, which is at a high benefit.

Scenario 5: $\alpha C_3 + M < S_1 < C_3 + M$, $(1-\alpha)C_3 + M < S_2 < C_3 + M$ (medium revenue, medium revenue)

In Scenario 5, the stable points of the dynamic evolutionary system are (0,0) and (1,1). The ESS of the GTH and STH are passive referral and passive admission or active referral and active admission. For both hospitals, the benefits are moderate at this point. The benefit for both hospitals lies between the sum of the shared delay cost and penalty and the sum of the delay cost and the penalty. Both hospitals are affected by the cost-sharing coefficient and when one chooses to be negative, the other chooses to be negative and vice versa.

Scenario 6: $\alpha C_3 + M < S_1 < C_3 + M, S_2 < (1-\alpha)C_3 + M$ (medium revenue, low revenue)

In Scenario 6, the stable point of the dynamic evolution system is (1,1). The ESS of GTH and STH is active referral and active admission.

For tertiary hospitals, the benefits generated when treating patients negatively puts the GTH in a medium-benefit position and the STH in a low-benefit position, making both hospitals more inclined to choose to treat referred patients positively.

Scenario 7：$S_1 < \alpha C_3 + M$, $S_2 > C_3 + M$ (low revenue, high revenue)

In Scenario 7, the stable point of the dynamic evolution system is (1,0). The ESS of GTH and STH is active referral and passive admission. The GTH chooses to treat patients positively because of the lower revenue generated when treating patients negatively. For the STH, positive referrals bring higher revenue and therefore it will choose to admit patients negatively.

Scenario 8：$S_1 < \alpha C_3 + M$, $(1-\alpha)C_3 + M < S_2 < C_3 + M$ (low revenue, medium revenue)

In Scenario 8, the stable point of the dynamic evolution system is (1,1). The ESS of GTH and STH is active referral and active admission. For the GTH, the benefit generated when negatively referring patients is less than the sum of the penalty and the delay cost, so the GTH is more likely to choose to refer patients actively. Similarly, for the STH, the benefit of receiving patients negatively is moderate, so both hospitals choose to treat patients positively at this time.

Scenario 9：$S_1 < \alpha C_3 + M$, $S_2 < (1-\alpha)C_3 + M$ (low revenue, low revenue)

In Scenario 9, the stable point of the dynamic evolution system is (1,1). The ESS of GTH and STH is active referral and active admission. For both hospitals, the benefit when treating patients negatively is less than the sum of the penalty and the delay cost, so both hospitals will choose to treat patients positively.

4. Simulation analysis

The evolutionary stability of the strategy of the GTH and STH was simulated using MATLAB R2019b. The initial values for the nine scenarios were $M = 10$, $C_3 = 60$, $\alpha = 0.5$ and the initial values of S_1 and S_2 are shown in Table 5. The evolution diagrams of the nine scenarios are shown in Figure 3. The horizontal axis represents the probability that a GTH chooses to actively refer patients; the vertical axis represents the probability that an STH chooses to actively admit patients.

Table 5. Initial values of S_1 and S_2 for the nine scenarios.

	S_1	S_2		S_1	S_2		S_1	S_2
Scenario 1	80	85	Scenario 4	50	85	Scenario 7	30	85
Scenario 2	80	55	Scenario 5	50	55	Scenario 8	30	55
Scenario 3	80	35	Scenario 6	50	35	Scenario 9	30	35

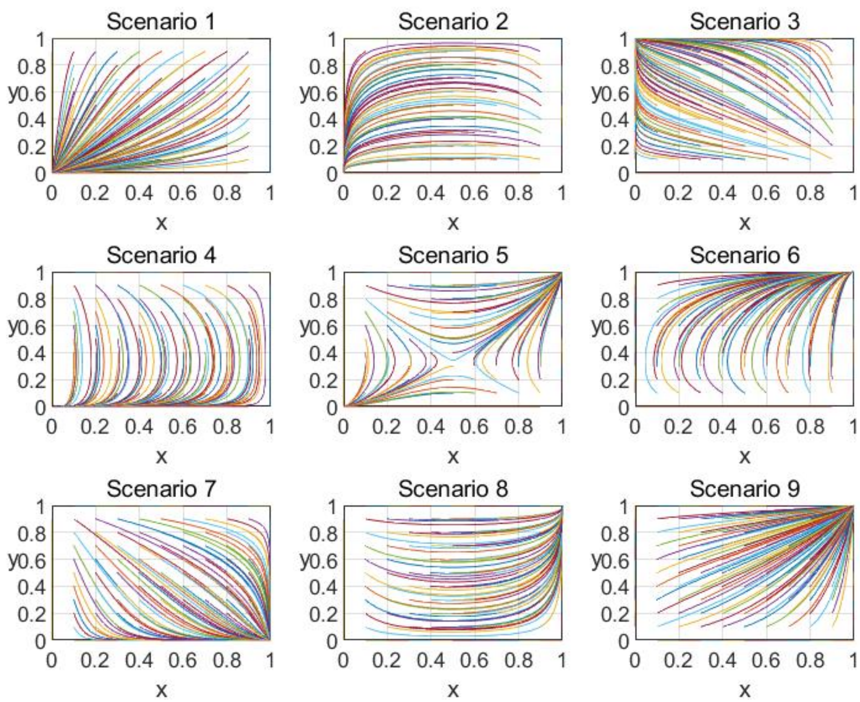

Figure 3. Dynamic evolutionary process of the nine scenarios.

4.1. Results for 9 scenarios

Taking Scenario 1 as an example, the lines shown in the figure all converge to (0,0), implying that the stabilization strategies of the GTH and STH converge to passive referral and passive admit.

Based on the analysis in Section 3.2, we summarize the relationship between the hospital's revenue status, LEP and stabilization strategy corresponding to the nine scenarios in Table 6. The hospital's strategic choices are analyzed and summarized from the perspective of hospital revenue.

High revenue state: (i) When the revenue of GTH are high enough, GTH chooses to refer patients negatively, regardless of whether STH treats patients negatively or not (see Scenarios 1–3). (ii) Similarly, when the revenue of STH is high enough, the strategy is to receive patients negatively (see Scenarios 1, 4 and 7).

Low revenue state: (i) When GTH has low revenue, regardless of whether the STH treats patients negatively or not, the revenue of the GTH is less than the sum of government punishment and shared delay costs. Under a low revenue state, GTH always choose to actively refer patients (see Scenarios 7–9). (ii) When the STH has a low revenue, regardless of whether the GTH treats patients negatively, the STH always chooses to actively receive patients (see Scenarios 3, 6 and 9).

Medium revenue state: (i) From the second and third columns of Table 6, it can be found that when GTH and STH are in a state of high revenue and medium revenue or medium revenue and high revenue, the obtained revenue by the hospitals in the negative treatment of patients are still higher than the delayed referrals costs and government punishment costs. Therefore, their LEP is (0,0), as shown in Scenarios 2 and 4. (ii) In Scenarios 6 and 8, when the status of GTH and STH belongs to the state with low revenue and medium revenue or medium revenue and low revenue, if the hospital treats patients negatively, their revenues are less than the sum of delay costs and government penalty costs. Therefore, the stability strategy of the two hospitals shifts to (1,1). (iii) When both GTH and STH are in a medium revenue state, with the intervention of the cost-sharing coefficient, the revenues of the two hospitals are in a relationship where there are 2 stabilization points in the system, i.e., (0,0)/(1,1). The selection of evolutionary stability strategies for two hospitals is related to the payment matrix and the initial state of the system [37].

Table 6. Stability point analysis of two hospitals in different revenue states.

Scenario	The range of parameter values		Revenue state		LEP
	GTH	STH	GTH	STH	
Scenario 1	$S_1 > M + C_3$	$S_2 > M + C_3$	High	High	(0,0)
Scenario 2	$S_1 > M + C_3$	$(1-\alpha)C_3 + M < S_2 < C_3 + M$		Medium	(0,0)
Scenario 3	$S_1 > M + C_3$	$S_2 < (1-\alpha)C_3 + M$		Low	(0,1)
Scenario 4	$\alpha C_3 + M < S_1 < C_3 + M$	$S_2 > C_3 + M$	Medium	High	(0,0)
Scenario 5	$\alpha C_3 + M < S_1 < C_3 + M$	$(1-\alpha)C_3 + M < S_2 < C_3 + M$		Medium	(0,0)/(1,1)
Scenario 6	$\alpha C_3 + M < S_1 < C_3 + M$	$S_2 < (1-\alpha)C_3 + M$		Low	(1,1)
Scenario 7	$S_1 < \alpha C_3 + M$	$S_2 > C_3 + M$	Low	High	(1,0)
Scenario 8	$S_1 < \alpha C_3 + M$	$(1-\alpha)C_3 + M < S_2 < C_3 + M$		Medium	(1,1)
Scenario 9	$S_1 < \alpha C_3 + M$	$S_2 < (1-\alpha)C_3 + M$		Low	(1,1)

Note: 0 represents a negative attitude, 1 represents a positive attitude.

4.2. Effect of parameters on the strategy in Scenario 5

Among the above nine scenarios, Scenario 5 is special. In Scenario 5, the strategies of the two hospitals converged to (0,0) and (1,1) respectively. Therefore, Scenario 5 is selected for analysis in this study to explore the changes in the hospital's strategy by changing the parameter values.

4.2.1. Impact of penalty cost M on evolution in Scenario 5

In Scenario 5, both hospitals are in a medium gain state and both hospitals have two ESS. Based on the initial values given in Table 6 and assuming the probability value $(x, y) = (0.5, 0.5)$, we investigated the effects of changes in penalty costs M, delay costs C_3 and cost-sharing coefficients α on the evolutionary stability of the GTH and STH.

In Figure 4, the solid line represents the evolutionary trend when $M = 10$ and the dashed line represents the variation trend when M takes other values ($M = 4$, 7, 13, 16, 19).

- When the government's penalty cost is small ($M = 4$ and $M = 7$), the ESS for GTH and STH is (0,0), i.e., negative referral and negative admission.
- As the penalty cost increases ($M = 13$, $M = 16$, $M = 19$), the ESS of the GTH and STH tends to decrease at the rate of (0,0) until at the critical value $M = 10$, the evolutionary stabilization strategy becomes (1,1).

In summary, in Scenario 5, as the cost of government penalties increases, the ESS of GTH and STH first changes from (0,0) to (1,1) and then stays at (1,1) unchanged and the rate of convergence first decreases and then increases. The two hospitals always treat patients with the same choice.

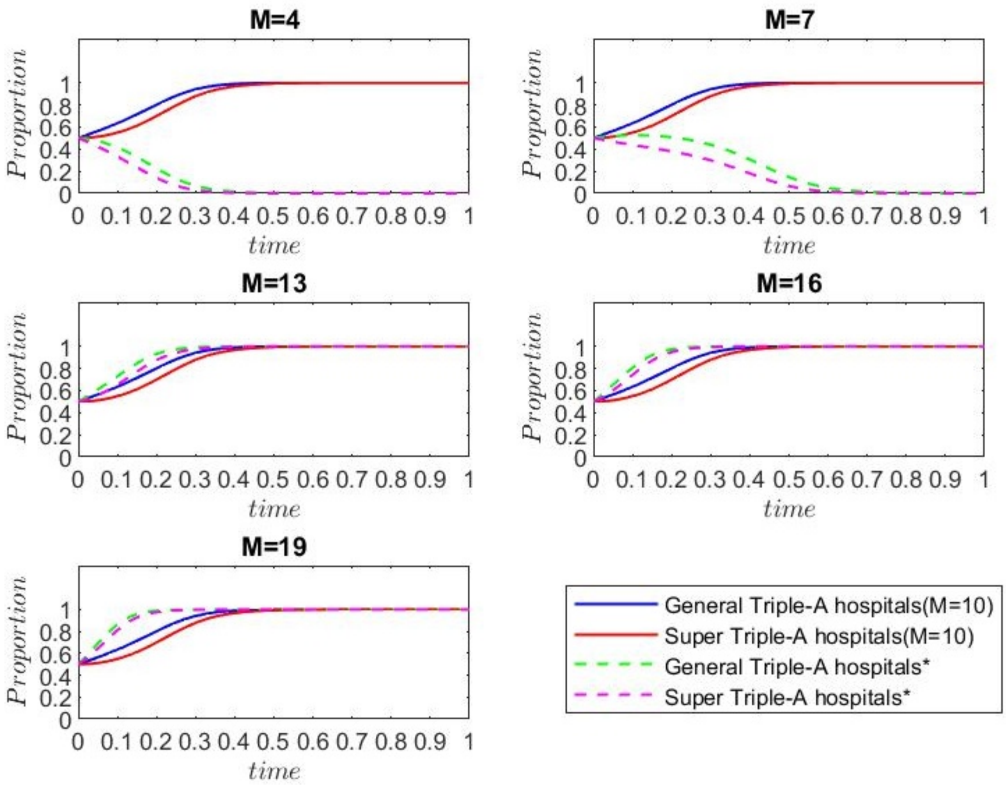

Figure 4. Trajectory of evolution under different penalty costs.

4.2.2. Impact of delay cost C_3 on evolution in Scenario 5

As shown in Figure 5, the evolutionary trajectory under changing delay cost is similar to that when changing the penalty cost in Section 4.1.

- When the delay cost $C_3 < 60$ ($C_3 = 50$ and $C_3 = 55$), the ESS is (0,0) and the convergence rate decreases as the delay cost increases.
- When the delay cost $C_3 = 60$, the ESS of GTH and STH is (1,1), i.e., active referral and passive admission.
- When the delay cost $C_3 > 60$ ($C_3 = 65$, $C_3 = 70, C_3 = 75$), the ESS is (1,1) and the convergence rate increases as the delay cost increases.

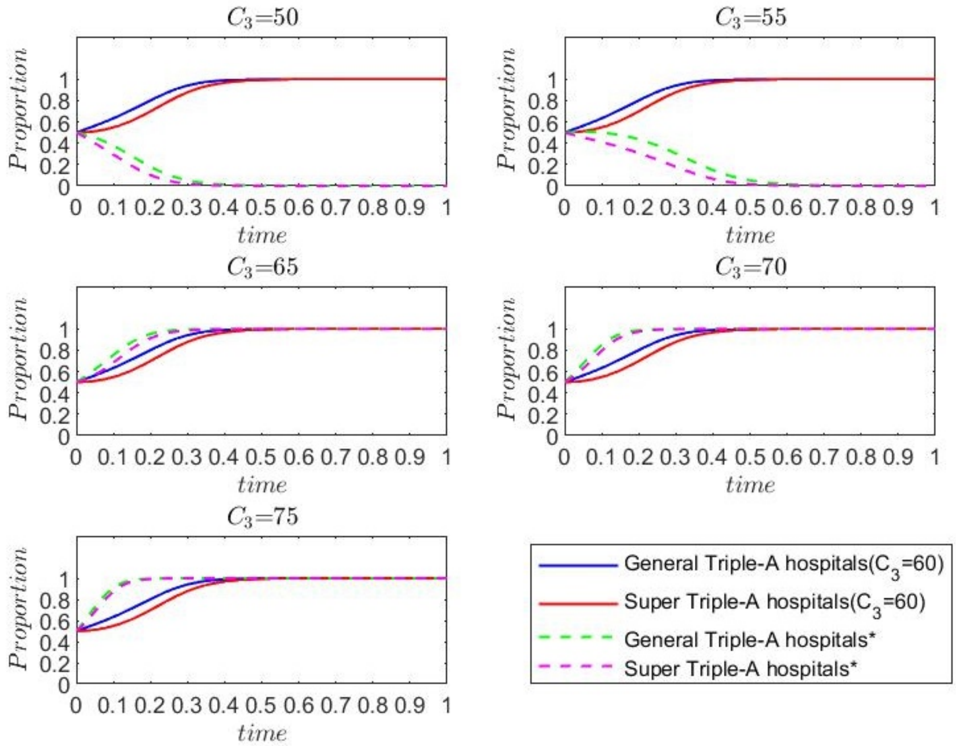

Figure 5. Trajectory of evolution under different delay costs.

4.2.3. Impact of delay cost-sharing coefficient α on evolution in Scenario 5

As shown in Figure 6, changing the cost-sharing coefficient, the GTH and STH ultimately move to active referral and active admission. When α gradually increases from 0.1 to 0.9, and $x < 0.5$, the cost of delay to be shared by the GTH increased and the green dashed line tended to be closer to a probability of 1; the GTH gradually changes from negative referrals to positive referrals; as α gradually increased, $(1-\alpha)$ gradually decreased and the value of delay costs shared by STH decreased. The red dashed line starts with a fast convergence to 1 and becomes a slow convergence to probability 1.

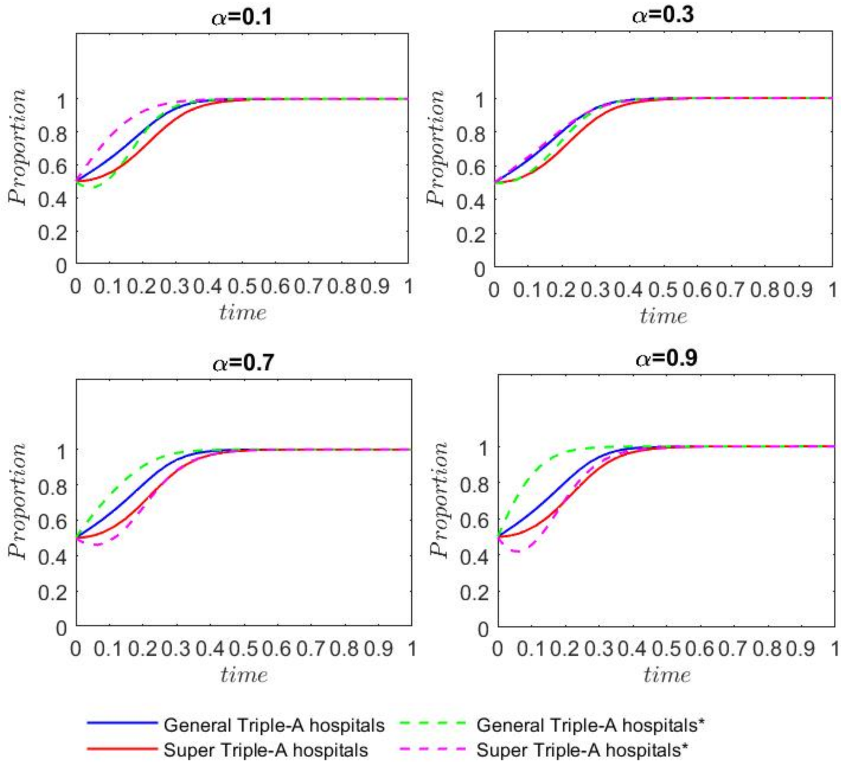

Figure 6. Trajectory of evolution under different delay cost-sharing coefficients.

5. Discussion and conclusions

We focus on two tertiary hospitals with both competitive and cooperative relationships, who form a loose medical association. STH has a stronger position by providing medical technology support to GTH. Although a cooperative relationship is established through an agreement, GTH are often reluctant to upwardly refer patients to STH. We constructed an evolutionary game model between GTH and STH regarding patient upward transfer, analyzed the dynamic evolutionary process of the two hospitals inpatient referral and conducted numerical simulations on the stability of the ESS. Combining the simulation results with the three characteristics of China's healthcare resources and service system, this paper summarizes the following conclusions and management insights.

This study found that hospitals have a preference for increasing revenue and reducing costs. The strategy choice of hospitals is primarily impacted by their revenue states. In this study we analyzed nine scenarios and classified hospitals by revenue states, which included three levels for high, medium and low. (i) Hospitals choose to treat patients negatively when they are in high revenue (see Scenarios 1, 4 and 7). Hospitals follow the rational assumptions in their own development process and in order to safeguard their own interests, hospitals like GTH have an inferior position and are usually reluctant to upwardly refer patients, as this means that they will lose the health insurance claim reimbursement. The reason STH is unwilling to accept patients is rooted in reasons such as insufficient nursing beds and overspending medical insurance reimbursements. Due to the unbalanced distribution of medical resources in China, there are significant differences in the capacity and service levels of the hospitals in different provinces and regions across China. For example, a certain tertiary hospital in the capital of a Chinese province is far more competitive than the ordinary tertiary hospitals in other prefectures in the same province because of its medical staff, medical equipment and government financial subsidies. (ii) When STH and GTH are in low revenue, they choose to treat patients positively. This is because the additional benefits of the hospital are much lower than the delay costs and government penalties caused by negative referrals. At this point, the hospital will actively seek cooperation to offset the losses caused by negative referrals. It is evident that when hospitals are in a clear state of high or low revenue (see Scenarios 1, 3, 4, 6, 7 and 9), their strategic behavior is clear and decisive. (iii) When the additional benefits to the hospitals are greater than the sum of the costs of delays and government penalties, the hospitals with the middle revenue will be negative and the reverse is positive (see Scenario 5).

After proposing the new healthcare reform in 2015, the Chinese government began to emphasize an integrated healthcare service system, hoping to improve the efficiency of the healthcare system through medical consortia. However, the implementation of the medical consortium is facing numerous difficulties due to disagreements between hospitals. Additionally, the lack of cooperation mechanisms between hospitals within the consortium make the operation of medical consortium more challenging. Our research precisely confirms that a scientific and reasonable cooperation mechanism can help to with improving the operation of the medical consortium. The delay cost C_3 and delay cost-sharing coefficient α in the model reflects the cooperation attribute. As the delay cost C_3 increases, the ESS of GTH and STH changes from (0,0) to (1,1) (Figure 5). When α gradually increases from 0.1 to 0.9 and $x < 0.5$, the cost of delay to be shared by the GTH increased, GTH's strategic choices shift from negative to positive referrals (Figure 6). Internal factor is a breakthrough for hospital collaboration. The delay cost-sharing factor ties the interests of hospitals within a medical consortium together. The strategic choice of a hospital with different cost-sharing factors will have a considerable impact on another hospital.

China's medical service system is dominated by public hospitals, so the government has a strong control over the healthcare system, manifested in the implementation of directive tasks is an important assessment index for hospitals. Therefore, in the Chinese context, after the model introduces the governmental punishment, the hospital strategy behavior changes as shown in Figure 4. As the cost of government penalties M increases, the ESS of GTH and STH changes from (0,0) to (1,1). Reasonable external interventions, such as government penalty mechanisms, drive further collaboration between hospitals. Government penalties can change a hospital's revenue status and, in turn, its strategic choices. It is particularly important for the government to penalize hospitals for treating patients negatively when their additional revenue is moderate. A reasonable penalty mechanism helps to restrain self-interested behavior among hospitals within the medical association, thus maximizing win-win cooperation between the two parties.

Based on the above findings, we provide the following suggestions and the answers for the following questions. What type of hospitals should be selected for collaboration? How to cooperate? When should the government intervene? (i) The revenue status of different hospitals varies in reality and the cooperation between medical consortia largely depends on the revenue level of the hospital itself. The members of the medical consortium should try to complement each other as much as possible. Hospitals with high revenue status not being able to take care of referral patients, so hospitals with high revenue status and medium revenue status or hospitals with medium revenue and low revenue status should be selected. (ii) For hospitals with competitive relationships, genuine cooperation cannot be achieved through signing agreements and can be implemented through third-party platforms that set referral standards and reward and punishment performance. (iii) Government regulatory mechanisms can help improve fragmentation within the healthcare consortium. Appropriate government penalties can change the strategic choice behavior of hospitals when there are moderate or high returns in the hospitals. Diversified forms of medical association should be designed and flexible evaluation systems should be adopted according to the state of revenue that hospitals are in.

In the future, we will consider adding the government's reward mechanism and comparing it with the government's punishment mechanism to analyze the degree of influence of the government's reward and punishment mechanism on the referral results of the medical association. In addition, we will consider applying the dynamic game method to study the evolutionary relationship among the tripartite subjects that include hospitals, patients and government.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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