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Collaborative Governance Strategies for Fever Clinics: A Multi-Scenario Evolutionary Game Analysis

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Purpose: China's fever clinics succeeded during the Coronavirus Disease 2019 pandemic but revealed operational deficiencies. This study explores multiparty coordination mechanisms in fever clinics to improve collaborative management and efficiency in epidemic control.

Patients and Methods: A tripartite evolutionary game model was constructed, involving "primary healthcare institutions—non-primary healthcare institutions—government" to analyze the evolutionary stable strategies among these entities in different scenarios. We implemented a simulation of evolutionary processes and conducted sensitivity analyses of government subsidies, punishments, and public supervision.

Results: Four evolutionarily stable strategies were identified: $B_4(0,0,1)$, $B_5(1,1,0)$, $B_6(1,0,1)$, and $B_7(0,1,1)$. The government gradually tended to be passive in emergency scenarios of the epidemic during the evolution process. Primary and non-primary healthcare institutions chose to participate in the coordinated response for epidemic prevention and control in transition scenarios. In addition, increased government subsidies and punishments resulted in the active participation of primary and non-primary healthcare institutions in the coordinated response for epidemic prevention and control. However, excessive subsidies and punishments led to lenient supervision when they exceeded a certain threshold. Meanwhile, the collaborative participation of non-primary healthcare institutions fluctuates in response to variations in government supervision. Under normal scenarios, public supervision had an obvious effect on driving primary healthcare institutions to participate in coordinated responses for epidemic prevention and control, thereby sharing the role of government supervision to a certain extent.

Conclusion: Government subsidies and punishments under a certain threshold effectively promoted the participation of primary and non-primary healthcare institutions in pandemic prevention and control. Additionally, participation in public supervision gradually increased with the gradual evolution of the pandemic. Therefore, our results suggested that the government should actively explore reasonable, dynamic thresholds for subsidies and punishments, promote public participation through diversified means, and explore diverse operation types of fever clinics to address the challenges of emerging infectious diseases in the future.

Keywords: fever clinics, public health emergency, coordination, evolutionary game model, simulation

Introduction

Chinese healthcare institutions were mandated to establish fever clinics following the SARS epidemic 2003 to enhance epidemic prevention and control systems. The Coronavirus Disease 2019 (COVID-19) pandemic underscored significant operational vulnerabilities in these clinics. Alleviation of the epidemic prevention policies in late 2022 by introducing the "Twenty Measures to Optimise Prevention and Control" [1] and the "New Ten Measures",[2] coupled with increasing viral transmissibility, resulted in a surge in infections, overwhelming primary healthcare institutions. The long-standing underinvestment in fever clinics exacerbated these challenges, resulting in clinic closures and refusals to accept patients.[3] Consequently, local governments advised the public to avoid visiting primary healthcare facilities,[4] causing

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these clinics to fail in their screening and diversion functions. This impediment to the hierarchical diagnosis and treatment system forced many febrile patients to visit fever clinics in non-primary healthcare institutions. However, these non-primary clinics encounter challenges such as layout inefficiencies and inadequate equipment, among other issues,[5] hindering the establishing of an effective treatment system during large-scale infectious disease outbreaks. Additionally, the patient influx created medical surges and secondary complications, such as healthcare rationing[6] and nosocomial infections.[7] In response, the State Council's Joint Prevention and Control Mechanism issued policies mandating the establishment of fever clinics at all eligible healthcare institutions above the secondary level and prohibiting arbitrary closures.[8,9] Meanwhile, local governments increased their investments in fever clinics and consultation rooms to address public health limitations.[10]

In fact, during the COVID-19 pandemic, fever clinics in other countries also faced numerous challenges. For example, Singapore's fever clinics — Public Health Preparedness Clinics (PHPCs) struggled with shortages of medical resources.[11] In Japan, infectious disease clinics turned away febrile patients due to capacity limitations.[12,13] Similarly, fever clinics in Italy were overwhelmed by an influx of patients, disrupting the hierarchical diagnosis and treatment system and leaving critically ill febrile patients without adequate care.[14] These challenges highlight that the development and optimization of fever clinics have become a pressing issue in the field of public health.

Currently, with the gradual waning of the COVID-19 pandemic in China, discussions on the future direction of fever clinics in the post-pandemic era have resurfaced. Multiple healthcare managers and clinicians have expressed concerns regarding the operational cost-benefit balance owing to the decreased number of febrile patients and the general reluctance of medical staff to rotate in fever clinics,[15] causing stagnation in various medical alliances. The underperformance of fever clinics is detrimental to the monitoring, prevention, and orderly functioning of the hierarchical diagnosis and treatment system for infectious diseases, as evidenced by subsequent peaks in Influenza A[16] and Mycoplasma pneumoniae infections.[17] Considering the potential threat of a future "Disease X",[18] ensuring the continuous operation and efficient response of fever clinics is a crucial and urgent issue.

Literature Review

Previous studies of fever clinics have typically focused on topics such as architectural design,[19] nursing management,[20,21] and resource allocation.[22] Few scholars have investigated the operations of fever clinics and their critical issues. For example, Ding Hui[23] comprehensively reviewed the complex processes and cross-infection issues in fever clinics, detailing the processes of pre-examination, triage, diagnosis, treatment, and prevention, and proposed optimization strategies and recommendations. Few researchers have examined fever clinic operations from the perspective of multi-stakeholder collaborations involving public participation. Scholars typically focused on single entities, such as the government,[24] healthcare institutions,[25] or patients.[26] However, the efficient and high-quality operation of fever clinics within a tiered medical system requires coordination between various levels of healthcare institutions and government, in addition to the public's role in supervising these operations.[27] Especially, previous studies have confirmed that enhancing public health literacy and awareness of supervisory participation can promote the exercise of supervisory power,[28] thereby encouraging the active involvement of all stakeholders in coordinated responses to epidemic prevention and control.

Certain scholars have acknowledged the importance of government supervision and incentives as factors influencing decision-making.[29,30] Nonetheless, government supervision and incentives require dynamic adjustment to adapt to changes in different scenarios. For example, Fan[31] introduced a dynamic incentive mechanism that considered changes in the social environment and epidemic prevention and control situations in a simulation experiment. A comparison of decision changes under dynamic and static incentive mechanisms demonstrated that the dynamic mechanism more effectively addressed varying social environments and epidemic prevention situations. Current research predominantly explores potential influencing factors from the interaction perspectives between government incentives, public supervision, and healthcare institutions;[31] however, it lacks sufficient consideration of specific factors such as nosocomial infections[7] and medical surges causing healthcare congestion.[32]

Researchers often focus on single scenarios, such as pre-epidemic normalcy or emergency states.[6] However, the risks and impact of fever vary across scenarios due to epidemics' cyclical nature. Only a few scholars have recognized the necessity of considering multiple temporal contexts. Xiao Hongju[33] analyzed the differences in work characteristics and management models of fever clinics during routine prevention periods and epidemic outbreaks and proposed operational mechanisms and strategies tailored to different scenarios. Moreover, previous research has overlooked issues such as rigidity in transitioning between "normal" and "emergency" scenarios, a lack of flexibility and mobility, and a disconnection between peacetime and wartime modes. A significant gap exists in research on the "transitional scenario" of health emergencies.

Regarding research methods, scholars commonly adopt evolutionary game theory for studies involving multiple agents, particularly when data is difficult to obtain or quantify directly.[31,34] The collaborative response to epidemic control in China's fever clinics involves various stakeholders, including the government, primary and non-primary healthcare institutions, and the public. These stakeholders engage in strategic decision-making characterized by bounded rationality and complex interactive game dynamics, aligning with the assumptions of dynamic evolutionary game theory. Nevertheless, evolutionary game studies specifically targeting fever clinics are scarce.

From a theoretical perspective, previous scholars have primarily relied on evolutionary game theory and collaborative governance theory for multi-stakeholder interactions. The evolutionary game theory can simulate the strategy choices of parties under bounded rationality and accurately predict their final stable evolutionary strategies using replicator dynamic equations.[35,36] The collaborative governance theory advocates the participation of multiple stakeholders in the governance of public affairs through cooperation to maximize governance effectiveness.[37] Combining these two theories within a tiered medical system allows further analyses of the games and collaborative interactions among fever clinics at different levels.

In summary, previous research reveals several gaps:

1. Lack of focus on fever clinics at different levels of healthcare institutions and insufficient consideration of multi-stakeholder collaboration, particularly concerning government and public supervision.
2. The non-dynamic, static consideration of key factors, such as government supervision, subsidies, and public participation across different scenarios, ignores the need for dynamic adjustments.
3. Limited application of multi-stakeholder evolutionary game simulation methods in fever clinic studies.
4. Insufficient consideration of typical risk factors in fever clinics during infectious disease outbreaks.

Therefore, we aimed to address these gaps by focusing on multi-stakeholder collaborative governance to ensure efficient epidemic prevention and control. We examined strategy choices in the collaborative governance of fever clinics involving the government, primary and non-primary healthcare institutions, and the public along with integrating a hierarchical diagnosis and treatment system. Moreover, we examined risk factors, such as nosocomial infections and medical surges. After that, we constructed a tripartite evolutionary game model across different scenarios to simulate the impact of dynamic adjustments in government subsidies, punishments, and public supervision on stakeholders' decisions. This study examines the evolution of key stakeholders' roles in fever clinics during the COVID-19 pandemic, exploring multi-party collaborative governance strategies for epidemic prevention and control. These strategies are designed to ensure the provision of equitable and orderly healthcare services to the public, offering scientific foundations for managing future potential infectious disease outbreaks, such as "Disease X".

Materials and Methods

Problem Description

This study addressed the challenges encountered by fever clinics in participating in collaborative epidemic prevention and control, particularly regarding chain reactions and secondary issues arising from inefficiencies in the tiered healthcare system. We constructed an evolutionary game model involving different stakeholders under various scenarios and analyzed the evolutionarily stable strategies of each entity during the collaborative operation of fever clinics, as shown in Figure 1. The following primary questions were addressed:

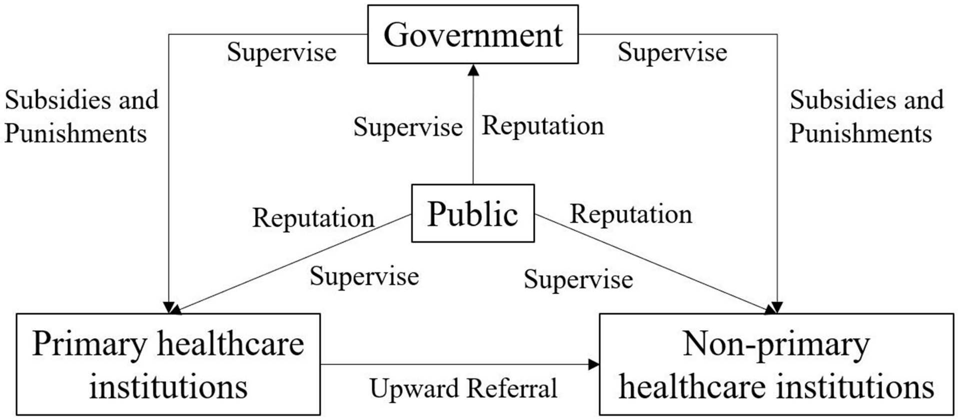

Figure 1 Theoretical framework of tripartite evolutionary game model.

1. What emergency strategies should fever clinics adopt at different levels of healthcare institutions for pandemic prevention and control in different scenarios?
2. How do government incentives and punishments influence the strategic choices of entities in an emergency response chain during sudden public health events?
3. How does public supervision, considered a variable in the tripartite evolutionary game model of "government-primary healthcare institutions-non-primary healthcare institutions", affect the strategic choices of the three entities?

Model Assumptions

Assumption 1: The evolutionary game model involves three stakeholders: primary healthcare institutions, non-primary healthcare institutions, and governments. Each stakeholder operates with bounded rationality and makes independent decisions to maximize their benefits. In addition, they can learn and adapt to environmental changes by adjusting their strategies accordingly.

Assumption 2: Primary healthcare institutions can adopt two strategies for fever clinics in epidemic prevention: actively participate in the coordination of epidemic prevention and control (probability x) or negatively participate (probability 1 - x, where $0 \leq x \leq 1$). All patients with fever were assumed first to visit a primary healthcare institution (all were considered infectious). Primary healthcare institutions can promptly diagnose and treat all patients and refer severe cases to non-primary healthcare institutions. "Active participation in collaboration" involves operating fever clinics and engaging in epidemic control, with operating costs and benefits denoted as C_{z1} and R_1. During participation, they incur costs (C_r) but gain benefits from treating patients with fever (E_1), receiving subsidies from non-primary healthcare institutions (M_t), and receiving government subsidies (αS_g, where α is the distribution coefficient). "Negatively participating in collaboration" involves negatively running fever clinics, refusing patients with fever, and referring all patients to non-primary healthcare institutions, avoiding the risk of in-hospital infections but facing a public discovery probability (L_1, $0 \leq L_1 \leq 1$), resulting in average losses (P_1L_1) and government punishments (W_1). They also gained additional benefits (V_1) from other services.

Assumption 3: Non-primary healthcare institutions have the same strategic options: actively participating in epidemic response coordination (probability y) or negatively participating (probability 1 - y, where $0 \leq y \leq 1$). "Actively participating in coordination" involves operating fever clinics and promptly treating patients with severe fever referred from primary institutions. The costs and benefits are C_{z2} and R_2. Actively participating in the coordination incurs costs (C_2) but yields benefits from treating patients with fever (E_2) and receiving government subsidies (1 - α) S_g, in addition to subsidies to primary institutions (M_t). "Negatively participating in coordination" involves negatively running fever clinics, avoiding costs but gaining additional benefits (V_2) from other services. However, they face in-hospital infection risks (K) with average losses (Kb, where b is infection probability) and risks of patient complaints and government supervision (P_2, W_2), with probabilities (L_2, $0 \leq L_2 \leq 1$), resulting in average losses (P_2L_2, W_2L_2). If both institution types in a tiered healthcare system participate, they gain synergy benefits (T), such as efficient resource use and improved treatment, distributed by a coefficient (r, $0 \le r \le 1$). If primary institutions do not participate, non-primary institutions risk resource strain, thereby incurring basic losses (C_3). If neither participates, additional losses (C_4) occur, with losses varying with resource–strain probability (d).

Assumption 4: Assume the total number of patients (h) includes a proportion of mild cases (q, $0 \le q \le 1$). The maximum capacity of a non-primary healthcare institution is defined as n. Non-primary institutions face a resource strain when h exceeds n. If primary institutions participate in the coordination, non-primary institutions effectively avoid strain, expressed mathematically as $h(1 - q) \le n$. This assumes that primary institutions share the patient load, thus reducing the burden on non-primary institutions. Conversely, if primary institutions do not participate, the probability (d) of exceeding n reflects the risk of resource strain without assistance, which is influenced by factors such as patient number fluctuations and actual capacity limits.

Assumption 5: The government can choose between strict and lenient supervision strategies, with probabilities z and 1 - z ($0 \le z \le 1$), respectively. Strict supervision involves government monitoring of the participation of primary and non-primary healthcare institutions in coordinated pandemic response efforts to ensure effective emergency health management. The government's basic operational costs and benefits are C_g and R_c, respectively. When choosing strict supervision, the government incurs monitoring costs C_s, imposes punishments W_1 and W_2 on institutions that do not participate, and provides incentive subsidies S_g to those that do, with a distribution coefficient α ($\alpha \in [0,1]$). Lenient supervision means that the government does not monitor the participation of healthcare institutions in the pandemic response unless there are public reports of misconduct. The public and government will respond if the institutions' lack of participation causes a social impact (probability L_3, $L_3 \in [0,1]$), leading to corresponding losses P_3L_3, such as reputational damage, punishments from higher authorities, and the maintenance of logistics and supplies. Additionally, under lenient supervision, the government will provide subsidies for S_g due to concerns regarding its reputation, regardless of healthcare institutions' participation in the pandemic response. The government will gain social benefits E_c from the active collaboration of healthcare institutions only if both primary and non-primary institutions choose to participate in a pandemic response.
The relevant parameters above are shown in Table S1. In addition, based on these assumptions, the expected payoffs of primary healthcare institutions, non-primary healthcare institutions, and the government under different strategy choices are summarized in Table 1.

Model Analysis

Stability Analysis of Primary Healthcare Institutions' Strategies

Based on the aforementioned research hypotheses, we constructed a game payoff matrix with mixed strategies for primary healthcare institutions, non-primary institutions, and the government, as shown in Table 1.

Evolutionary Equilibrium Strategy Trend of Primary Healthcare Institutions

The payoff matrix of the mixed strategy game in Table 1 is as follows:

Table 1 The Payoff Matrix of the Evolutionary Game Model Between Government, Primary, and Non-Primary Healthcare Institutions

Portfolio of Gaming Strategies	Primary Healthcare Institutions' Fever Clinics	Non-Primary Healthcare Institutions' Fever Clinics	Government
(1,1,1)	$-C_{z1}+R_1+\alpha S_g+qhE_1+h(1-q)M_t+rT-C_r$	$-C_{z2}+R_2+h(1-q)E_2+(1-\alpha)S_g+(1-r)T-C_2-h(1-q)M_t$	$R_c-C_g+E_c-C_s-S_g$
(1,1,0)	$-C_{z1}+R_1+\alpha S_g+qhE_1+h(1-q)M_t+rT-C_r$	$-C_{z2}+R_2+h(1-q)E_2+(1-\alpha)S_g+(1-r)T-C_2-h(1-q)M_t$	$R_c-C_g+E_c-S_g$
(1,0,1)	$-C_{z1}+R_1+\alpha S_g+qhE_1+h(1-q)M_t-C_r$	$-C_{z2}+R_2+h(1-q)E_2-h(1-q)M_t+V_2-Kb-P_2L_2-W_2$	$R_c-C_g+W_2-C_s-\alpha S_g$
(1,0,0)	$-C_{z1}+R_1+\alpha S_g+qhE_1+h(1-q)M_t-C_r$	$-C_{z2}+R_2+h(1-q)E_2+(1-\alpha)S_g-h(1-q)M_t+V_2- Kb-P_2L_2-W_2L_2$	$R_c-C_g+W_2L_2-S_g-P_3L_3$
(0,1,1)	$-C_{z1}+R_1+hM_t+V_1-P_1L_1-W_1$	$-C_{z2}+R_2+hE_2-dC_3+(1-\alpha)S_g-C_2-hM_t$	$R_c-C_g+W_1-C_s-(1-\alpha)S_g$
(0,1,0)	$-C_{z1}+R_1+\alpha S_g+hM_t+V_1-P_1L_1-W_1L_1$	$-C_{z2}+R_2+hE_2-dC_3+(1-\alpha)S_g-C_2-hM_t$	$R_c-C_g+W_1L_1-S_g-P_3L_3$
(0,0,1)	$-C_{z1}+R_1+hM_t+V_1-P_1L_1-W1$	$-C_{z2}+R_2+hE_2-dC_3-dC_4-hM_t+V_2- Kb-P_2L_2-W_2$	$R_c-C_g+W_1+W_2-C_s$
(0,0,0)	$-C_{z1}+R_1+\alpha S_g+hM_t+V_1-P_1L_1-W_1L_1$	$-C_{z2}+R_2+hE_2-dC_3-dC_4+(1-\alpha)S_g-hM_t+V_2- Kb-P_2L_2-W_2L_2$	$R_c-C_g+W_1L_1+W_2L_2-S_g-P_3L_3$

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The expected benefit for the primary healthcare institution in choosing the "actively participate in collaboration" strategy is V_{12}, and the expression is as follows:

$$V_{12} = yz(-C_{z1} + R_1 + hM_t + V_1 - P_1L_1 - W_1) + y(1-z)\left(-C_{z1} + R_1 + \alpha S_g + hM_t + V_1 - P_1L_1 - W_1L_1\right) + (1-y)z(-C_{z1} + R_1 + hM_t + V_1 - P_1L_1 - W_1) + (1-y)(1-z)\left(-C_{z1} + R_1 + \alpha S_g + hM_t + V_1 - P_1L_1 - W_1L_1\right) \tag{1}$$

The expected return for choosing the "negatively participate in collaboration" strategy is V_{11}, and the expression is as follows:

$$V_{11} = yz[-C_{z1} + R_1 + \alpha S_g + hqE_1 + h(1-q)M_t + rT - C_r] + y(1-z)[-C_{z1} + R_1 + \alpha S_g + hqE_1 + h(1-q)M_t + rT - C_r] + (1-y)z[-C_{z1} + R_1 + \alpha S_g + hqE_1 + h(1-q)M_t - C_r] + (1-y)(1-z)\left[-C_{z1} + R_1 + \alpha S_g + hqE_1 + h(1-q)M_t - C_r\right] \tag{2}$$

The average expected return of the primary healthcare institution is V_{13}. The expression is as follows:

$$V_{13} = xV_{11} + (1-x)V_{12} \tag{3}$$

Therefore, the replication dynamic equation of primary healthcare institutions is as follows:

$$F(x) = -x(x-1)\left(W_1z - V_1 - C_r + W_1L_1 + P_1L_1 - W_1L_1z + hqE_1 - hqM_t + \alpha S_g z + rTy\right) \tag{4}$$

The first-order derivatives of x and the set G(z) are as follows:

$$d(F(x))/dx = (1-2x)\left(W_1z - V_1 - C_r + W_1L_1 + P_1L_1 - W_1L_1z + hqE_1 - hqM_t + \alpha S_g z + rTy\right) \tag{5}$$

$$G(z) = \left(W_1z - V_1 - C_r + W_1L_1 + P_1L_1 - W_1L_1z + hqE_1 - hqM_t + \alpha S_g z + rTy\right) \tag{6}$$

Using the stability theorem of differential equations, the probability of a primary healthcare institution choosing to actively participate in collaboration in a steady state must satisfy $F(x) = 0$ and $d(F(x))/dx < 0$. Since $\partial G(z)/\partial z = W_1 - W_1L_1 + \alpha S_g > 0$, G(z) is an increasing function for z. Thus, when $z = z = (V_1 + C_r - W_1L_1 - L_1P_1 - E_1hq + qhM_t - rTy)/(W_1 - W_1L_1 + \alpha S_g)$, $G(z)=0$, at which point $d(F(x))/dx \equiv 0$ and the primary healthcare institution cannot determine a stabilization strategy. According to Eq. (4) ~ (6), When $z < z^*$, $G(z)<0$, at which point $dF(x)/dx|_{x=0}<0$ and $x=0$ is the Evolutionary Stable Strategy (ESS), which is defined as a strategy that is uninvadable under evolutionary dynamics.[38] Conversely, when $z > z^*$, $G(z) > 0$, at which point $dF(x)/dx|_{x=1}<0$ and $x = 1$ is the ESS. The evolutionary phase diagram of the primary healthcare institution's strategy is shown in Figure 2.

Volume A_1 (V_{A1}) represents the probability that primary healthcare institutions choose to participate negatively in the collaboration, as shown in Figure 2. Volume A_2 represents the probability that they will actively participate in collaboration. These are calculated as follows:

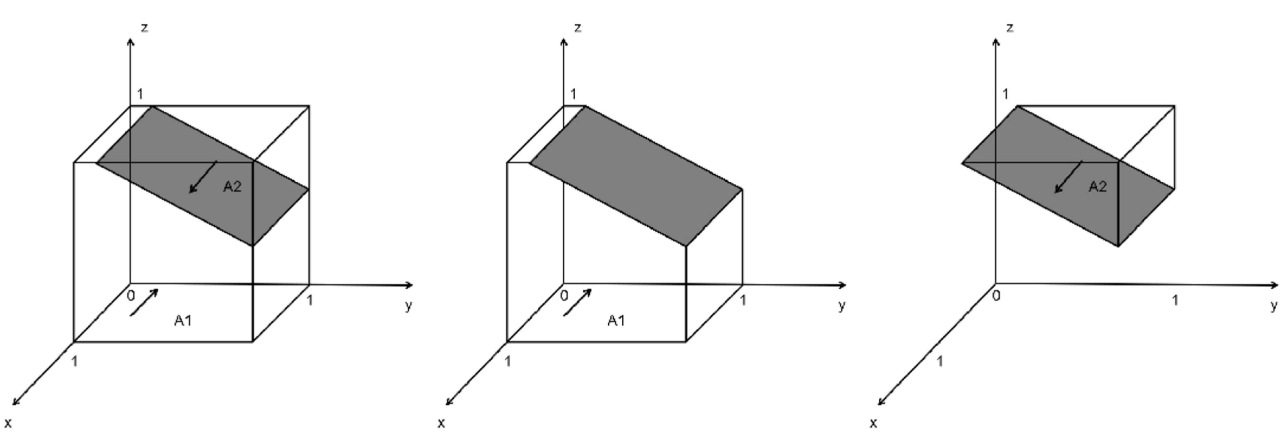

Figure 2 Phase diagram of the evolution of primary healthcare institution.

$$V_{A1} = \int_0^1 \int_0^1 \frac{V_1 + C_r - W_1L_1 - P_1L_1 - E_1hq + M_thq - rTy}{W_1 - W_1L_1 + \alpha S_g} dx * dy = \frac{2V_1 + 2C_r - 2W_1L_1 - 2P_1L_1 - 2E_1hq + 2M_thq - rT}{2(W_1 - W_1L_1 + \alpha S_g)} \tag{7}$$

$$V_{A2} = 1 - \int_0^1 \int_0^1 \frac{V_1 + C_r - W_1L_1 - P_1L_1 - E_1hq + M_thq - rTy}{W_1 - W_1L_1 + \alpha S_g} dx * dy = 1 - \frac{2V_1 + 2C_r - 2W_1L_1 - P_1L_1 - 2E_1hq + 2M_thq - rT}{2(W_1 - W_1L_1 + \alpha S_g)} \tag{8}$$

$$V_{A2} = 1 - V_{A1} \tag{9}$$

Corollary 1: The likelihood of primary healthcare institutions actively participating in coordinated pandemic response efforts is negatively correlated with the costs of operating fever clinics, the additional benefits of non-cooperation, and the subsidies obtained through patient referrals. It is positively correlated with the benefits of coordinating with non-primary healthcare institutions, government subsidies, the average loss due to patient complaints regarding non-cooperation, and revenue from treating patients with fever.

Proof: The probability x of the primary healthcare institution to choose the "actively participate in collaboration" strategy, ie, V_{A2}, is obtained by taking the partial derivatives of C_r, V_1, M_t, S_g, L_1P_1, E_1, and rT. The following was calculated:

$$\frac{\partial V_{A2}}{\partial C_r} = \frac{\partial V_{A2}}{\partial V_1} = -\frac{1}{W_1 - W_1L_1 + \alpha S_g} < 0 \tag{10}$$

$$\frac{\partial V_{A2}}{\partial M_t} = -\frac{hq}{W_1 - W_1L_1 + \alpha S_g} < 0 \tag{11}$$

$$\frac{\partial V_A}{\partial S_g} = -\frac{a(2V_1 + 2C_r - 2W_1L_1 - 2L_1P_1 - 2E_1hq + 2M_thq - rT)}{2(W_1 - W_1L_1 + \alpha S_g)^2} > 0 \tag{12}$$

$$\frac{\partial V_A}{\partial (L_1P_1)} = \frac{L_1}{W_1 - W_1L_1 + \alpha S_g} > 0 \tag{13}$$

$$\frac{\partial V_A}{\partial E_1} = \frac{hq}{W_1 - W_1L_1 + \alpha S_g} > 0 \tag{14}$$

$$\frac{\partial V_A}{\partial (rT)} = \frac{1}{2(W_1 - W_1L_1 + \alpha S_g)} > 0 \tag{15}$$

Therefore, V_{A2} is an increasing function of S_g, L_1P_1, E_1, and rT. That is, as S_g, L_1P_1, E_1, and rT increase, V_{A2} gradually increases, and the probability of the primary healthcare institution choosing the "actively participate in collaboration" strategy increases. Alternatively, as C_r, V_1, and M_t increase, V_{A2} gradually decreases.

Evolutionary Equilibrium Strategy Trend of Non-Primary Healthcare Institutions

The expected benefits for non-primary healthcare institutions in choosing to "actively participate in collaboration" and "negatively participate in collaboration" are V_{21} and V_{22}, respectively.

$$\begin{aligned} V_{21} = {} & xz[-C_{z2} + R_2 + h(1-q)E_2 + (1-\alpha)S_g + (1-r)T - C_2 - h(1-q)M_t] + x(1-z)[-C_{z2} + \\ & R_2 + h(1-q)E_2 + (1-\alpha)S_g + (1-r)T - C_2 - h(1-q)M_t] + (1-x)z[-C_{z2} + R_2 + hE_2 - dC_3 + \\ & (1-\alpha)S_g - C_2 - hM_t] + (1-x)(1-z)[-C_{z2} + R_2 + hE_2 - dC_3 - dC_4 + (1-\alpha)S_g - hM_t + V_2 - \\ & Kb - P_2L_2 - W_2L_2] \end{aligned} \tag{16}$$

$$V_{22} = xz[-C_{z2} + R_2 + h(1-q)E_2 - h(1-q)M_t + V_2 - Kb - P_2L_2 - W_2] + x(1-z)[-C_{z2} + R_2 + h(1-q)E_2 + (1-\alpha)S_g - h(1-q)M_t + V_2 - Kb - P_2L_2 - W_2L_2] + (1-x)z[-C_{z2} + R_2 + hE_2 - dC_3 - dC_4 - hM_t + V_2 - Kb - P_2L_2 - W_2] + (1-x)(1-z)[-C_{z2} + R_2 + hE_2 - dC_3 - dC_4 + (1-\alpha)S_g - hM_t + V_2 - Kb - P_2L_2 - W_2L_2] \tag{17}$$

Therefore, the replication dynamic equation of a non-primary healthcare institution is as follows:

$$V_{23} = yV_{21} + (1-y)\ V_{22} \tag{18}$$

The replication dynamic equation of a non-primary healthcare institution is as follows:

$$F(y) = -y(y-1)\left(C_4d - V_2 - C_2 + Kb + W_2z + S_gz + Tx + W_2L_2 + P_2L_2 - W_2L_2z - C_4dx - \alpha S_gz - rTx\right) \tag{19}$$

The first-order derivatives of x and the set J(z) are as follows:

$$d(F(y))/dy = (1-2y)\left(C_4d - V_2 - C_2 + Kb + W_2z + S_gz + Tx + W_2L_2 + P_2L_2 - W_2L_2z - C_4dx - \alpha S_gz - rTx\right) \tag{20}$$

$$J(z) \ = \ C_4d - V_2 - C_2 + Kb + W_2z + S_gz + Tx + W_2L_2 + P_2L_2 - W_2L_2z - C_4dx - \alpha S_gz - rTx \tag{21}$$

Using the stability theorem of differential equations, the probability of a non-primary healthcare institution choosing to participate actively in collaboration in a steady state must satisfy F(y) = 0 and d(F(y))/dy < 0. Since ∂ J(z)/∂z = W_2+S_g-W_2L_2-αS_g > 0, J(z) is an increasing function for z. Thus, when z = z = (C_4d-V_2-C_2+Kb+W_2L_2+L_2P_2+Tx-C_4dx-rTx)/(W_2L_2+αS_g-W_2-S_g), J(z) = 0, at which point d(F(y))/dy = 0 and the non-primary healthcare institution cannot determine a stabilisation strategy. According to Eq. (19) ~ (21), When z < z*, J(z) < 0, at which point dF(y)/dy|y = 0 < 0 and y = 0 is the ESS. Conversely, when z > z*, J(z) > 0, at which point dF(y)/dy|y =1 < 0 and y = 1 is the ESS. An evolutionary phase diagram of the strategy of non-primary healthcare institutions is shown in Figure 3.

Volume B_1 (V_{B1}) represents the probability that non-primary healthcare institutions will choose to actively participate in the collaboration, as shown in Figure 3. Volume B_2 (V_{B2}) represents the probability of negative participation in the collaboration. These are calculated as follows:

$$V_{B1} = \int_0^1\int_0^1 \frac{C_4d - V_2 - C_2 + Kb + W_2L_2 + L_2P_2 + Tx - C_4dx - rTx}{W_2L_2 + \alpha S_g - W_2 - S_g}\,dx\,dy = \frac{2(C_4d - V_2 - C_2 + Kb + W_2L_2 + L_2P_2 - T + C_4d + rT}{2(W_1 - W_1L_1 + \alpha S_g)} \tag{22}$$

$$V_{B2} = 1 - \int_0^1\int_0^1 \frac{C_4d - V_2 - C_2 + Kb + W_2L_2 + L_2P_2 + Tx - C_4dx - rTx}{W_2L_2 + \alpha S_g - W_2 - S_g}\,dx\,dy = 1 - \frac{2(C_4d - V_2 - C_2 + Kb + W_2L_2 + L_2P_2) - T + C_4d + rT}{2(W_1 - W_1L_1 + \alpha S_g)} \tag{23}$$

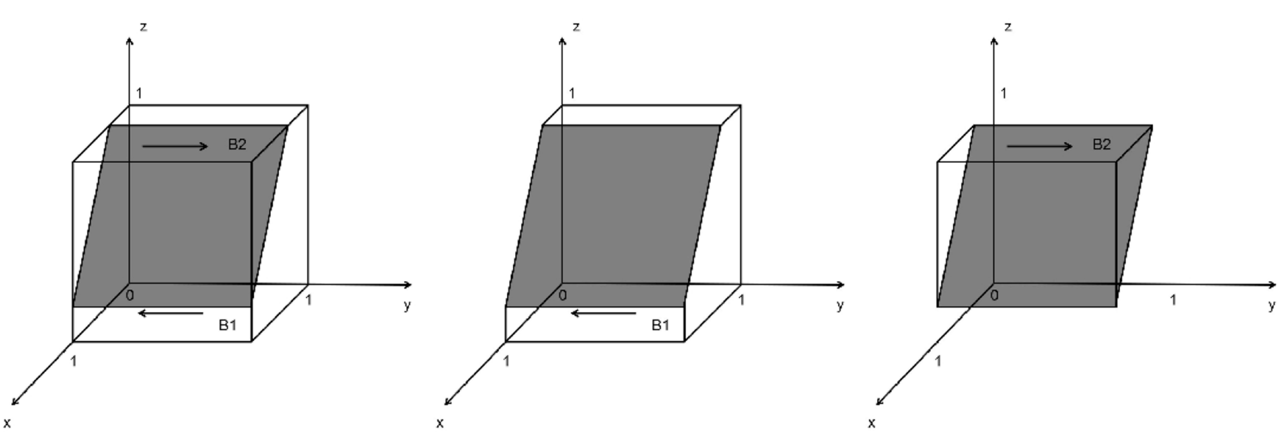

Figure 3 Phase diagram of the evolution of non-primary healthcare institution.

Corollary 2: The probability of non-primary healthcare institutions participating in a coordinated pandemic response is negatively correlated with the costs of maintaining fever clinics and the additional benefits of non-cooperation. It is positively correlated with government subsidies, coordination benefits with primary healthcare institutions, losses from hospital-acquired infections, the probability of such infections, and the average loss from patient complaints during non-cooperation.

Proof: The probability y that the non-primary healthcare institution will choose the "actively participate in collaboration" strategy, ie, V_{B2}, is obtained by taking the partial derivatives of C_2, V_2, Kb, S_g, L_2P_2, and rT. The following was calculated: $\partial V_{B2}/\partial C_2<0$, $\partial V_{B2}/\partial V_2<0$, $\partial V_{B2}/\partial S_g>0$, $\partial V_{B2}/\partial T>0$, $\partial V_{B2}/\partial (Kb)>0$, and $\partial V_{B2}/\partial (L_2P_2)>0$. Therefore, as S_g, L_2P_2, Kb, and rT increase, V_{B2} gradually increases, and the probability of the non-primary healthcare institution choosing the "actively participate in collaboration" strategy increases. Alternatively, as C_2 and V_2 increase, V_{B2} gradually decreases.

Government Strategy Stability Analysis

The government's expected benefits V_{31} as cooperators, V_{32} as defectors, and average expected benefits V_{33} are as follows:

$$V_{31} = xy\left(R_c - C_g + E_c - C_s - S_g\right) + (1-x)y\left(R_c - C_g + E_c - S_g\right) + x(1-y)[R_c - C_g + W_1 - C_s - (1-\alpha)S_g] + (1-x)(1-y)[R_c - C_g + W_1L_1 - S_g - P_3L_3] \tag{24}$$

$$V_{32} = xy[R_c - C_g + W_2 - C_s - \alpha S_g] + (1-x)y[R_c - C_g + W_2L_2 - S_g - P_3L_3] + x(1-y)[R_c - C_g + W_1 + W_2 - C_s] + (1-x)(1-y)\left(R_c - C_g + W_1L_1 + W_2L_2 - S_g - P_3L_3\right) \tag{25}$$

$$V_{33} = zV_{31} + (1-z)V_{32} \tag{26}$$

Therefore, the replicator dynamic equation for the government is as follows:

$$F(z) = z(z-1)\left(C_s - W_1 - W_2 - S_g + W_1x + W_2y + S_gy + W_1L_1 + W_2L_2 - P_3L_3 - W_1L_1x - W_2L_2y + \alpha S_gx - \alpha S_gy + P_3L_3xy\right) \tag{27}$$

Taking the first-order derivative of F(z) yields the following:

$$dF(z)/dz = (2z-1)\left(C_s - W_1 - W_2 - S_g + W_1x + W_2y + S_gy + W_1L_1 + W_2L_2 - P_3L_3 - W_1L_1x - W_2L_2y + \alpha S_gx - \alpha S_gy + P_3L_3xy\right) \tag{28}$$

The set K(y) is as follows:

$$K(y) = \left(C_s - W_1 - W_2 - S_g + W_1x + W_2y + S_gy + W_1L_1 + W_2L_2 - P_3L_3 - W_1L_1x - W_2L_2y + \alpha S_gx - \alpha S_gy + P_3L_3xy\right) \tag{29}$$

Using the stability theorem of differential equations, the probability of the government choosing strict supervision in the steady state must satisfy F(z) = 0 and d(F(z))/dz < 0. Since $\partial K(y)/\partial y = W_2+S_g-W_2L_2-\alpha S_g+L_3P_3x>0$, K(y) is an increasing function of y. Thus, when $y=y=[(C_s-W_1-W_2-S_g+W_1L_1+W_2L_2-L_3P_3) + x(W_1-W_1L_1+\alpha S_g)]/(W_2L_2+\alpha S_g-L_3P_3x-W_2-S_g)$, K(y) = 0, at which point d(F(z))/dz ≡ 0 and the government cannot determine a stabilization strategy. According to Eq. (27) ~ (29), when y > y*, K(y) > 0, at which point d(F(z))/dz|z=0<0 and z=0 is the ESS. Conversely, when y < y*, K(y) < 0, at which point d(F(z))/dz|z =1 < 0 and z = 1 is the ESS. An evolutionary phase diagram of the government is shown in Figure 4.

As shown in Figure 4, volume C_1 (V_{C1}) represents the probability that the government will choose to supervise strictly. Volume C_2 (V_{C2}) indicates the probability of strict supervision. These are calculated as follows:

$$V_{C1} = \int_0^1\int_0^1 \frac{\left(C_s - W_1 - W_2 - S_g + W_1L_1 + W_2L_2 - L_3P_3\right) + x\left(W_1 - W_1L_1 + \alpha S_g\right)]}{W_2 * L_2 + \alpha S_g - L_3P_3x - W_2 - S_g}\,dx\,dz \tag{30}$$

$$V_{C2} = 1 - V_{C1} \tag{31}$$

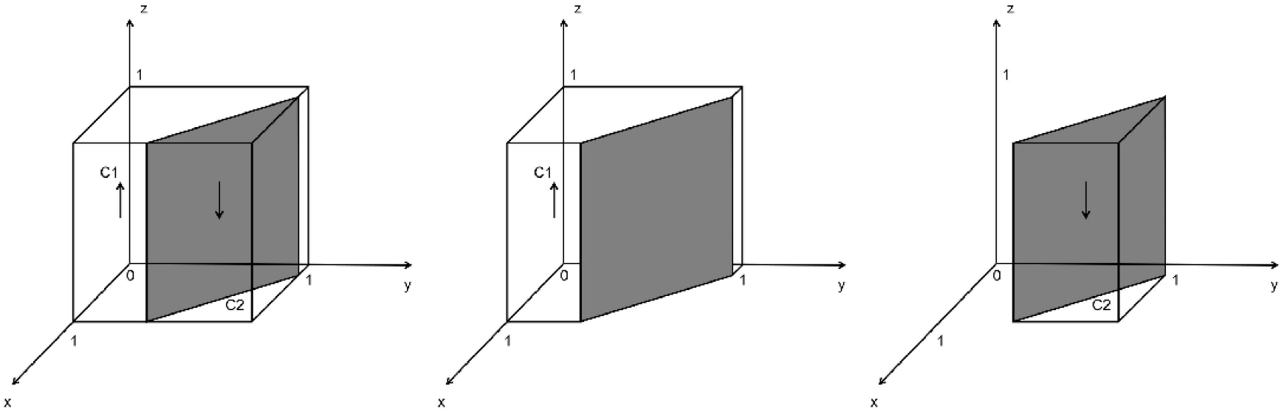

Figure 4 Phase diagram of the evolution of government.

Corollary 3: The probability of strict government supervision positively correlates with the average loss from patient complaints under lax supervision and negatively correlates with supervision costs.

Proof: The probability y that the government will choose the "strict supervision" strategy, ie, V_{C1}, is obtained by taking the partial derivatives of C_S and L_3P_3. According to Eq. (30) ~ (31), the following is calculated: $\partial V_{C1}/\partial L_3P_3 > 0$, $\partial V_{C1}/\partial C_s < 0$. Therefore, as L_3P_3increases, V_{C1} gradually increases, and the probability of the government choosing the "strict supervision" strategy increases. Alternatively, as C_s increases, V_{C2} gradually decreases.

Evolutionary Stability Analysis of the System

According to Friedman[38] (1991), ESSs occur only among pure strategies, excluding mixed strategies. Therefore, eight pure strategy points can be obtained: B_1 (0, 0, 0), B_2 (1, 0, 0), B_3 (0, 1, 0), B_4 (0, 0, 1), B_5 (1, 1, 0), B_6 (1, 0, 1), B_7 (0, 1, 1), and B_8 (1, 1, 1). The Jacobian matrix of the three-party evolutionary game system is as follows:

$$J = \begin{bmatrix} J11 & J12 & J13 \\ \mathrm{J21} & J22 & J23 \\ J31 & J32 & J33 \end{bmatrix} = \begin{bmatrix} \frac{dF(x)}{dx} & \frac{dF(x)}{dy} & \frac{dF(x)}{dz} \\ \frac{dF(y)}{dx} & \frac{dF(y)}{dy} & \frac{dF(y)}{dz} \\ \frac{dF(z)}{dx} & \frac{dF(z)}{dy} & \frac{dF(z)}{dz} \end{bmatrix} \tag{32}$$

Among this:

$$\frac{dF(x)}{dx} = -x*\left(W_1z - V_1 - C_r + W_1L_1 + L_1P_1 - W_1L_1z + E_1hq - M_thq + \alpha S_gz + Wry\right) - (x-1)\left(W_1z - V_1 - C_r + W_1L_1 + L_1P1 - W_1L_1z + E_1hq - Mthq + \alpha S_gz + rTy\right) \tag{33}$$

$$\frac{dF(x)}{dy} = -rTx(x-\ 1) \tag{34}$$

$$\frac{dF(x)}{dz} = -x(x-\ 1)\left(W_1\ + \alpha M_g\ -\ W_1L_1\right) \tag{35}$$

$$\frac{dF(y)}{dx} = y(y-\ 1)(C_4d - T + rT) \tag{36}$$

$$\frac{dF(y)}{dy} = -y(C_4d-\ V_2\ -\ C_2\ + Kb +\ W_2z + S_gz + Tx +\ W_2L_2\ +\ L_2P_2\ -\ W_2L_2z -\ C_4dx - \alpha S_gz - rTx) -\ (y-\ 1)(C_4d-\ V_2\ -\ C_2\ + Kb +\ W_2z + S_gz + Tx +\ W_2L_2\ +\ L_2P_2\ - W_2L_2z -\ C_4dx - \alpha S_gz - rTx) \tag{37}$$

$$\frac{dF(y)}{dz} = -y(y - 1)\left(W_2 + S_g - \alpha S_g - W_2 L_2\right) \tag{38}$$

$$\frac{dF(z)}{dx} = z(z - 1)\left(W_1 + \alpha S_g - W_1 L_1 + L_3 P_3 y\right) \tag{39}$$

$$\frac{dF(z)}{dy} = z(z - 1)\left(W_2 + S_g - \alpha S_g - W_2 L_2 + L_3 P_3 x\right) \tag{40}$$

$$\begin{aligned}\frac{dF(z)}{dz} = {} & z(C_s - W_1 - W_2 - S_g + W_1 x + W_2 y + S_g y + W_1 L_1 + W_2 L_2 - L_3 P_3 - W_1 L_1 x \\ & - W_2 L_2 y + \alpha S_g x - \alpha S_g y + L_3 P_3 xy) + (z - 1)(C_s - W_1 - W_2 - S_g + W_1 x + W_2 y + S_g y \\ & + W_1 L_1 + W_2 L_2 - L_3 P_3 - W_1 L_1 x - W_2 L_2 y + \alpha S_g x - \alpha S_g y + L_3 P_3 xy)\end{aligned} \tag{41}$$

Based on Lyapunov's theorem,[39] the stability of a replicated dynamic system can be determined by the eigenvalues of a Jacobian matrix composed of a set of replicated dynamic equations, as Eq. (13) ~ (41). The equilibrium point of the ESS occurs if all the eigenvalues of the Jacobian matrix are negative. Table 2 presents the stability analysis of the eight pure-strategy equilibria.

Table 2 shows that the equilibrium point B_8 (1,1,1) has both positive and negative eigenvalues, rendering it evolutionarily unstable The equilibrium points B_1 (0,0,0), B_2 (1,0,0), and B_3 (0,1,0) hold if government supervision costs are very high, which is unrealistic. Thus, this study focuses on four evolutionarily stable points that satisfy the premise conditions and reflect real-world scenarios: B_4 (0,0,1), B_5 (1,1,0), B_6 (1,0,1), and B_7 (0,1,1).

Equilibrium Point B_4 (0,0,1)

In normal scenarios with low pandemic risk, the public is unable to play an effective role in supervision and reporting. Therefore, the government becomes the leading force in coordinating emergency health responses. In the absence of public supervision and the threat of emergencies, primary healthcare institutions benefit more from not participating in coordinated responses, ie, $E_1hq-C_r+S_g\alpha<V_1-W_1+M_thq-L_1P_1$. Similarly, non-primary healthcare institutions also benefit more from not participating, as follows: $(1-\alpha)$ $Sg-C_2<V_2-Kb-L_2P_2-W_2-C_4d$, they are more likely to choose non-participation. Consequently, $W_1-C_r-V_1+\alpha S_g+L_1P_1+E_1hq-M_thq<0$, $W_2-C_2+S_g-V_2+C_4d-\alpha S_g+Kb+L_2P_2<0$. Additionally, under normal scenarios, the cost of government supervision is relatively low. Assuming it is much lower than the punishments for healthcare institutions, that is, $-S_g-L_3P_3<(1-L_1)W_1+(1-L_2)W_2-C_s$, all eigenvalues at the equilibrium point B_4 (0,0,1) are less than 0, making it a stable point.

Equilibrium Point B_6 (1,0,1)

As the number of patients with an infectious disease increases, the epidemic shifts to a transitional scenario. The public has become increasingly aware of the importance of coordinated emergency health responses and supervision, and the probability of the government choosing to supervise also rises. As the first point of contact, primary healthcare

Table 2 Equilibrium Point Stability Analysis

Equilibrium Point	λ1	λ2	λ3	Symbols	Stability
$B_1(0,0,0)$	$W_1L_1-V_1-C_r+L_1P_1+E_1hq-M_thq$	$C_4d-V_2-C_2+Kb+W_2L_2+L_2P_2$	$W_1-C_s+W_2+S_g-W_1L_1-W_2L_2+L_3P_3$	(-, -, +)	Unstable
$B_2(1,0,0)$	$C_r+V_1-W_1L_1-L_1P_1-E_1hq+M_thq$	$T-V_2-C_2+Kb-rT+W_2L_2+L_2P_2$	$W_2-C_s+S_g-\alpha S_g-W_2L_2+L_3P_3$	(-, -, +)	Unstable
$B_3(0,1,0)$	$rT-V_1-C_r+W_1L_1+L_1P_1+E_1hq-M_thq$	$C_2+V_2-C_4d-Kb-W_2L_2-L_2P_2$	$W_1-C_s+\alpha S_g-W_1L_1+L_3P_3$	(-, -, +)	Unstable
$B_4(0,0,1)$	$W_1-C_r-V_1+\alpha S_g+L_1P_1+E_1hq-M_thq$	$W_2-C_2+S_g-V_2+C_4d-\alpha S_g+Kb+L_2P_2$	$C_s-W_1-W_2-S_g+W_1L_1+W_2L_2-L_3P_3$	(-, -, -)	ESS
$B_5(1,1,0)$	$C_r+V_1-rT-W_1L_1-L_1P_1-E_1hq+M_thq$	$C_2+V_2-T-Kb+rT-W_2L_2-L_2P_2$	$-C_s$	(-, -, -)	ESS
$B_6(1,0,1)$	$C_r-W_1+V_1-\alpha S_g-L_1P_1-E_1hq+M_thq$	$W_2-C_2+S_g-V_2+T-\alpha S_g+Kb-rT+L_2P_2$	$C_s-W_2-S_g+\alpha S_g+W_2L_2-L_3P_3$	(-, -, -)	ESS
$B_7(0,1,1)$	$W_1-C_r-V_1+\alpha S_g+rT+L_1P_1+E_1hq-M_thq$	$C_2-W_2-S_g+V_2-C_4d+\alpha S_g-Kb-L_2P_2$	$C_s-W_1-\alpha S_g+W_1L_1-L_3P_3$	(-, -, -)	ESS
$B_8(1,1,1)$	$C_r-W_1+V_1-\alpha S_g-rT-L_1P_1-E_1hq+M_thq$	$C_2-W_2-S_g+V_2-T+\alpha S_g-Kb+rT-L_2P_2$	C_s	(-, -, +)	Unstable

Notes: ① Unstable, The conditions for pure strategies are not met, making this equilibrium point unstable; ② ESS, Evolutionarily Stable Strategy.

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institutions encountering more patients during the pandemic must balance the need to avoid public scrutiny losses with the relatively low cost of participating in coordinated responses at this stage. Thus, the net benefit of their participation outweighs non-participation, ie, V_1-W_1-L_1P_1+$M_t$hq<E_1hq-C_r+αS_g. Due to this stage, the epidemic risk is still manageable or not fully recognized, and normal healthcare orders are mostly unaffected. Non-primary healthcare institutions find the costs of non-participation lower and continue their strategy under normal scenarios: (1-α) Sg+W_2+(1-r) T-C_2<V_2-Kb-L_2P_2. Meanwhile, although public awareness of supervision is gradually increasing, the overall level is still relatively low. Assuming that the government's punishment for non-primary healthcare institutions is much greater than their supervision costs and subsidies, and (1-L_2)*W_2-C_s-(1-α) S_g>0. B_6 (1,0,1) emerges as a stable point in the evolutionary game.

Equilibrium Point B_7 (0,1,1)

As the epidemic progresses and the number of patients rises, primary healthcare institutions, the first point of contact, often negatively participate owing to limited capacity and risk management, ie, E_1hq-C_r+αS_g+rT<V_1-W_1-L_1P_1+$M_t$hq. However, this negative response leads to an influx of patients into non-primary healthcare institutions. As the final line of defense, if these institutions avoid the responsibility of treating patients it could lead to immeasurable serious consequences and punishments. Therefore, they are compelled to actively participate in epidemic control, ie, V_2-Kb-L_2P_2-C_4d<(1-α) Sg+W_2-C_2. Furthermore, it is assumed that when -αS_g < (1-L_1) W_1-C_s, the equilibrium point B_7 (0,1,1) will become a stable point.

Equilibrium Point B_5 (1,1,0)

In the "emergency scenario", public awareness of the importance of multiparty collaboration for health and safety increases. Public supervision and reporting by healthcare institutions increases. Thus, even with minimal government supervision, the benefits of active epidemic control participation for these institutions are higher: V_1-(W_1+P_1)L_1 +$M_t$hq<E_1hq-C_r+rT and V_2-Kb-(W_2+P_2)L_2<(1-r)T-C_2. Consequently, the probability of active participation increases. The government tends to adopt a more lenient supervisory role since both types of institutions choose collaboration.

Parameter Setting

We used MATLAB R2023a to conduct a simulation based on the actual values to verify the effectiveness of the evolutionary stability strategy. We analyzed the evolution process of the tripartite agent behavior and its sensitivity to changes in key parameters under different scenarios.

Regarding parameter settings, we set the monthly operating cost, income, and other related parameters of fever clinics under normal scenarios according to Tian[40] (2017), ensuring that the ESS points meet stable and balanced conditions under various scenarios. We combined the current consumer price index and expert consultation and assigned different values to the relevant parameters in other scenarios by approximate conversion, as shown in Table 3. And, the initial willingness of the primary healthcare institutions, non-primary healthcare institutions, and government to participate x = y = z = 0.5.

Results

Dynamic Evolution Results

Based on the aforementioned values of the relevant parameters satisfying the stability conditions (Table 3). We validated the robustness of the results by testing different iteration numbers (10, 50, and 100). Specifically, when the iterations were set to 10, 50, and 100, the model's output remained consistent, indicating that the evolutionary process had already converged, and further increases in iterations did not significantly affect the outcome. Based on these results and consistent with prior studies, we ultimately selected 50 iterations as a sufficient and reliable representation of the evolutionary process.[41] The strategy combinations of the tripartite evolutionary game finally converge to B_4 (0,0,1), B_6 (1,0,1), B_7 (0,1,1), and B_5 (1,1,0), indicating that the simulation is consistent with the analysis of strategic stability and has guiding significance for a coordinated response to epidemic prevention and control. Figure 5 shows the results of this evolution.

Table 3 Parameter Settings in Different Scenarios

Parameters	Normal Scenario (0,0,1)	Pre-Transition Scenario (1,0,1)	Post-Transition Scenario (0,1,1)	Emergency Scenario (1,1,0)
S_g	10	10	10	10
α	0.3	0.3	0.3	0.3
h	600	2000	3000	6000
E_1	0.02	0.02	0.02	0.02
q	0.6	0.6	0.6	0.6
M_t	0.002	0.002	0.002	0.002
T	10	10	10	10
r	0.3	0.3	0.3	0.3
C_r	5	15	40	45
V_1	15	10	8	5
P_1	10	10	10	10
L_1	0.1	0.2	0.25	0.5
W_1	5	5	5	5
C_4	25	25	25	25
d	0	0.05	0.2	0.3
C_2	15	20	25	30
V_2	35	30	15	10
K	60	60	60	60
b	0.01	0.2	0.3	0.4
P_2	20	20	20	20
L_2	0.05	0.1	0.2	0.3
W_2	20	20	20	20
C_s	3	6	6.5	10
P_3	30	30	30	30
L_3	0	0	0	0

Abbreviations: COVID-19, the Corona Virus Disease 2019; ESS, evolutionary stabilization strategy.

Sensitivity Analysis

We conducted a parameter sensitivity analysis to explore the effects of government subsidy intensity (S_g), punishment intensity (W_1, W_2), and public supervision probability (L_1, L_2) on the evolution of coordinated response strategies for primary and non-primary healthcare institutions participating in epidemic prevention and control.

The Impact of Government Subsidy Intensity

Under normal scenarios (B_4 (0,0,1)), the level of government subsidy intensity, S_g, was set to 10, 30, 50, and 70 for the simulation. The results are shown in Figure 6. As government subsidies increased, the tripartite strategy combination gradually changed from (0,0,1) to (1,0,1) and (1,1,1) and finally ended with (1,1,0) with an increase in government subsidies. Increasing government subsidies during the evolution process increases the probability of primary and non-primary healthcare institutions actively participating in the coordinated response to epidemic prevention and control. However, in the later stages of the evolution, government subsidies exceeding a certain threshold result in negative supervision.

The Impact of Government Punishment Intensity

In the simulation of different scenarios, the severity of punishments W_1 and W_2 by the government was set to (5, 10, 20, 30) and (20, 30, 40, 50), respectively. Under normal scenarios (B_4 (0,0,1)), an increase in government punishment will incline primary and non-primary healthcare institutions to participate in a coordinated response to epidemic prevention and control, as shown in Figure 7a and b. In the pre-transition scenario (B_6 (1,0,1)), as the government's punishment continues to increase, the strategic choices of non-primary healthcare institutions and the government fall into a cycle (when the government chooses the "1" strategy, non-primary healthcare institutions choose the "0" strategy), and both tend toward the ESS (1,1,0) (Figure 7c). In the

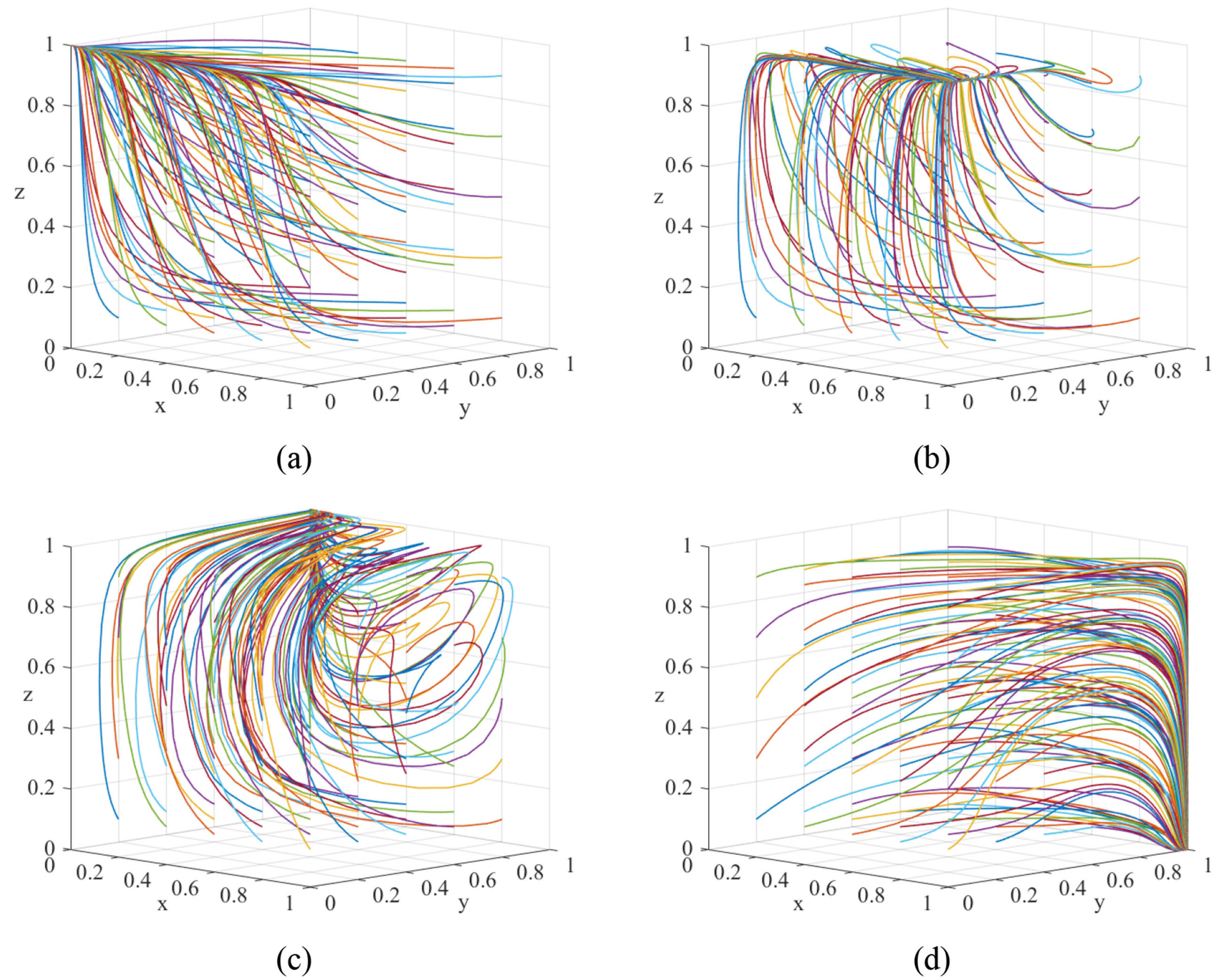

Figure 5 Parameter simulation of equilibrium points (evolved 50 times). (**a**) Converge to point B_4 (0,0,1); (**b**) Converge to point B_6 (1,0,1); (**c**) Converge to point B_7 (0,1,1); and (**d**) Converge to point B_5 (1,1,0).

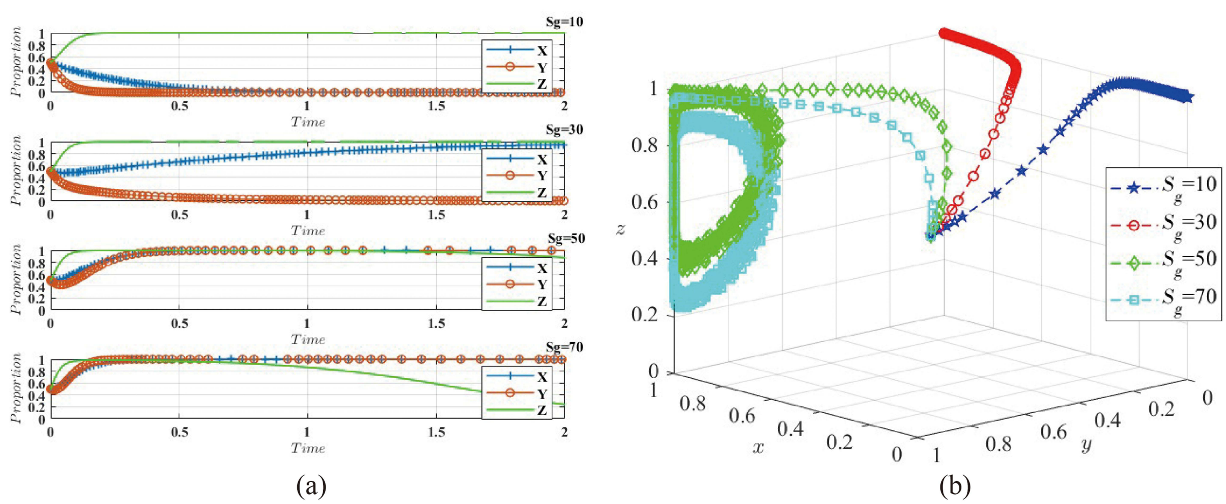

Figure 6 The effect of government subsidy intensity (S_g=10, 30, 50, 70) on the behavior evolution of three stakeholders under normal scenarios (B_4 (0,0,1)). (**a**) The trend of S_g; (**b**) The evolutionary process of S_g.

post-transition scenario, when the government's punishment exceeds a certain threshold, the strategy of active participation in epidemic prevention and control and coordinated response tends to stabilize. The government constantly hesitates between the "0" strategy and the "1" strategy but finally chooses negative supervision (as shown in Figure 7d).

The Impact of Public Supervision Probability

The public supervision probabilities L_1 and L_2 under normal scenarios (B_4 (0,0,1)) were set as (0.1, 0.3, 0.5, 0.7) and (0.05, 0.35, 0.65, 0.95), respectively. During the evolution process, the increase in L_1 under normal (B_4 (0,0,1)) will gradually cause primary healthcare institutions to actively participate in the coordinated response to epidemic prevention and control, and the tripartite strategy combination will trend from (0,0,1) to (1,0,1) (as shown in Figure 8a). An increase in L_2 does not affect each agent's final strategy choice but it affects its decision-making speed. Specifically, an increase in active public supervision will prolong the enthusiasm of non-primary healthcare institutions to participate in the coordinated response to epidemic prevention and control and reduce the speed of the government's active participation in supervision (as shown in Figure 8b).

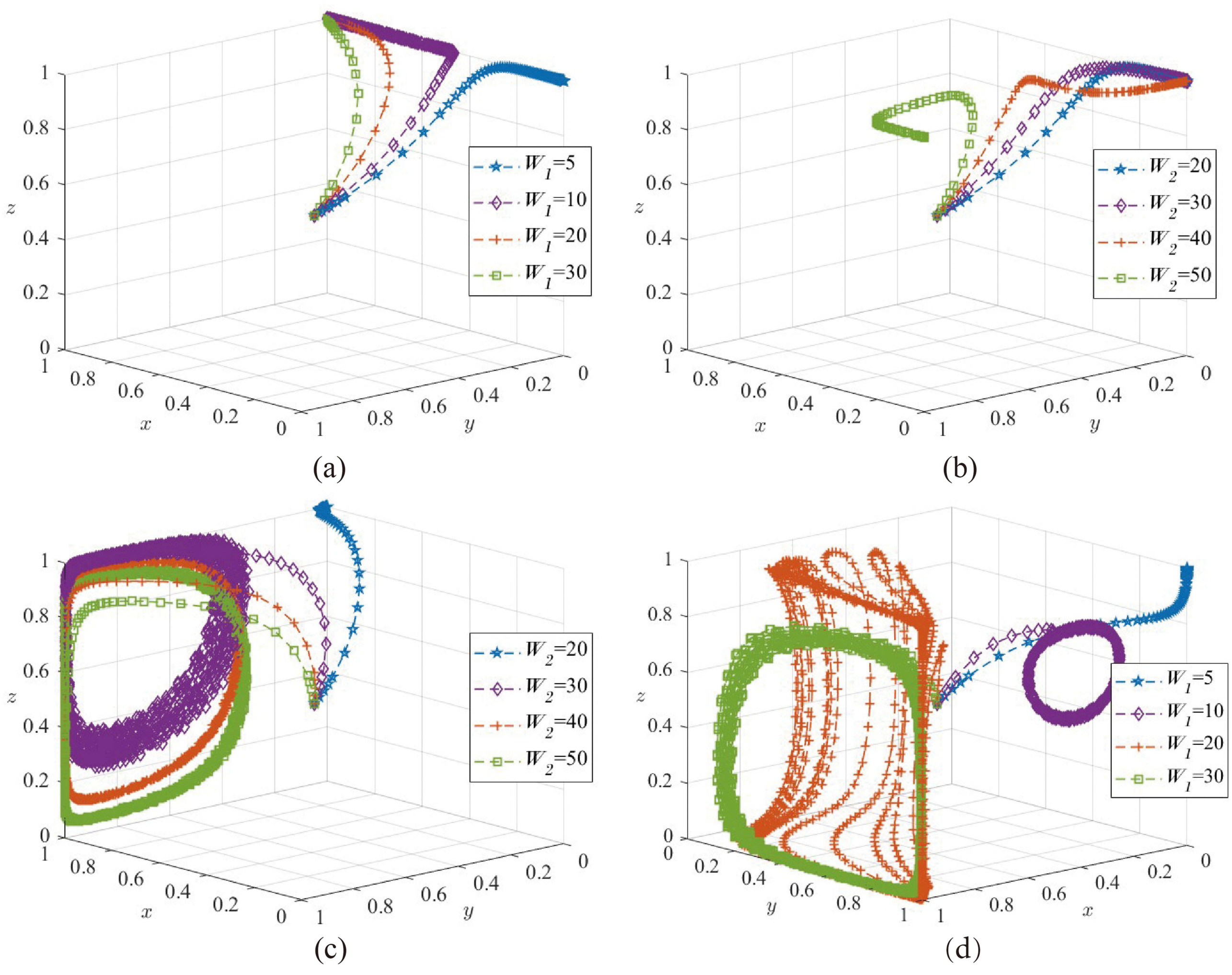

Figure 7 The effect of government punishment intensity on the behavior evolution of three stakeholders under different scenarios. (**a**) Impact of W_1 under normal scenarios (B_4 (0,0,1)); (**b**) Impact of W_2 under normal scenarios (B_4 (0,0,1)); (**c**) Impact of W_2 under pre-transition scenarios (B_6 (1,0,1)); (**d**) Impact of W_1 under post-transition scenarios (B_7(0,1,1)).

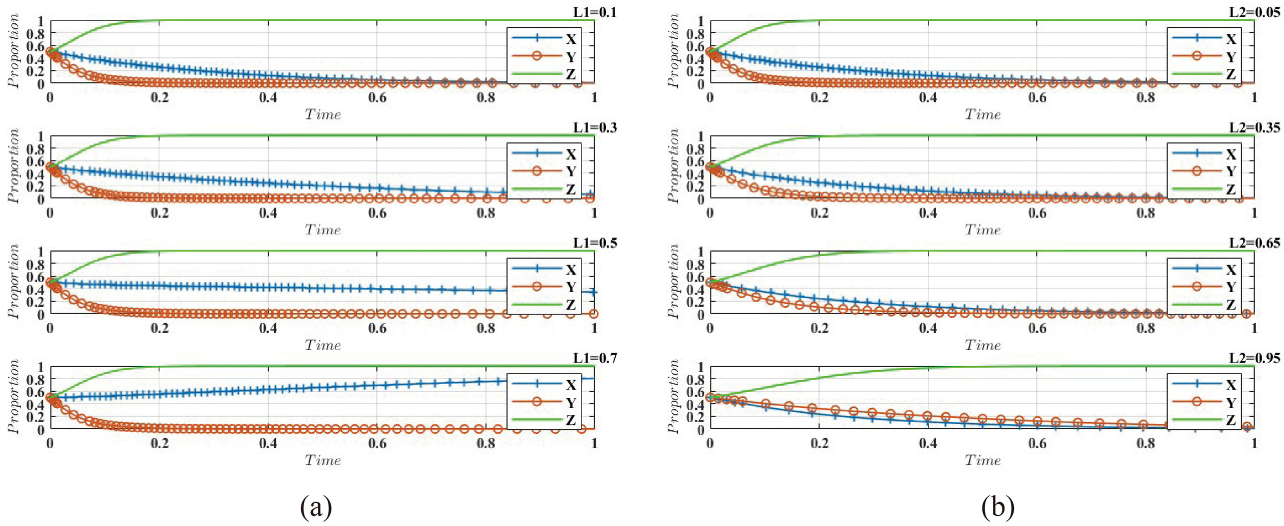

Figure 8 The effect of public supervision probability on the behavior evolution of three stakeholders. (**a**) Impact of L_1 (supervision probability of primary healthcare institutions) under normal scenarios (B_4 (0,0,1)); (**b**) Impact of L_2 (supervision probability of non-primary healthcare institutions) under normal scenarios (B_4 (0,0,1)).

Discussion

We developed a tripartite evolutionary game model involving the government, primary healthcare institutions, and non-primary healthcare institutions. We systematically analyzed the stability of game equilibrium strategy combinations and employed numerical simulations to examine the factors influencing equilibrium strategy selection in various scenarios. Finally, we proposed several policy implications based on these findings.

This study shows that the optimal equilibrium point in emergency scenarios is achieved when primary and non-primary healthcare institutions actively participate in a coordinated epidemic prevention and control response. The government uses subsidies and punishments rather than strict regulations to maximize the interests of all parties involved. However, increasing the subsidies and punishments from local governments to healthcare institutions for active participation is not always beneficial. As emergency management enters abnormal scenarios and subsidies and punishments exceed a certain threshold, the government's operating costs increase, and lax supervision ensues, increasing the likelihood of primary and non-primary healthcare institutions not actively participating in the collaboration. This is also consistent with the findings of Gong H[41] (2023) et al. Additionally, the implementation of these strategies may face real-world challenges. For instance, some scholars have pointed out that the shortage of medical resources in primary healthcare institutions is a key factor limiting their participation in epidemic prevention and control.[42] Therefore, this study suggested that higher authorities should strengthen government supervision and hold it accountable for leniency in emergency scenarios.[29] Higher authorities should aim for sustainable governance through comprehensive measures such as laws and performance evaluations. Furthermore, government departments and healthcare institutions should provide more comprehensive and accurate real-world data, collaborating with research institutions to develop more fit-for-purpose models using advanced simulation tools. These efforts can support the scientific exploration of dynamic thresholds for subsidies and punishment across various scenarios[31] and facilitate pilot evaluations in selected areas to enhance coordinated epidemic prevention and control responses. Last but not least, while public supervision and government interventions, such as subsidies and punishments, aim to enhance participation and coordination in epidemic prevention and control, they may inadvertently restrict institutional decision-making and flexibility. However, with the continuous improvement of China's healthcare alliances and the gradual decentralization of management authority, the establishment and functional adjustment of alliance management departments are expected to achieve a coordinated balance between government oversight and institutional autonomy.[43]

Public benefits from health services play a crucial role in this supervision. Multiple studies have recognized the importance of public participation in collaborative governance. Public supervision plays a relatively limited role in non-primary healthcare institutions, only moderately increasing their likelihood of participating in collaboration. Nevertheless, it compels primary healthcare institutions to engage in coordinated pandemic prevention and control during emergencies. Public supervision and participation serve as "standby" mechanisms in emergencies, reducing government supervision costs during emergency responses.[27] Nevertheless, public participation in supervision is constrained by factors such as public compliance levels, and institutional capacity. First, the public lacks awareness of participating in epidemic surveillance during normal times, hindering their preparedness for sudden outbreaks.[28] Second, although laws grant the public the right to participate in supervision, and the channels for participation have improved, the subsidies remain vague and insufficient to mobilize public enthusiasm fully.[44] Therefore, the government should enhance laws and regulations, incentivize public participation in supervision through education and other means, and raise awareness about pandemic prevention and control.

Research has shown that primary healthcare institutions demonstrated high sensitivity and rapidly engaged in epidemic prevention and response coordination as the pandemic transitioned to a non-routine state. Following the SARS epidemic, the Chinese government substantially invested in infectious disease surveillance and prevention at the primary level, developing the world's largest direct reporting network for infectious diseases. Primary healthcare institutions have significantly improved their capacity to identify and respond to common infectious diseases, such as influenza and tuberculosis. However, the vulnerability of primary fever clinics became more apparent as the pandemic intensified. These clinics are constrained by early planning deficiencies, limited physical space, and a persistent shortage of professional human resources.[45] Their lack of awareness and flexibility in handling unconventional infectious diseases further contributed to their functional deficiencies, as evidenced during the COVID-19 pandemic.[4]

In addition, this research reported a phenomenon of "wavering" in decision-making within non-primary healthcare institutions, accompanied by fluctuations in government supervision. Public medical institutions in China often operate on self-raised funds and receive minimal government financial support. Non-primary healthcare institutions face a heavy operational burden and low likelihood of large-scale epidemics, resulting in insufficient investment in fever clinics and infection control management. These institutions must allocate and invest additional resources when the number of patients at a fever clinic exceeds a certain threshold, affecting their regular diagnostic and treatment revenues. Therefore, this study recommends that the government provide targeted funding support for fever clinics, considering construction and operational costs. Healthcare institutions should establish more detailed and refined treatment processes for their fever clinics while ensuring the implementation of the "Three Zones and Two Pathways" plan.[46] In addition, medical alliances should continue to improve the hierarchical medical system and actively explore diverse forms of fever in clinics to respond effectively to the challenges of emerging infectious diseases.

The constructed evolutionary game model included multiple agents and used real data to simulate scenarios; however, it inevitably had limitations. First, this study focused on government, public, and primary and non-primary healthcare institutions in epidemic prevention and control; however, it does not fully reflect the situation regarding other relevant players. Second, the simulation parameters are derived based on existing empirical data from the literature and expert consultations, and may not fully capture the complexities of real-world conditions. Then, our assumptions may not comprehensively account for all variables, which could limit the interpretability of the model and the generalizability of the study findings. In future research, we will extend our analysis beyond fever clinics by incorporating other public health emergency units (eg, vaccination sites, and emergency care units). Utilizing a multi-agent stochastic evolutionary game approach, we aim to include a broader range of stakeholders (eg, NGOs or private healthcare facilities) and relevant variables, while leveraging more accurate and comprehensive data for analysis.

Conclusion

In this study, four evolutionary stability points were matched with different epidemic prevention and control scenarios to conduct simulations. By adjusting the intensity of government subsidies and punishments, we found that both primary and non-primary healthcare institutions can be well motivated under a certain threshold. However, the government will cause negative supervision beyond this threshold. In addition, public supervision can significantly supplement the effect of government supervision, particularly when the intensity of public supervision increases with epidemic severity. Therefore, the government should enhance the hierarchical diagnosis and treatment system during emergencies, collaborate with research institutions to actively conduct pilot studies to explore reasonable dynamic thresholds for subsidies and punishment and propose flexible policy measures to adapt to the evolving scenarios of epidemic prevention and control. Meanwhile, the public should be actively guided to participate in epidemic prevention and control, and channels for public participation in supervision should be improved. Additionally, government agency supervision should be strengthened to maintain strict long-term supervision of pandemic prevention and control. Although the evolutionary game model provides valuable theoretical insights, its practical application may be constrained by real-world factors. Future research could expand the model's applicability by incorporating other stakeholders and applying it to other public health events.

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Data Sharing Statement

All data generated or analyzed during this study are included in this published article.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors report no conflicts of interest in this work.

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