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Information collaboration analysis in different tiers of healthcare system with co-produced incentives

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Abstract: Information collaboration is crucial for optimizing resource allocation and improving diagnostic efficiency across hospital tiers through enhanced information technology capacity. To characterize the dynamic decision-making mechanism between general hospitals (GHs) and primary healthcare centers (PHCs), a two-player differential game model was constructed to analyze the relationship between optimal investment levels and corresponding payoffs and explore how GHs can incentivize collaboration by adjusting their investment intensity and sharing PHCs' costs. The results indicate that information collaboration is a win-win strategy. Its dynamic equilibrium shows that GHs make intensive efforts in the early stage of digital construction. However, such investment decreases over time as patient information accessibility becomes limited. Under the collaboration mode, although GHs' digital investment is lower than that in the independent operation, the total system payoff significantly increases. This improvement arises because PHCs, with their locational and informational advantages, undertake major digitalization tasks, allowing GHs to focus resources on disease treatment. The introduction of collaboration incentives strengthens this performance improvement.

Key words: information collaboration; co-produced incentives; differential game; incentive mechanism

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Driven by advances in information technology (IT), hospitals across tiers have implemented medical information systems. However, these systems remain fragmented, with diagnostic and treatment data stored separately. When patients transfer between hospitals, the absence of interoperable medical records leads to repeated consultations and examinations, which in turn increases healthcare costs and wastes medical resources[1]. Information collaboration addresses systemic healthcare needs, enhances hospital reputation, and improves care efficiency. For doctors, access to patients' historical data strengthens diagnostic accuracy and treatment decisions[2]. For patients, Health Information Exchange (HIE) decreases diagnostic costs, readmission rates, and length of stay, thereby improving satisfaction. Amid strained healthcare resources, information collaboration supports hierarchical treatment policies, optimizes resource allocation, and promotes patient flow balance by increasing the service capacity of primary hospitals.

Given the high cost of data validation, storage, and synchronization, understanding the mechanisms and incentives behind information collaboration has become increasingly critical. Over the years, scholars have extensively examined healthcare informatization, focusing on two major themes, namely, the development of IT infrastructure[3-4] and coordination across healthcare tiers. Eftekhari et al. [5] identified HIE as critical in improving referral efficiency[6]. Gomes et al. [7] attributed the growth of health informatization to the twin pressures of chronic disease and care quality demands. Moreover, Niu et al. [8] indicated that hospitals are more likely to adopt HIE under price competition owing to quality improvements and cost offset effects.

Research on informatization incentives emphasizes how payment and participation mechanisms affect adoption. Cheng et al. [9] noted that traditional payment systems may inhibit IT investment, calling for new incentives. Rajapakshe et al. [10] found that rebates motivate HIE participation, whereas based on an evolutionary game analysis, Liang et al. [11] showed that patient participation and data quality are decisive for HIE sustainability. Ozdemir et al. [12] demonstrated that heterogeneous providers may lack record-sharing incentives, requiring selective subsidies. Furthermore, Zhao[13] investigated information asymmetry in elderly care through option contracts. He et al. [14] developed a three-party evolutionary game involving government, operators, and the public; although not directly about HIE, their insights into regulatory costs, penalties, and compensation inform incentive mechanisms for healthcare information sharing. These studies confirm the benefits of informatization but reveal the need for effective cross-tier coordination, an area that remains underexplored.

Studies on interhospital coordination mainly focus on service-level and payment incentives. Zhang et al. [15]

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found that redistributing revenues from high- to low-tier institutions expands capacity and decreases congestion, whereas Chen et al. [16] and Yu et al. [17] showed that subsidies and priority mechanisms improve system performance by guiding patients to primary care. Wang et al. [18] identified referral payment thresholds that optimize performance, whereas Li et al. [19] confirmed that capacity-sinking programs enhance lower-tier utilization when patient value differentials are high. However, information disclosure does not always yield benefits. Kim et al. [20] and Zhang et al. [21] reported that disclosure timing and pricing shape patient strategies, sometimes disadvantaging lower tiers. Payment-based coordination has also been widely studied. Adida et al. [22] demonstrated that outcome-based penalties outperform fee-for-service models; Zhou et al. [23-24] revealed that bundled and differentiated Medicare policies improve welfare and guide patient choices; Sun et al. [25] verified that cost-sharing and flexible pricing stimulate preventive efforts; Bravo et al. [26] and Liu et al. [27] emphasized risk- and cost-sharing mechanisms that coordinate capacity allocation while minimizing costs.

Despite substantial findings, most studies employed static analytical approaches that overlook the dynamic, adaptive nature of interhospital collaboration. Factors such as organizational scale and policy incentives have been identified; however, conventional models fail to capture long-term strategic adjustments driven by policy evolution and experiential learning. Although differential game theory has been introduced, applications remain limited to single-tier contexts, with cross-tier dynamic frameworks still lacking. Moreover, existing studies primarily focused on horizontal coordination, insufficiently examining cost-sharing and benefit allocation mechanisms between primary and higher-level hospitals.

To address these gaps, this study investigated information collaboration mechanisms within a two-tier healthcare system. A dynamic differential game model was developed in a Stackelberg framework, with general hospitals (GHs) acting as leaders and primary care institutions as followers. State differential equations describe the joint evolution of collaboration levels, driven by both parties' efforts. The model clarifies how GHs can promote collaboration through optimal effort and cost-sharing (e. g. , subsidies), thereby providing theoretical and decision-making guidance for improving coordination efficiency in healthcare systems. While empirical studies such as that by Li et al. [4] demonstrated that HIE access decreases length of stay and readmissions, the present study contributes by analyzing institutional decision-making behavior and proposing dynamic incentive mechanisms using a differential game perspective.

1 Problem Statement

1.1 Cross-tier information collaboration in the healthcare system

With increasing chronic disease prevalence, effective patient health management becomes crucial. Comprehensive health management requires access to clinical data (diagnoses/treatments) and daily health metrics. While GHs can enhance information systems to collect such data, resource constraints make continuous tracking of patients' daily health information difficult and costly. Additionally, geographical distance and long waiting times decrease patient visits to GHs, compromising information timeliness.

Consequently, collaboration across healthcare tiers has gained increasing interest. By sharing GH-acquired clinical data, primary healthcare centers (PHCs) can deliver efficient health management services (e. g. , family doctors and rehabilitation). Simultaneously, GHs' specialized capabilities can analyze PHI-generated patient data, enabling prompt health interventions that decrease readmission rates. Moreover, PHCs' proximity to patients and lower staffing costs facilitate more responsive health monitoring.

GHs can incentivize PHC participation through resource-sharing or subsidies. Compared to GHs, PHCs have lower patient information requirements and experience smaller cost impacts from readmissions, which discourages independent information system development and timely data maintenance.

We modeled this information collaboration between healthcare tiers. Regarding market position and influence, GHs are large-scale comprehensive medical institutions with a higher reputation, more specialist resources, and advanced equipment, attracting a large number of patients. Thus, GHs hold a dominant role in pricing, service scope, and technology adoption. Patients often prioritize tertiary hospitals, whereas PHCs assume a supportive role in patient triage and auxiliary care. Regarding resource and technological advantages, GHs lead in medical technology, research capabilities, and financial investment, enabling them to pioneer new treatments or establish industry standards. This indicates that GHs act as leaders and PHCs as followers in the model. This assumption is consistent with prior studies on China's tiered healthcare system[19]. Given GHs' dominant position in the healthcare system, we established the following leadership structure:

Assumption 1 This study considers a GH and a PHC. The relationship between the GH and the PHC is modeled as a Stackelberg game.

1.2 Relationship between informatization level and cost

The level of information collaboration among hospitals significantly impacts patient acceptance of health intervention services, driven by joint efforts of GHs and PHCs. In health management, GHs focus their efforts on developing information systems and enhancing health data analysis capabilities, whereas PHCs primarily undertake information collection and maintenance activities. Due to technical constraints, the marginal impact of GHs' efforts diminishes as collaboration levels increase. Conversely, IT advantages proportionally expand with growing patient data volumes in PHCs[28].

Assumption 2 The level of informatization is determined by the GH's effort and PHC's effort simultaneously. This dynamic process can be described by a differential equation presented as follows:

$$\dot{\eta}(t) = \gamma_H e_H(t)\sqrt{1-\eta(t)} + \gamma_P e_P(t) - \varepsilon\eta(t) \quad (1)$$

where $\eta(t)$ is the information collaboration level at time t, and $\eta(t)$ in the beginning of taking actions is $\eta(0) = \eta_0 = 0$. If the GH's effort is $e_H(t)$ and the impact of effort on the collaboration level of GH is γ_H, the information collaboration level will increase by $\gamma_H e_H(t)\sqrt{1-\eta(t)}$. If the PHC's effort is $e_P(t)$ and the impact of effort on collaboration level of PHC is γ_P, the information collaboration level increases by $\gamma_P e_P(t)$. This differential Eq. (1) has been used in several studies. Moreover, the information collaboration level between GHs and PHCs suffers from a decay rate of ε; that is, it will inevitably decrease without sustained maintenance and investment. This is primarily due to the ongoing friction between dynamically evolving healthcare demands, technological environments, and operational processes conversely and relatively static coordination systems on the other, which include the divergence of technical standards during iteration, leading to incompatibility between system interfaces and data formats; and the decline in data accuracy, completeness, and standardization caused by the lack of long-term data quality control mechanisms. Furthermore, $\dot{\eta}(t)$ characterizes the change in the information collaboration level resulting from the efforts of healthcare institutions.

Assumption 3 The extra costs of the GH and PHC to take actions to improve the information collaboration level are assumed to be quadratic functions. The traditional marginal cost is zero.

Quadratic cost functions have been adopted by previous studies[13, 23]. If the marginal costs from the collaboration effort the of GH and PHC are k_H and k_P, respectively, the extra cost for the GH's effort C_H is defined as follows:

$$C_H(e_H(t)) = \frac{k_H^2(e_P(t))}{2} \quad (2)$$

The extra cost for the efforts made by the primary care institution C_P is defined as follows:

$$C_P(e_P(t)) = \frac{k_P^2(e_P(t))}{2} \quad (3)$$

2 Models

2.1 Case without co-produced effort

In this scenario, GHs operate without collaborating with PHCs. They conduct their own IT development and directly provide health management services to patients, including prevention and post-treatment management.

The non-collaborative case is referred to as Case N, denoted with the superscript N. The GH's profit function is formulated as follows:

$$J_H^N = \max_{e_H^N(t)} \int_0^\infty e^{-\phi t}\left[\pi_H \eta^N(t) - \frac{k_H^2(e_H^N(t))}{2}\right]$$

$$\text{s.t.} \quad \dot{\eta}^N(t) = \gamma_H e_H^N(t)\sqrt{1-\eta^N(t)} - \varepsilon\eta^N(t) \quad (4)$$

where J_H^N denotes the total profit of the GH under informatization decisions; π_H is the marginal revenue obtained by the GH through healthcare informatization, derived from reduced treatment expenses due to lower patient readmission rates and avoided duplicate examination costs; $\eta^N(t)$ represents the information collaboration level when the GH's informatization effort is $e_H^N(t)$; $\dot{\eta}^N(t)$ denotes the rate of change in the information collaboration level under Case N; ϕ is the depreciation rate of the healthcare institution's value.

The Hamilton-Jacobi-Bellman (HJB) equation is as follows:

$$\phi V_H^N = \max_{e_H^N(t)} \left\{\left[\pi_H \eta^N(t) - \frac{k_H^2(e_H^N(t))}{2}\right] + (V_H^N)'\left[\gamma_H e_H^N(t)\sqrt{1-\eta^N(t)} - \varepsilon\eta^N(t)\right]\right\} \quad (5)$$

where V_H^N represents the revenue of the GH under Case N.

As in the study by Jørgensen et al. [28], the parameters in Eq. (5) are independent of time.

Lemma 1 Under Case N, the optimal level of the GH's informatization effort e_H^{N*} is formulated as follows:

$$e_H^{N*} = \frac{\gamma_H A_H^N}{k_H}\sqrt{1-\eta(t)} \quad (6)$$

where

$$\eta(t) = \frac{\gamma_H^2 A_H^N}{k_H\varepsilon + \gamma_H^2 A_H^N}\left\{1 - \exp\left[-\left(\varepsilon + \frac{\gamma_H^2 A_H^N}{k_H}\right)t\right]\right\} \quad (7)$$

$$A_H^N = \frac{k_H\left[\sqrt{(\phi+\varepsilon)^2 + \frac{2\pi_H\gamma_H^2}{k_H}} - (\phi+\varepsilon)\right]}{\gamma_H^2} \quad (8)$$

2.2 Case with co-produced effort

This section analyzes the co-produced effort scenario without cost-sharing. This scenario is referred to as Case C, denoted with the superscript C. In this case, the GH and PHC make sequential decisions: the GH first determines its information collaboration effort level, and then the PHC sets its effort according to this decision. Both parties aim to maximize their respective profits.

The objective functions of the GH and PHC are formulated as follows:

$$J_{\mathrm{H}}^{\mathrm{C}} = \max_{e_{\mathrm{H}}^{\mathrm{C}}(t)} \int_0^{\infty} \mathrm{e}^{-\phi t}\left[\pi_{\mathrm{H}}\eta^{\mathrm{C}}(t) - \frac{k_{\mathrm{H}}^2(e_{\mathrm{H}}^{\mathrm{C}}(t))}{2}\right] \tag{9}$$

$$J_{\mathrm{P}}^{\mathrm{C}} = \max_{e_{\mathrm{P}}^{\mathrm{C}}(t)} \int_0^{\infty} \mathrm{e}^{-\phi t}\left[\pi_{\mathrm{P}}\eta^{\mathrm{C}}(t) - \frac{k_{\mathrm{P}}^2(e_{\mathrm{P}}^{\mathrm{C}}(t))}{2}\right] \tag{10}$$

$$\text{s.t.}\quad \dot{\eta}^{\mathrm{C}}(t) = \gamma_{\mathrm{H}} e_{\mathrm{H}}^{\mathrm{C}}(t)\sqrt{1-\eta^{\mathrm{C}}(t)} + \gamma_{\mathrm{P}} e_{\mathrm{P}}^{\mathrm{C}}(t) - \varepsilon\eta^{\mathrm{C}}(t)$$

where π_{P} represents the marginal revenue obtained by the PHC through informatization, which is generated from the fees paid by patients for their participation in primary care; $J_{\mathrm{H}}^{\mathrm{C}}$, $J_{\mathrm{P}}^{\mathrm{C}}$ denotes the total profit of the GH and PHC, respectively, under informatization decisions; $\eta^{\mathrm{C}}(t)$, $\dot{\eta}^{\mathrm{C}}(t)$ represent the information collaboration level and its rate of change under Case C, respectively, when the GH's informatization effort is $e_{\mathrm{H}}^{\mathrm{C}}(t)$ and the PHC's informatization effort is $e_{\mathrm{P}}^{\mathrm{C}}(t)$. Hence, the HJB equation for decision makers can be written as follows:

$$\phi V_{\mathrm{H}}^{\mathrm{C}} = \max_{e_{\mathrm{H}}^{\mathrm{C}}(t)}\left\{\left[\pi_{\mathrm{H}}\eta(t) - \frac{k_{\mathrm{H}}^2(e_{\mathrm{H}}^{\mathrm{C}}(t))}{2}\right] + (V_{\mathrm{H}}^{\mathrm{C}})'\left[\gamma_{\mathrm{H}} e_{\mathrm{H}}^{\mathrm{C}}(t)\sqrt{1-\eta^{\mathrm{C}}(t)} + \gamma_{\mathrm{P}} e_{\mathrm{P}}^{\mathrm{C}}(t) - \varepsilon\eta^{\mathrm{C}}(t)\right]\right\} \tag{11}$$

$$\phi V_{\mathrm{P}}^{\mathrm{C}} = \max_{e_{\mathrm{P}}^{\mathrm{C}}(t)}\left[\pi_{\mathrm{P}}\eta(t) - \frac{k_{\mathrm{P}}^2(e_{\mathrm{P}}^{\mathrm{C}}(t))}{2}\right] + (V_{\mathrm{P}}^{\mathrm{C}})'\left[\gamma_{\mathrm{H}} e_{\mathrm{H}}^{\mathrm{C}}(t)\sqrt{1-\eta^{\mathrm{C}}(t)} + \gamma_{\mathrm{P}} e_{\mathrm{P}}^{\mathrm{C}}(t) - \varepsilon\eta^{\mathrm{C}}(t)\right] \tag{12}$$

where $V_{\mathrm{H}}^{\mathrm{C}}$, $V_{\mathrm{P}}^{\mathrm{C}}$ represents the revenue of GH and PHC under Case C.

Lemma 2 Under Case C, the optimal level of the GH's informatization effort $e_{\mathrm{H}}^{\mathrm{C}*}$ and the optimal level of the PHC's informatization effort $e_{\mathrm{P}}^{\mathrm{C}*}$ are formulated as follows, respectively:

$$e_{\mathrm{H}}^{\mathrm{C}*} = \frac{\gamma_{\mathrm{H}} A_{\mathrm{H}}^{\mathrm{C}}}{k_{\mathrm{H}}}\sqrt{1-\eta^{\mathrm{C}}(t)} \tag{13}$$

$$e_{\mathrm{P}}^{\mathrm{C}*} = \frac{\gamma_{\mathrm{P}} A_{\mathrm{P}}^{\mathrm{C}}}{k_{\mathrm{P}}} \tag{14}$$

where

$$\eta^{\mathrm{C}}(t) = \frac{k_{\mathrm{P}}\gamma_{\mathrm{H}}^2 A_{\mathrm{H}}^{\mathrm{C}} + k_{\mathrm{H}}\gamma_{\mathrm{P}}^2 A_{\mathrm{P}}^{\mathrm{C}}}{k_{\mathrm{P}}(k_{\mathrm{H}}\varepsilon + \gamma_{\mathrm{H}}^2 A_{\mathrm{H}}^{\mathrm{C}})}\left\{1 - \exp\left[-\left(\varepsilon + \frac{\gamma_{\mathrm{H}}^2 A_{\mathrm{H}}^{\mathrm{C}}}{k_{\mathrm{H}}}\right)t\right]\right\} \tag{15}$$

$$A_{\mathrm{H}}^{\mathrm{C}} = \frac{k_{\mathrm{H}}\left[\sqrt{(\phi+\varepsilon)^2 + \frac{2\pi_{\mathrm{H}}\gamma_{\mathrm{H}}^2}{k_{\mathrm{H}}}} - (\phi+\varepsilon)\right]}{\gamma_{\mathrm{H}}^2} \tag{16}$$

$$A_{\mathrm{P}}^{\mathrm{C}} = \frac{\pi_{\mathrm{P}}}{\sqrt{(\phi+\varepsilon)^2 + \frac{2\pi_{\mathrm{H}}\gamma_{\mathrm{H}}{}^2}{k_{\mathrm{H}}}}} \tag{17}$$

2.3 Case with co-produced incentives

In this case, the GH is willing to provide an incentive by sharing part of the information collaboration cost for the PHC. This scenario is referred to as Case I, denoted with the superscript I.

Thus, the GH determines its informatization effort $e_{\mathrm{H}}^{\mathrm{I}}(t)$ and cost-sharing rate θ simultaneously, and then the PHC decides its informatization effort $e_{\mathrm{P}}^{\mathrm{I}}(t)$ by using the given parameters, including $e_{\mathrm{H}}^{\mathrm{I}}(t)$ and θ.

Under Case I, the objective functions of the GH and PHC are formulated as follows:

$$J_{\mathrm{H}}^{\mathrm{I}} = \max_{e_{\mathrm{H}}^{\mathrm{I}}(t),\theta} \int_0^{\infty} \mathrm{e}^{-\phi t}\left[\pi_{\mathrm{H}}\eta^{\mathrm{I}}(t) - \frac{k_{\mathrm{H}}^2(e_{\mathrm{H}}^{\mathrm{I}}(t))}{2} - \theta e_{\mathrm{P}}^{\mathrm{I}}(t)\right] \tag{18}$$

$$J_{\mathrm{P}}^{\mathrm{I}} = \max_{e_{\mathrm{P}}^{\mathrm{I}}(t)} \int_0^{\infty} \mathrm{e}^{-\phi t}\left[\pi_{\mathrm{P}}\eta^{\mathrm{I}}(t) + \theta e_{\mathrm{P}}^{\mathrm{I}}(t) - \frac{k_{\mathrm{P}}^2(e_{\mathrm{P}}^{\mathrm{I}}(t))}{2}\right] \tag{19}$$

$$\text{s.t.}\quad \dot{\eta}^{\mathrm{I}}(t) = \gamma_{\mathrm{H}} e_{\mathrm{H}}^{\mathrm{I}}(t)\sqrt{1-\eta^{\mathrm{I}}(t)} + \gamma_{\mathrm{P}} e_{\mathrm{P}}^{\mathrm{I}}(t) - \varepsilon\eta^{\mathrm{I}}(t)$$

where $J_{\mathrm{H}}^{\mathrm{I}}$, $J_{\mathrm{P}}^{\mathrm{I}}$ denotes the total profit of the GH and PHC, respectively, under informatization decisions; $\eta^{\mathrm{I}}(t)$, $\dot{\eta}^{\mathrm{I}}(t)$ represent the information collaboration level and its rate of change under Case I, respectively.

Thus, the HJB equation for decision makers can be written as follows:

$$\phi V_{\mathrm{H}}^{\mathrm{I}} = \max_{e_{\mathrm{H}}^{\mathrm{I}}(t),\theta}\left\{\left[\pi_{\mathrm{H}}\eta^{\mathrm{I}}(t) - \frac{k_{\mathrm{H}}^2(e_{\mathrm{H}}^{\mathrm{I}}(t))}{2} - \theta e_{\mathrm{P}}^{\mathrm{I}}(t)\right] + (V_{\mathrm{H}}^{\mathrm{I}})'\left[\gamma_{\mathrm{H}} e_{\mathrm{H}}^{\mathrm{I}}(t)\sqrt{1-\eta^{\mathrm{I}}(t)} + \gamma_{\mathrm{P}} e_{\mathrm{P}}^{\mathrm{I}}(t) - \varepsilon\eta^{\mathrm{I}}(t)\right]\right\} \tag{20}$$

$$\phi V_{\mathrm{P}}^{\mathrm{I}} = \max_{e_{\mathrm{P}}^{\mathrm{I}}(t)}\left\{\left[\pi_{\mathrm{P}}\eta^{\mathrm{I}}(t) + \theta e_{\mathrm{P}}^{\mathrm{I}}(t) - \frac{k_{\mathrm{P}}^2(e_{\mathrm{P}}^{\mathrm{I}}(t))}{2}\right] + (V_{\mathrm{P}}^{\mathrm{I}})'\left[\gamma_{\mathrm{H}} e_{\mathrm{H}}^{\mathrm{I}}(t)\sqrt{1-\eta^{\mathrm{I}}(t)} + \gamma_{\mathrm{P}} e_{\mathrm{P}}^{\mathrm{I}}(t) - \varepsilon\eta^{\mathrm{I}}(t)\right]\right\} \tag{21}$$

where $V_{\mathrm{H}}^{\mathrm{I}}$, $V_{\mathrm{P}}^{\mathrm{I}}$ represents the revenue of the GH and PHC under Case I.

Lemma 3 Under Case I, the optimal level of the GH's informatization effort $e_{\mathrm{H}}^{\mathrm{I}*}$ and the optimal level of the PHC's informatization effort $e_{\mathrm{P}}^{\mathrm{I}*}$ are formulated as follows:

$$e_{\mathrm{H}}^{\mathrm{I}*} = \frac{\gamma_{\mathrm{H}} A_{\mathrm{H}}^{\mathrm{I}}}{k_{\mathrm{H}}}\sqrt{1-\eta^{\mathrm{I}}(t)} \tag{22}$$

$$\theta^* = \frac{\gamma_{\mathrm{P}}(A_{\mathrm{H}}^{\mathrm{I}} - A_{\mathrm{P}}^{\mathrm{I}})}{2} \tag{23}$$

$$e_P^{I*} = \frac{\gamma_P(A_P^I + A_H^I)}{2k_P} \tag{24}$$

where

$$\eta^I(t) = \left[\frac{\gamma_H^2 A_H^I}{k_H\varepsilon + \gamma_H^2 A_H^I} + \frac{k_H\gamma_P^2(A_H^I + A_P^I)}{2k_P(k_H\varepsilon + \gamma_H^2 A_H^I)}\right] \cdot \left\{1 - \exp\left[-\left(\varepsilon + \frac{\gamma_H^2 A_H^I}{k_H}\right)t\right]\right\} \tag{25}$$

$$A_H^I = \frac{k_H\left[\sqrt{(\phi+\varepsilon)^2 + \frac{2\pi_H\gamma_H^2}{k_H}} - (\phi+\varepsilon)\right]}{\gamma_H^2} \tag{26}$$

$$A_P^I = \frac{\pi_P}{\sqrt{(\phi+\varepsilon)^2 + \frac{2\pi_H\gamma_H^2}{k_H}}} \tag{27}$$

3 Model Analysis

3.1 Comparison of equilibrium in three cases

Proposition 1 The effort of hospitals can be compared as follows: $e_H^{N*} > e_H^{C*} > e_H^{I*}, e_P^{C*} < e_P^{I*}$.

Proposition 2 The revenue of hospitals can be compared as follows: $V_H^{N*} < V_H^{C*} < V_H^{I*}$, $V_P^{C*} < V_P^{I*}$.

Proposition 3 The information collaboration level can be compared as follows: $\eta^N(t) < \eta^C(t) < \eta^I(t)$.

Propositions 1-3 establish the following: (1) information collaboration levels are highest under co-production incentives (Case I) and lowest without collaboration (Case N); (2) GHs expend minimal effort, but achieve maximal revenue with incentives (Case I), whereas without collaboration (Case N), they exert maximal effort for minimal revenue; (3) PHCs increase effort and revenue under incentivized collaboration (Case I) compared to non-incentivized collaboration (Case C). Numerical simulations adopt the following parameter values: $\varepsilon + \phi = 0.2$, $\gamma_H = 0.25$, $\gamma_P = 0.2$, $\pi_H = 2$, $\pi_P = 1$, $k_H = 2$, and $k_P = 2$. The total revenue of a health system with two-tier hospitals is represented by $V_T(t) = V_H(t) + V_P(t)$.

Figs. 1 and 2 support the findings of Propositions 1 and 2, respectively. Fig. 3 shows that the total system value is highest in Case I and lowest in Case N. This series of propositions demonstrates that in practice, GHs implement resource-sharing initiatives to enhance healthcare system informatization. When incentivized through these measures, PHCs increase efforts in collecting and maintaining patient health information. Consequently, the GH revenue and total system revenue increase as more patients choose health management services. Thus, the co-production incentive model achieves the lowest GH effort level alongside the highest system informatization. Critically, this approach transfers information construction efforts from GHs to PHCs, enabling GHs to direct resources to disease treatment.

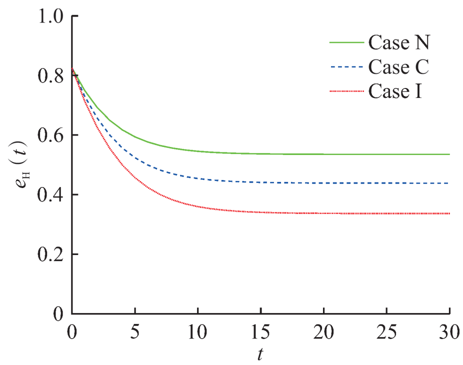

Fig. 1 Effort level of general hospital under three cases

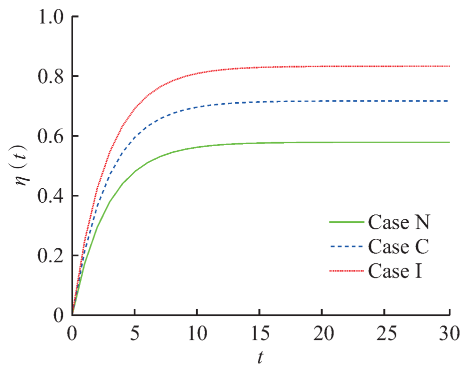

Fig. 2 Information collaboration level under three cases

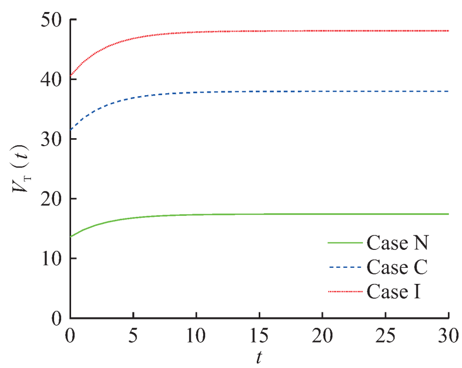

Fig. 3 Revenue of total system under three cases

3.2 Sensitivity analysis

Proposition 4 The effect of the marginal revenue π_P of primary care providers on the equilibrium solution is as follows: $\frac{\partial\eta(t)}{\partial\pi_P} > 0$, $\frac{\partial e_H^*(t)}{\partial\pi_P} < 0$, $\frac{\partial e_P^*(t)}{\partial\pi_P} > 0$, and $\frac{\partial V_T^*(t)}{\partial\pi_P} > 0$.

These propositions indicate that PHCs increase effort for higher profits when their marginal revenue from information collaboration increases, whereas GHs simultaneously reduce health information tracking efforts while achieving greater informatization profits. This supports practical price adjustments for primary care services, such as implementing packaged family doctor fees. Given the non-intuitive relationship between GHs' marginal revenue and equilibrium outcomes, numerical simulations were conducted. Fig. 4 presents three key patterns: information collaboration levels decrease monotonically with GHs' marginal revenue; collaboration peaks under co-production incentives (Case I) and reaches its minimum without collaboration (Case N), aligning with prior propositions; and all three cases exhibit temporal growth at progressively slower rates. Complementarily, Fig. 5 reveals that the GH's optimal effort increases monotonically with their marginal revenue; required effort is minimized under co-production incentives (Case I) and maximized without collaboration (Case N); and informational effort decreases over time across all cases, with deceleration rates gradually slowing.

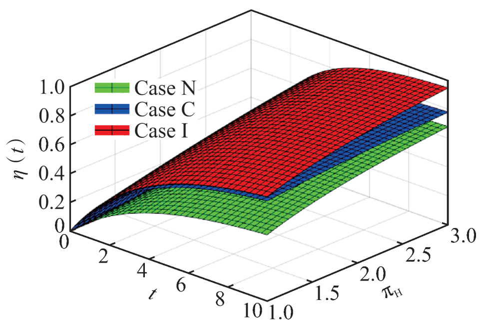

Fig. 4 Effect of marginal revenue on the information collaboration level

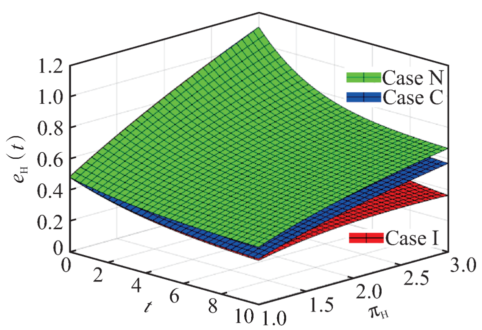

Fig. 5 Effect of marginal revenue on the effort of general hospitals

Fig. 6 reveals that the optimal revenue of the system is monotonically increasing with respect to the marginal revenue of the GH; in the same way as the previous proposition, co-production can make the equilibrium revenue of the system increase; and in all the three cases, the optimal revenue of the system is monotonically increasing with time, and the rate of increase is gradually slow.

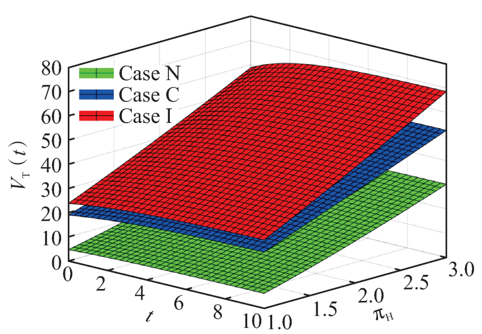

Fig. 6 Effect of marginal revenue on the total revenue of the system

Proposition 5 The effect of the marginal cost of information effort in primary hospitals on the equilibrium solution is as follows: $\frac{\partial \eta(t)}{\partial k_{\mathrm{P}}} < 0$, $\frac{\partial e_{\mathrm{H}}^{*}(t)}{\partial k_{\mathrm{P}}} > 0$, $\frac{\partial e_{\mathrm{P}}^{*}(t)}{\partial k_{\mathrm{P}}} < 0$, and $\frac{\partial V_{\mathrm{T}}^{*}(t)}{\partial k_{\mathrm{P}}} < 0$.

These propositions indicate that higher marginal costs at PHCs detrimentally decrease system-wide information collaboration levels and their own effort exertion. Consequently, GHs should increase efforts in patient health management to mitigate readmission-related costs. Therefore, PHCs should prioritize marginal cost control, whereas GHs enhance systemic performance by assisting regionally disadvantaged centers, particularly those with lower informatization levels and marginal effort costs, to participate in information collaboration.

Given the non-intuitive relationship between GHs' marginal costs and equilibrium outcomes, numerical simulations were conducted. Fig. 7 presents that system information collaboration decreases monotonically with GHs' marginal costs, exhibiting progressively slower deceleration. Figs. 8 and 9 further reveal monotonically decreasing patterns for both GHs' optimal effort and total system revenue relative to marginal cost increases.

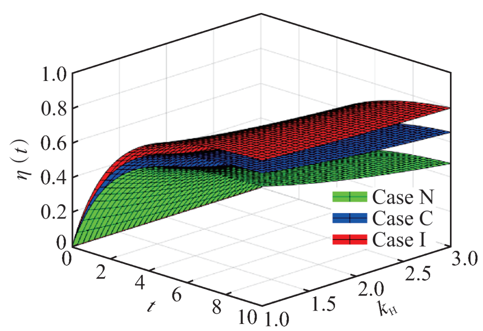

Fig. 7 Effect of marginal cost on the information collaboration level

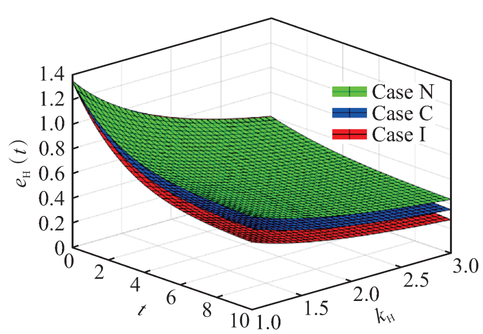

Fig. 8 Effect of marginal cost on the effort of general hospitals

Proposition 6 The efficiency factor that refers to the impact of the efforts of PHCs on the level of health system informatization affects the equilibrium solution as

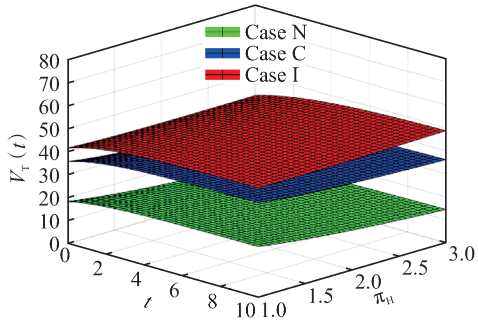

Fig. 9 Effect of marginal cost on the total revenue of the system

follows: $\frac{\partial \eta(t)}{\partial \gamma_P} > 0$, $\frac{\partial e_H^*(t)}{\partial \gamma_P} < 0$, $\frac{\partial e_P^*(t)}{\partial \gamma_P} > 0$, and $\frac{\partial V_T^*(t)}{\partial \gamma_P} > 0$.

These propositions demonstrate that higher efficiency in converting PHCs' efforts into information collaboration levels incentivizes greater effort toward healthcare system informatization. In practice, GHs enhance this process by guiding collaboration efforts, whereas PHCs improve conversion efficiency by adopting new technology.

Figs. 10 to 12 reveal how GHs' efficiency factor (γ_H) impacts equilibrium outcomes. Without co-production, both information collaboration levels and total revenue increase monotonically with γ_H. However, under co-production, this monotonic relationship reverses when $\gamma_H < \gamma_P$ (primary centers' efficiency), with both revenues showing monotonically decreasing trends. When

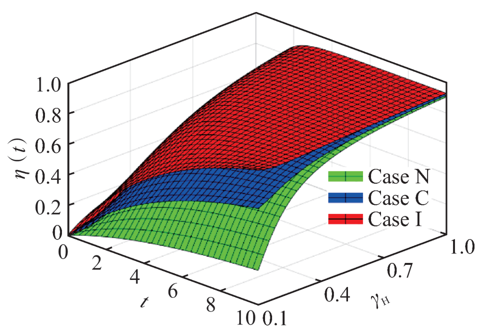

Fig. 10 Effect of the efficiency factor on the information collaboration level

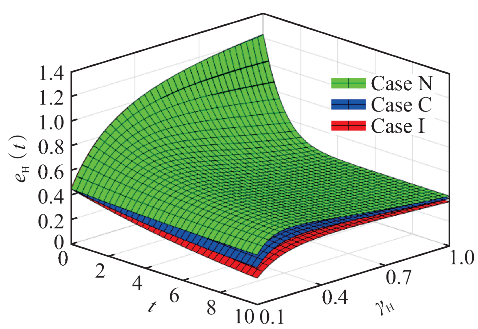

Fig. 11 Effect of efficiency factor on the effort of general hospitals

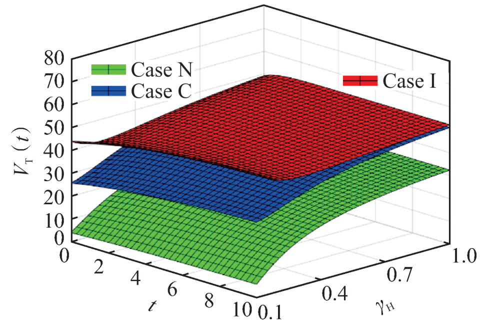

Fig. 12 Effect of efficiency factor on the total revenue of the system

$\gamma_H > \gamma_P$, revenue patterns become non-monotonic. Furthermore, as depicted in Fig. 11, GHs' informational effort exhibits an inverted U shape across all cases—initially increases and then decreases as γ_H increases.

4 Conclusions

This study models information collaboration across healthcare tiers using a dynamic game framework to quantify collaboration levels, effort allocation, and institutional revenues under three scenarios. Comparative analysis of hospital relationships yields actionable policy suggestions. To our knowledge, this is the first study to analyze cross-tier hospital information collaboration with dynamic game behavior and quantify effort extent through analytical modeling. This study systematically investigates information collaboration within a tiered healthcare system. In response to the real-world challenge of fragmented medical information in chronic disease management, we developed a Stackelberg game model with the GH as the leader and the PHC as the follower. By establishing a state differential equation to describe the dynamic evolution of information collaboration levels and by employing quadratic cost functions with diminishing marginal returns, we applied the optimal control theory to derive equilibrium strategies for three scenarios: without co-produced effort, with co-produced effort, and with co-produced incentives. Furthermore, sensitivity analysis of key parameters revealed the influence of collaboration benefit coefficients and cost structures on system performance, providing theoretical foundations and managerial insights for designing incentive mechanisms in healthcare information collaboration. The key conclusions are as follows:

(1) The co-production incentive model outperforms non-collaborative and collaborative-without-incentive cases.

(2) Higher marginal revenue and efficiency factors at PHCs consistently increase system informatization levels and participant revenues.

(3) Under co-production incentives, GHs achieve maximal revenue with minimal effort, as effort transfers

to PHCs—freeing GHs to focus resources on disease treatment and medical research.

Limitations and future directions are as follows: the relationship between collaboration levels and participant revenues may show nonlinearities, with marginal profits influenced by strategic interactions. Subsequent studies should investigate alternative incentive mechanisms within two-tiered health systems.

References

[1] YARAGHI N, DU A Y, SHARMAN R, et al. Health information exchange as a multisided platform: Adoption, usage, and practice involvement in service co-production [J]. Information Systems Research, 2014, 26 (1): 1-18.

[2] ADJERID I, ADLER-MILSTEIN J, ANGST C. Reducing medicare spending through electronic health information exchange: The role of incentives and exchange maturity [J]. Information Systems Research, 2018, 29(2): 341-361.

[3] HUANG Z, YUAN L. Enhancing learning and exploratory search with concept semantics in online healthcare knowledge management systems: An interactive knowledge visualization approach [J]. Expert Systems with Applications, 2024, 237: 121558.

[4] LI Y, LU L X, LU S F, et al. The value of health information technology interoperability: Evidence from interhospital transfer of heart attack patients [J]. Manufacturing & Service Operations Management, 2021, 24(2): 827-845.

[5] EFTEKHARI S, YARAGHI N, GOPAL R D, et al. Impact of health information exchange adoption on referral patterns [J]. Management Science, 2022, 69(3): 1615-1638.

[6] KIM K, TSE E T S. Dynamic search engine competition with a knowledge-sharing service [J]. Decision Support Systems, 2012, 52(2): 427-437.

[7] GOMES J, ROMÃO M. Information system maturity models in healthcare [J]. Journal of Medical Systems, 2018, 42(12): 235.

[8] NIU B Z, XU H T, DAI Z P. Check only once? Health information exchange between competing private hospitals [J]. Omega, 2022, 107: 102556.

[9] CHENG N N, LI H F, BANG Y. Pay-for-performance schemes and hospital HIT adoption [J]. Decision Support Systems, 2023, 164: 113868.

[10] RAJAPAKSHE T, KUMAR S, SEN A R, et al. Sustainability planning for healthcare information exchanges with supplier rebate program [J]. Operations Research, 2020, 68(3): 793-817.

[11] LIANG Y X, ZHAO L D. Sustainability of health information exchange platform based on information cooperation [J]. Journal of Southeast University (English Edition), 2021, 37(3): 332-338.

[12] OZDEMIR Z, BARRON J, BANDYOPADHYAY S. An analysis of the adoption of digital health records under switching costs [J]. Information Systems Research, 2011, 22(3): 491-503.

[13] ZHAO J. Coordination of elderly healthcare service supply chain with information asymmetry: Designs of option contracts under different demand distribution statuses [J]. RAIRO—Operations Research, 2020, 54(5): 1291-1307.

[14] HE Y M, TONG X, RAN B, et al. Research on game strategies of participants in highway prevention and control of noise pollution [J/OL]. Journal of Southeast University (English Edition), 2025 [2025-10-10]. https://link.cnki.net/urlid/32.1325.N.20251010.1030.003.

[15] ZHANG Z G, YIN X L. Designing a sustainable two-tier service system with customer's asymmetric preference for servers [J]. Production and Operations Management, 2021, 30(11): 3856-3880.

[16] CHEN W H, ZHANG Z G, HUA Z S. Analysis of two-tier public service systems under a government subsidy policy [J]. Computers & Industrial Engineering, 2015, 90: 146-157.

[17] YU M, ZHOU W, JIANG B W. Referral strategies and capacity decisions in a tiered hospital system with gatekeeping designs: Exemplified with Chinese healthcare system [J]. Computers & Industrial Engineering, 2022, 171: 108447.

[18] WANG J J, LI Z P, SHI J, et al. Hospital referral and capacity strategies in the two-tier healthcare systems [J]. Omega, 2021, 100: 102229.

[19] LI Z P, WANG J J, CHANG A C, et al. Capacity reallocation via sinking high-quality resource in a hierarchical healthcare system [J]. Annals of Operations Research, 2021, 300(1): 97-135.

[20] KIM I, SPRINGER M. Effects of waiting time information on the performance of a two-tier service system [J]. Journal of the Operational Research Society, 2024, 75 (4): 634-646.

[21] ZHANG Z G, YIN X L. Information and pricing effects in two-tier public service systems [J]. International Journal of Production Economics, 2021, 231: 107897.

[22] ADIDA E, BRAVO F. Contracts for healthcare referral services: Coordination via outcome-based penalty contracts [J]. Management Science, 2018, 65(3): 1322-1341.

[23] ZHOU C H, LAN Y F, ZHAO R Q, et al. Incentive schemes for readmissions reduction in coordinating reverse referral healthcare services [J]. Computers & Industrial Engineering, 2023, 176: 108938.

[24] ZHOU C H, LAN Y F, LI W F, et al. Medicare policies in a two-tier healthcare system with overtreatment [J]. Omega, 2022, 109: 102607.

[25] SUN H, WANG H Y. Enhancing customers prevention efforts: An incentive feedback mechanism design [J]. Journal of Southeast University (English Edition), 2021, 37(4): 436-444.

[26] BRAVO F, LEVI R, PERAKIS G, et al. Care coordination for healthcare referrals under a shared-savings program [J]. Production and Operations Management,

2023, 32(1): 189-206.

[27] LIU H L, YU Y M, BENJAAFAR S, et al. Price-directed cost sharing and demand allocation among service providers with multiple demand sources and multiple facilities[J]. Manufacturing & Service Operations Management, 2021, 24(1): 647-663.

[28] JØRGENSEN S, TABOUBI S, ZACCOUR G. Retail promotions with negative brand image effects: Is cooperation possible?[J]. European Journal of Operational Research, 2003, 150(2): 395-405.

分层医疗体系中基于协同激励的信息协作分析

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摘要：医疗信息协作是不同层级医院通过提升信息技术能力实现资源优化配置与诊疗效率提升的重要途径。为研究综合医院与基层医疗中心在信息协作中的动态决策机制，构建了基于微分博弈的双主体协作模型，分析最优投入水平与收益产出关系，并探讨综合医院通过调整投入力度和提供成本分摊以激励协作的作用机制。结果表明，信息协作本质上是双赢策略，其动态均衡特征体现为综合医院在数字化建设初期投入强度较高，但随着患者信息可及性受限，该投入呈时间递减趋势。在协作模式下，尽管综合医院的数字化投入低于独立运作水平，但系统总收益显著提升；究其原因在于，基层医疗中心凭借区位与信息优势承担主要数字化任务，从而释放综合医院资源聚焦疾病诊疗。协作激励机制进一步强化了此收益提升效果。

关键词：信息协作；协同激励；微分博弈；激励机制

中图分类号：C934