To Introduce or Not? Strategic Analysis of Hospital Operations with Telemedicine

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Abstract

Despite its efficiency in reducing the impact of pandemics (e.g., the COVID-19), whether to introduce telemedicine as an additional way to serve chronically ill patients remains controversial for hospitals in many countries. This paper builds a stylized model to investigate a hospital's telemedicine strategy and the corresponding impacts on its operations regarding outpatient management of chronic diseases. We implement our analysis from three key concerns of the hospital in the presence of a pandemic: the differences in medical consumption and reimbursement between in-person and telemedicine modalities and the effort cost of infection reduction resulting from the pandemic. We find that in the absence of the pandemic, the hospital prefers to introduce telemedicine when the differences in medical consumption and reimbursement are both small. In the presence of the pandemic, we find that the introduction of telemedicine does not always benefit the hospital and that it is better not to introduce telemedicine in some cases since it may exacerbate the negative influence of the pandemic on the hospital's total costs. Furthermore, we surprisingly find that the hospital may set greater in-person capacity but less telemedicine capacity in response to the outbreak of the pandemic under certain conditions, which contradicts public beliefs. Finally, we show that social welfare can be improved by introducing telemedicine when the effort cost of infection reduction and the difference in reimbursement are both of moderate size. The condition under which social welfare is improved tightens with a greater difference in medical consumption.

Keywords: OR in health services; telemedicine; medical consumption; pandemic; reimbursement

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1. Introduction

Telemedicine, which allows direct, synchronous, and remote communication between a physician and a patient (Wootton et al., 2017), has been playing an active role in the outpatient management of chronic diseases. For instance, patients with high blood pressure in the stabilization period can periodically remotely visit their physicians and obtain an adjusted prescription, generating much convenience for them by reducing unnecessary in-person visits (Grustam et al., 2014; Farabi et al., 2020). With such a perception, telemedicine is gradually adopted by medical organizations to deliver services to their chronically ill patients in addition to the traditional in-person modality, especially during a pandemic to prevent contact infections (Axel et al., 2020). For instance, with the support of Cisco's healthcare technologies, the Sky Lakes Medical Center in North America has moved to implement and scale telehealth practice (Michael, 2020). Recently, a survey conducted by McKinsey shows that approximately half of the patients intend to continue using telemedicine after the COVID-19 pandemic subsides.[1] However, in many countries (e.g., Germany and China), we observe considerable variability in the adoption of telemedicine, even following the outbreak of the pandemic. By 2020, only 52% of outpatient departments in Germany had implemented telemedicine, a 50% increase from the end of 2017 (Laura & Tobias, 2020). In China, the total adoption level of telemedicine in 3-A (the highest level) hospitals increased to 12.76%, and that in the top 100 hospitals increased to 71%.[2] To better serve chronically ill patients, especially during a pandemic, it is critical to find out the reason behind this phenomenon and provide insights for hospitals on whether to adopt telemedicine.

Hospitals will naturally consider the difference in medical consumption between the in-person and telemedicine modalities when making service decisions. Healthcare services are commonly accompanied by the consumption of medical resources, for example, medical tests and medications, from which hospitals can enhance their incomes to cover input costs to minimize their total costs (Gawande, 2009; Joseph, 2015). In healthcare markets selling credence goods, the prescription of such medical resources relies on the discretion of doctors and is unconditionally accepted by patients. Dr. Gawande, a general surgeon in the U.S., said that "doctors are far more concerned about doing too little than doing too much, and can profit from such medical consumption" (Gawande, 2015). This is also the case in Japan (Iizuka, 2007) and Switzerland (Kaiser & Schmid, 2016). Considering the different medical environments between the in-person and telemedicine modalities (i.e., at hospital vs. at home), patients' medical consumption may be distinct under different service modalities,[3] which can thus significantly alter hospitals' incentives. However, prescription of such

[1]Source: https://www.mckinsey.com/industries/financial-services/our-insights/how-insurance-can-prepare-for-the-next-distribution-model.

[2]By 2020, 325 out of 2,548 3-A hospitals in China have implemented telemedicine, https://vcbeat.top/OTU2NDIwYmFjYmViYWYxZWUzYWRmMWIwYTk5OTNhYmQ. By the end of December 2020, 71 of China's top 100 hospitals had implemented telemedicine, https://vcbeat.top/MTY2YjZlZmE4ZGY5NzY3Yzk1MTkxNjI4NTE1MTM5Mjg.

[3]According to a survey we conducted in a cardiovascular hospital in Tianjin, China, the average medical consump-

resources may be affected by the service time physicians spend with patients (Wang et al., 2019). As an example, a longer service time allows more thorough questioning and examination, which can reduce the medical consumption required. Although the impact of medical consumption has been widely noted in reality, it has not been intensively explored in the academic literature, especially its impact on hospitals' choices regarding telemedicine.

Whether hospitals adopt telemedicine is also influenced by the reimbursement policies provided by health insurers, which play roles by affecting patients' choices on the way they seeking care with. At present, health insurers in different areas have different attitudes toward telemedicine patients. According to a report conducted by the Commonwealth Fund of the U.S., as of March 15, 2021, 23 states in the U.S. mandate payment parity for telemedicine, 3 states require that the reimbursement rate for telemedicine services cannot be lower than that for identical services provided in person, and 4 states eliminate cost sharing of patients for services provided by telemedicine, suggesting that patients from other states may receive lower or no reimbursement for telemedicine services (JoAnn et al., 2021). The difference in reimbursement policies significantly affects patients' choices on the way they seek care with, i.e., in person or via telemedicine, which subsequently influences hospitals' strategy on telemedicine. Although prior studies in the telemedicine literature recognize the importance of this issue (e.g., Sun et al., 2020), they do not theoretically or empirically investigate the issue of insurer reimbursement. As such, we are motivated to fill this gap by examining the impact of reimbursement on hospitals' telemedicine strategy.

In the presence of a pandemic, hospitals should devote effort to reduce infection risk for in-person patients, while they need not do so for telemedicine patients. The emergence of a pandemic commonly reduces the willingness of patients to seek care in person due to the risk of contact infection (Rajan et al., 2013). For instance, in China, 58% of hospitals experienced a more than 30% decrease in their chronically ill patients during the COVID-19 pandemic. According to WHO (2018) and a survey conducted by Boston Consulting Group (Jonathan et al., 2020), patients' willingness to seek care in person can be improved by infection-reduction effort exerted by hospitals. We emphasize that hospitals' effort consists in optional infection-reduction measures (e.g., more frequent disinfection) that are additional to the standard procedure that hospitals are required to implement. Undeniably, the infection-reduction effort increases demand for in-person service, but it also increases hospitals' input costs.[4] Furthermore, the effort cost of infection reduction varies across hospitals and depends on the selection of disinfection supplies, the layout of hospital facilities, the path design of patient visits, and so forth (Rutala & Weber, 1999; Reiling et al.,

tion costs of in-person and telemedicine patients are indeed not the same (CNY 24.88 per minute for the former and CNY 18.88 per minute for the latter). Nevertheless, in the U.S., patients seeking care via telemedicine reported paying the same amount that they would have paid if they had sought care in person (Medicare, 2020). In addition, patients in some countries are also likely to pay a higher amount for telemedicine to prevent the overuse of telemedicine.

[4]As a result of the COVID-19 pandemic, hospitals in North America have had to pay even closer attention to infection-reduction costs, which were formerly $28 billion to $45 billion each year, https://www.modernhealthcare.com/safety-quality/infection-control-covid-19-era.

2008; Donker et al., 2010). However, such effort costs are not necessary for hospitals that deliver services to patients via telemedicine because the telemedicine modality allows patients to receive care at home and perfectly avoids human contact. This difference in infection-reduction effort costs between the two modalities further motivates us to explore why telemedicine is not widely adopted by hospitals, even with the presence of a pandemic.

Based on the above, we are motivated to explore the following questions. First, which strategy (introducing telemedicine vs. not) will hospitals prefer in the absence of a pandemic? Second, does the outbreak of a pandemic always increase the total costs for hospitals, and if so, will hospitals prefer to introduce telemedicine to alleviate such an increase? Third, how does the introduction of telemedicine affect hospitals' decisions on capacity and infection-reduction effort? Would hospitals set a larger telemedicine capacity but a lower in-person capacity in response to the outbreak of a pandemic as the public believes? Fourth, what is the preference of the social planner (e.g., the government), who aims at maximizing social welfare, regarding the introduction of telemedicine?

To examine these questions, we consider a monopoly healthcare market with a single cost-minimizing hospital providing outpatient services for a population of routine (i.e., non-pandemic-related) patients with chronic diseases. To incorporate the influence of reimbursement policy, we assume an exogenous health insurer who can reimburse in-person and telemedicine patients at different rates. Given the different reimbursement rates, the hospital chooses whether to adopt telemedicine and makes its operational decisions, and then patients choose the way they seek care with, in person or via telemedicine. We develop a theoretical model to qualitatively analyze the joint impact of medical consumption, reimbursement, and pandemic effect on the hospital's telemedicine strategy, which helps provide insights for hospital managers. Such a stylized model is in the same spirit as many studies in the healthcare management literature (e.g., Tarakci et al., 2009; Rajan et al., 2013; Qian et al., 2017; Rajan et al., 2019; Wang et al., 2021). In the following, four cases will be analyzed: (i) Case BN – before the introduction of telemedicine with no pandemic; (ii) Case BY – before the introduction of telemedicine with a pandemic; (iii) Case AN – after the introduction of telemedicine with no pandemic; and (iv) Case AY – after the introduction of telemedicine with a pandemic. After deriving the equilibrium solutions of these cases, we explore the equilibrium strategy of the hospital on whether introducing telemedicine under the market conditions without and with the outbreak of the pandemic. We also examine the impact of the pandemic on the total costs of the hospital both without and with telemedicine. Then, we investigate the impact of the pandemic and telemedicine on the (in-person and telemedicine) capacity and infection-reduction effort decisions of the hospital, as well as that on social welfare. Finally, we conduct a detailed case study to demonstrate the feasibility of using the proposed model in practice. From the derived results, the key findings of our study can be summarized as follows.

First, in the absence of the pandemic, the hospital prefers to introduce telemedicine as an additional modality to the in-person approach to deliver services to patients when the differences in medical consumption and reimbursement are both relatively small. Second, the outbreak of the pandemic can help the hospital without telemedicine reduce total costs only when the medical consumption difference is large and the infection-reduction effort cost is relatively low. However, we surprisingly find that the introduction of telemedicine is not always beneficial for the reduction of the hospital's total costs as the public believes, even during the pandemic, which significantly depends on the differences in medical consumption and reimbursement, and the effort cost. Third, in contrast to public expectations, we find that the outbreak of the pandemic will prompt the hospital to allocate more in-person capacity but less telemedicine capacity when the differences in medical consumption and reimbursement are both large and the effort cost is low. Fourth, social welfare can be improved by introducing telemedicine, especially during the pandemic.

The remainder of this paper is organized as follows. In the next section, we provide a brief review on the mostly relevant literature and specify the contribution of our paper. In Section 3, we describe the research problem in detail. Section 4 characterizes the equilibrium decisions of the hospital and conducts sensitivity analysis of these decisions under each case. Section 5 provides insights on the equilibrium strategy of the hospital without and with the outbreak of the pandemic. In Section 6, we investigate the impact of the pandemic and telemedicine on the hospital's equilibrium decisions and the social welfare, and we also conduct a detailed case study. Our model is further developed by considering alternative model assumptions (e.g., nonlinear function for medical consumption cost, additional medical consumption of in-person patients in the presence of the pandemic, and nonlinear function for infection risk cost of patients) in Section 7. Section 8 concludes the paper with a summary of main results and related management insights as well as avenues for future research.

2. Literature Review

Our work is closely related to the literature on the economic feasibility of telemedicine (e.g., Labiris et al., 2005; Dowie et al., 2008; Theodore et al., 2015; Bavafa et al., 2019; Sun et al., 2020). These studies empirically investigate the cost effectiveness and socioeconomic benefits of telemedicine. However, there are limited theoretical studies on telemedicine services. These studies include Tarakci et al. (2009), who explore the optimal investment level of telemedicine and staffing policy when considering various cost components, including staffing, technology investment, incorrect treatment, and waiting. Rajan et al. (2013) analyze the impact of telemedicine on the market share of a specialty hospital deploying this technology and on its competing hospital in the region. Later, they turn to explore the impact of telemedicine on the speed-quality tradeoff when chronically ill patients have heterogeneous treatment utilities in both revenue-maximizing and welfare-maximizing settings (Rajan et al., 2019). Wang et al. (2021) explore how the price and capacity strategies of a telemedicine firm affect these of a general hospital.

Our paper extends this stream of literature in three ways. First, to the best of our knowledge, we are one of the very few theoretical studies that study the equilibrium strategy of hospitals on telemedicine for serving chronically ill patients. We enrich the existing literature by investigating the joint impacts of medical consumption, reimbursement difference and pandemic effect on the hospital's decision on whether to introduce telemedicine. Second, given the advantage of telemedicine in combating infection, we investigate the reason for the observation in practice that telemedicine has not been widely implemented even in the presence of the pandemic. Third, we find that the introduction of telemedicine does not always alleviate the impact of the pandemic on the hospital's total costs and the social welfare, which runs counter to public beliefs.

Literature on pandemic influence can be divided into two streams. The first stream focuses on investigating the impact of pandemics on psychological health among individuals (e.g., Earls et al., 2008; Wu et al., 2020; Braquehais et al., 2020; Pierce et al., 2020). These papers empirically study the psychological impact of the pandemic on adolescent, students' parents, healthcare professionals, general public, respectively. The second stream concentrates on exploring the impact of a pandemic on healthcare system. Therein, some studies focus on the healthcare systems that deliver service for infected patients. For example, Woodul et al. (2019) evaluate the ability of a region's healthcare system to provide service for infected patients when the pandemic is prevailing. Steier & Moxham (2020) explore the impact of a pandemic on long-term investment decisions of hospitals when facing a sudden and substantial surge in demand of infected patients. There are also some papers examining the healthcare systems that provide services for non-infected patients. Squitieri & Chung (2020) provide necessary and timely public health information on plastic surgery and guide surge capacity protocols for nonemergent surgery of non-infected patient by sharing a conceptual framework. Katayama et al. (2020), Kristoffersen et al. (2020), and Guo et al. (2020) empirically examine the impact of a pandemic on emergency medical service systems that deliver care to non-infected patients.

Our paper belongs to the second substream of literature that focuses on non-emergency services and extends it in three ways. First, we are one of the very few theoretical studies that investigate whether hospitals should introduce telemedicine to deliver outpatient services for non-infected patients with chronic diseases during the pandemic. Second, we aim to understand the impact of the pandemic on hospital operations and find out whether telemedicine can help hospitals alleviate losses generated by the pandemic. Third, we find that the negative influence of the pandemic on the total costs of hospitals and social welfare can be eliminated by selecting appropriate infection-reduction measures and adjusting the differences in medical consumption and reimbursement between the in-person and telemedicine modalities, which provides managerial insights for hospital managers and governments on service operations during the pandemic.

Our work closely relates to a growing body of literature that studies healthcare operational problems. One substream of the operations management research in healthcare concentrates on improving operational efficiency, in which patients are typically treated as production units in the healthcare process and do not make any decisions. We refer the reader to Lakshmi & Appa (2013) for a comprehensive review of this literature pre-2013. More recently, Kozlowski & Worthington (2015) investigate the consequences that a maximum waiting time policy may have for the utilization of public hospital resources. Yan et al. (2018) propose a dual-variable-based heuristic to design sparse and efficient structures for operational problems in hospitals. Sun et al. (2020) investigate whether telemedicine enhances emergency room care delivery. Another substream, to which our work belongs, focuses on health policy issues involving capacity, financing, and market structure. Papers in this substream typically model patients' choice between different service alternatives, which differs substantially from the above substream. Andritsos & Tang (2014) investigate the role of private care and increased patient mobility on healthcare systems' operations in Europe. Qian et al. (2017) compare different subsidy schemes adopted by governments in terms of alleviating long waiting times for patients seeking public healthcare services. Rajan et al. (2019) study an operational problem on how the introduction of telemedicine affects a hospital's operations in chronic care, which is very close to our work. However, distinct from Rajan et al. (2019), who assume the same capacity of in-person and telemedicine modalities, we provide insights on capacity management when the hospital can set different capacities for the two service modalities. Another study that is highly related to our paper is Wang et al. (2019). Specifically, both the optimization models in our papers take medical consumption into account, which is an important operational factor noted by hospitals. Wang et al. (2019) study the quality-speed tradeoff of a hospital in discretionary healthcare services and provide patients only with the in-person modality. In contrast, we capture the competition in patient demand between the in-person and telemedicine modalities and model the medical consumption difference between the two modalities as the key factor that affects the hospital's decisions. Additionally, compared to the aforementioned works in the second substream, we also contribute to this stream by analyzing the impact of telemedicine on the hospital's operational decisions in different market conditions (i.e., without and with the pandemic) and different reimbursement policies. Through this analysis, we provide detailed guidelines for hospital managers and governments on how to serve chronically ill patients during the pandemic.

3. Problem Description

We consider a monopoly healthcare market with a single hospital providing outpatient services for a population of routine (i.e., non-pandemic-related) patients with chronic diseases, for example, cardiovascular diseases. Telemedicine (T) may be introduced by the hospital to cover periodic outpatient visits by these chronically ill patients during their stabilization period in addition to the traditional in-person modality (I). Furthermore, this market may be impacted by a pandemic (e.g., the COVID-19) that reduces service demand (Ortal et al., 2020). When the pandemic is active, the hospital should exert effort e to improve medical conditions and minimize the risk of infection for patients who seek outpatient care in person. This effort is additional to the standard procedure that the hospital is required to implement and may include using more expensive and effective cleaning and sanitation supplies, scheduling more frequent routing environment cleaning, and so forth. The notations and definitions used in this paper are listed in Appendix A.

The delivery process of healthcare services, whether in person or via telemedicine, will consume some medical resources (e.g., medical tests, pharmaceuticals). We use the specific function $m(\mu_i) = \rho_i\mu_i$ ($i = \mathrm{I}, \mathrm{T}$) to model the medical consumption cost suffered by patients, where $\rho_i > 0$ is the medical consumption cost coefficient and μ_i is the capacity selected by the hospital for service modality i. Such a linear assumption on medical consumption is consistent with evidence in previous studies (Gawande, 2009, 2015; Wang et al., 2019) that a lower capacity, that is, a longer service time, allows more thorough questioning and examination, and then can reduce the medical consumption required. It also helps reduce technical complexities and helps generate theoretical insights on hospital operations. In Subsection 7.1, we extend such a linear function on medical consumption into a nonlinear form and find that all of conclusions remain qualitatively unchanged. For the sake of simplicity, we further assume that $\rho_{\mathrm{I}} = \delta$ and $\rho_{\mathrm{T}} = 1$, where $\delta \in (0, \infty)$ is the medical consumption difference between the two modalities. Specifically, if $0 < \delta < 1$, then patients seeking care in person incur less medical consumption costs than they would via telemedicine for the same capacity of the two modalities, which occurs when telemedicine is not welcomed to be used by patients for some reasons (e.g., overuse) (Daschle & Dorsey, 2015; Mehrotra et al., 2020). In contrast, if $\delta > 1$, then seeking care via telemedicine is less expensive for patients, which has been verified in some literature on outpatient management of chronic diseases (Farabi et al., 2020; Wosik et al., 2021) and data from a survey we conducted in a cardiovascular hospital in Tianjin, China, as mentioned in the Introduction. $\delta = 1$ means that both types of patients pay the same amount for the same service (Medicare, 2020). Implicitly, in the main text, we do not consider the additional medical resource consumption required by in-person patients during the pandemic, for example, nucleic acid testing. However, we account for such addition consumption in Subsection 7.2 and find that our main results still hold. Furthermore, we assume that the hospital can benefit from the medical consumption and retain a fraction $\theta \in [0, 1]$ of the medical consumption cost $m(\mu_i)$ (Liu et al., 2009; Wang et al., 2019). However, the hospital incurs a cost $\frac{1}{2}\beta_i\mu_i^2$ $(i = \mathrm{I}, \mathrm{T})$ for maintaining capacity μ_i. Such a convex function adopted in our model is in the same spirit as many studies in the service operations field (e.g., Brekke et al., 2008; Allon & Federgruen, 2009; Folland et al., 2016). Furthermore, we assume that $\beta_{\mathrm{T}} > \hat{\beta}$ (for the specific expression of the threshold, see Appendix A, Table A2), where $\hat{\beta} > 0$ implies that the telemedicine modality requires a relatively high cost for capacity realization, for example, installing a webcam and fulfilling other hardware and software requirements (Polisena et al., 2009; Moffatt & Eley, 2011).

Patients have already subscribed to an available Medicare program, and therefore, they will be reimbursed by a health insurer at certain rates for their medical consumption costs whether seeking care in person or via telemedicine. However, the rates at which patients are reimbursed can differ between the two service modalities. For example, as reported in JoAnn et al. (2021), in the presence of COVID-19 pandemic, 23 states mandate payment parity for telemedicine services, and 7 states reduce or eliminate cost sharing for services provided by telemedicine, suggesting that health insurers in other states provide lower or no reimbursement for telemedicine care. Thus, to fully capture the fact that the health insurer will impose or ease restrictions on telemedicine, we assume different reimbursement rates for the two service modalities, and denote them as $1 - r$ and $1 - \eta r$, respectively, where $r \in (\hat{r}, 1]$ is the copayment rate of in-person patients and $\eta \in [0, 1/r]$ is the reimbursement difference between the two modalities (for the specific expression of the threshold, see Appendix A, Table A2). To be specific, if $0 \leq \eta < 1$, then patients seeking care via telemedicine are reimbursed at a higher rate than those seeking care in person. If $1 < \eta \leq 1/r$, patients seeking care in person obtain a higher reimbursement. $\eta = 1$ implies that both types of patients are reimbursed at the same rate. It is worth noting here that r and η are assumed to be exogenous, which not only allows us to investigate the impact of reimbursement policy on the hospital's decision on telemedicine but also helps us obtain analytical solutions by simplifying our model.

Exerting effort to reduce the risk of infection for non-infected patients incurs a cost for the hospital.[5] To serve these in-person patients, the hospital incurs an effort cost equal to $\frac{1}{2}\gamma e^2$, where $\gamma > 0$ is the hospital's effort cost factor (Bala et al., 2013; Ma et al., 2019), which represents how easy it is to prevent the pandemic spread in outpatient service. The quadratic form of the effort cost means that the marginal cost is increasing, which subsequently indicates that the hospital's effort can indeed generate a positive effect for patients, but the cost of further actions is increasing (Adida & Bravo, 2019). Such an effort cost can be paid in exchange for a reduction in in-person patients' infection risk caused by physical contact. The infection risk generates disutility and negatively impacts patients' willingness to seek outpatient care in person (as we discuss in the Introduction). We call this disutility the infection risk cost incurred by patients, which is denoted as $\varphi(e)$, a decreasing function with respect to the effort selected by the hospital. Such a decreasing setting of $\varphi(e)$ is consistent with a recent survey conducted by Boston Consulting Group that found that hospitals can exert effort to prevent the spread of the pandemic in the clinic and improve the conditions that affect patients' willingness to seek care in person during the pandemic (Jonathan et al., 2020). The specific expression of $\varphi(e)$ is further assumed to be $\alpha(1 - e)$, where $\alpha > 0$ is the infection risk cost coefficient. The linear functional form of $\varphi(e)$ is adopted to reduce technical complexities and helps generate theoretical insights on hospital operations, which also captures the fact that the infection risk cost of patients is decreasing with the infection-reduction effort. In Subsection 7.3, we extend the linear expression to a nonlinear form and find that the main results still hold. Telemedicine patients, who benefit from the characteristic of telemedicine that patients receive care from the hospital at home (Bergmo, 1997; Rajan et al., 2013, 2019), do not expose themselves to the risk of infection in the process of their visits (Hollander & Carr, 2020). As such, the hospital need not expend any effort cost for these telemedicine patients in response to the presence of the pandemic.

Patients are rational, and they can freely make a choice between the two service modalities to maximize their own expected utility. Let U_{I} and U_{T} denote patient utility functions for in-person

[5] Note that our study focuses on the adoption of telemedicine in the outpatient department to cover periodic outpatient visits by chronically ill patients during their stabilization period. Such a department is responsible for its own profits and losses. For brevity, we use the word "hospital" to denote this department and do not distinguish them in our study, which can be widely seen in healthcare management literature (e.g., Jiang et al., 2012; Andritsos & Tang, 2018; Wang et al., 2021).

and telemedicine visits, respectively, which are given by:

$$U_{\mathrm{I}}=\begin{cases} v+u-tx-rm(\mu_{\mathrm{I}}), & \text{without the pandemic,}\\ v+u-tx-rm(\mu_{\mathrm{I}})-\varphi(e), & \text{with the pandemic,}\end{cases} \tag{1}$$

and

$$U_{\mathrm{T}}=v-t(1-x)-\eta rm(\mu_{\mathrm{T}}), \tag{2}$$

where $v+u$ and v $(v,\ u>0)$ represent the values of healthcare services delivered in person and via telemedicine, respectively.[6] The reasonability of $u>0$ originates from the fact that these in-person patients experience services with higher quality than telemedicine patients (Webster, 2020; Uscher-Pines et al., 2020). For example, an in-person visit with thorough inquiry and examination may always dominate a telemedicine visit (Morland et al., 2015). $t>|\alpha-u|$ is the unit mismatch cost incurred by patients. In practice, the service modalities may not be a perfect fit for patients for several reasons (e.g., distance and illness), and thus, patients incur mismatch costs. The unit mismatch cost is larger than a threshold such that patients have incentives to make a tradeoff between the two modalities. We follow a typical formulation often used in previous literature (e.g, Sun & Tyagi, 2012; Kwark et al., 2014) to model this mismatch cost. Specifically, we assume that the in-person and telemedicine modalities are located at positions 0 and 1 on a line of length 1, respectively, and Λ patients are uniformly distributed along the line. Thus, tx is the mismatch cost of a patient located at $x\in[0,1]$ seeking care in person, and $t(1-x)$ is that of the patient seeking care via telemedicine.

We next present our formulation of the hospital's optimization problem. In formulating the problem, it is necessary to introduce an indicator function $\mathbb{1}(\text{Set})$ such that its value is 1 if Set is true and 0 otherwise. To be specific, $\mathbb{1}(\text{Telemedicine})=1$ implies that telemedicine is introduced by the hospital, and $\mathbb{1}(\text{Pandemic})=1$ means that the pandemic is present in the market. As a result, four cases are considered in our model: (i) Case BN – before the introduction of telemedicine with no pandemic, (ii) Case BY – before the introduction of telemedicine with the pandemic, (iii) Case AN – after the introduction of telemedicine with no pandemic, and (iv) Case AY – after the introduction of telemedicine with the pandemic. In each case, we assume that the hospital minimizes its total costs (Liu et al., 2015; Qian et al., 2017; Tsai et al., 2021), which may include costs for implementing the in-person and telemedicine service modalities minus the benefits extracted from medical consumption in the two modalities and cost of infection reduction. Let C^j represent the hospital's total costs in case $j\in\{\mathrm{BN},\mathrm{BY},\mathrm{AN},\mathrm{AY}\}$, which can be generally written as

$$C^j=\left(\tfrac{1}{2}\beta_{\mathrm{I}}\mu_{\mathrm{I}}^2-\theta\lambda_{\mathrm{I}}^j m(\mu_{\mathrm{I}})\right)+\left(\tfrac{1}{2}\beta_{\mathrm{T}}\mu_{\mathrm{T}}^2-\theta\lambda_{\mathrm{T}}^j m(\mu_{\mathrm{T}})\right)\mathbb{1}(\text{Telemedicine})+\tfrac{1}{2}\gamma \mathrm{e}^2\mathbb{1}(\text{Pandemic}), \tag{3}$$

where $\lambda_{\mathrm{I}}^j=\Lambda x^j$ and $\lambda_{\mathrm{T}}^j=\Lambda(1-x^j)$ are the demands for the in-person and telemedicine service modalities in Case j, respectively. For the sake of simplicity, we normalize Λ to 1 hereafter. Note

[6] We assume that patients are all treated correctly, i.e., without any mistreatment; thus, the outcomes of treatments are the same, irrespective of how patients seek care.

that the values of the demands for the two service modalities before and after the introduction of telemedicine are derived differently. To be specific, the values of the demand for services in Cases BN and BY are calculated by setting $U_{\mathrm{I}}(\lambda_{\mathrm{I}}) = 0$, whereas the demand in Cases AN and AY comes from setting $U_{\mathrm{I}}(\lambda_{\mathrm{I}}) = U_{\mathrm{T}}(\lambda_{\mathrm{T}})$. This is because in our focal model, we focus on the setting with $\bar{v} < v < \hat{v}$, where the market is partially covered before the introduction of telemedicine but fully covered thereafter such that the hospital's tradeoff on whether to introduce telemedicine can be captured.[7] However, in Appendix B, for completeness, we analyze the setting in which the market is partially covered whether before or after the introduction of telemedicine. In Table 1, we summarize the four cases along with the hospital's decision variables, total costs, and demand for each service in each case. For example, in Case AN, given the reimbursement rates at which patients will be reimbursed by the health insurer, the hospital simultaneously sets the in-person and telemedicine capacities (i.e., μ_{I} and μ_{T}) as well as the effort level (i.e., e) to minimize its total costs. Then, based on the hospital's decisions, patients make a choice on how to seek care to maximize their own utility; as a result, the demand for each service modality is realized.

Table 1. Model settings of four cases.

Case	Decision variables	Total costs C^j	Demand for service λ_i^j
BN	μ_{I}	$\frac{1}{2}\beta_{\mathrm{I}}\mu_{\mathrm{I}}^2 - \theta\lambda_{\mathrm{I}}^{\mathrm{BN}} m(\mu_{\mathrm{I}})$	$\{\lambda_{\mathrm{I}}^{\mathrm{BN}} \| U_{\mathrm{I}}(\lambda_{\mathrm{I}}^{\mathrm{BN}}) = 0\}$
BY	μ_{I}, e	$(\frac{1}{2}\beta_{\mathrm{I}}\mu_{\mathrm{I}}^2 - \theta\lambda_{\mathrm{I}}^{\mathrm{BY}} m(\mu_{\mathrm{I}})) + \frac{1}{2}\gamma e^2$	$\{\lambda_{\mathrm{I}}^{\mathrm{BY}} \| U_{\mathrm{I}}(\lambda_{\mathrm{I}}^{\mathrm{BY}}) = 0\}$
AN	μ_{I}, μ_{T}	$(\frac{1}{2}\beta_{\mathrm{I}}\mu_{\mathrm{I}}^2 - \theta\lambda_{\mathrm{I}}^{\mathrm{AN}} m(\mu_{\mathrm{I}})) + (\frac{1}{2}\beta_{\mathrm{T}}\mu_{\mathrm{T}}^2 - \theta\lambda_{\mathrm{T}}^{\mathrm{AN}} m(\mu_{\mathrm{T}}))$	$\{(\lambda_{\mathrm{I}}^{\mathrm{AN}}, \lambda_{\mathrm{T}}^{\mathrm{AN}}) \| U_{\mathrm{I}}(\lambda_{\mathrm{I}}^{\mathrm{AN}}) = U_{\mathrm{T}}(\lambda_{\mathrm{T}}^{\mathrm{AN}})\}$
AY	μ_{I}, μ_{T}, e	$(\frac{1}{2}\beta_{\mathrm{I}}\mu_{\mathrm{I}}^2 - \theta\lambda_{\mathrm{I}}^{\mathrm{AN}} m(\mu_{\mathrm{I}})) + (\frac{1}{2}\beta_{\mathrm{T}}\mu_{\mathrm{T}}^2 - \theta\lambda_{\mathrm{T}}^{\mathrm{AN}} m(\mu_{\mathrm{T}})) + \frac{1}{2}\gamma e^2$	$\{(\lambda_{\mathrm{I}}^{\mathrm{AY}}, \lambda_{\mathrm{T}}^{\mathrm{AY}}) \| U_{\mathrm{I}}(\lambda_{\mathrm{I}}^{\mathrm{AY}}) = U_{\mathrm{T}}(\lambda_{\mathrm{T}}^{\mathrm{AY}})\}$

4. Equilibrium Outcomes of the Hospital

In this section, we analyze the equilibrium outcomes on capacity and effort level of the hospital under the four cases mentioned above, i.e., Cases BN, BY, AN, and AY. These optimal outcomes are summarized in Table 2. Next, we analyze how these optimal outcomes are affected by the medical

[7] We specify that (i) for $v < \bar{v}$, the market can only be partially covered before or after the introduction of telemedicine, and thus there is no competition between the two service modalities, which does not enable us to capture the hospital's tradeoff on whether to introduce telemedicine (for brevity, we refer the reader to Appendix B for detailed analysis of this case); (ii) different from the above, for $\bar{v} < v < \hat{v}$, the market is partially covered before the introduction of telemedicine but fully covered after this introduction, which is the focal case in our paper; (iii) for $v > \hat{v}$, the market can be fully covered before the introduction of telemedicine, and as a result, the hospital has no incentives to exert effort to prevent infection for non-infected patients. It will choose not to introduce telemedicine given that it can benefit much more from serving patients in person than via telemedicine; as such, we do not analyze this case in depth.

consumption difference, the reimbursement difference and the infection-reduction effort cost, which are key factors that the hospital has to take into consideration when setting its capacities (in-person and telemedicine) and infection-reduction effort. All results presented here are obtained analytically, and proofs are offered in Appendix C.

Table 2. Optimal solutions under four cases.

Case	In-person capacity μ_{I}^{j}	Telemedicine capacity μ_{T}^{j}	Infection-reduction effort e^{j}
BN	$\frac{\theta\delta(v+u)}{2r\theta\delta^2+t\beta_{\mathrm{I}}}$	—	—
BY	$\frac{\gamma t\theta\delta(v+u-\alpha)}{\theta(2\gamma rt-\alpha^2\theta)\delta^2+\gamma t^2\beta_{\mathrm{I}}}$	—	$\frac{\alpha\theta^2\delta^2(v+u-\alpha)}{\theta(2\gamma rt-\alpha^2\theta)\delta^2+\gamma t^2\beta_{\mathrm{I}}}$
AN	$\frac{\theta\delta(\theta(3t\eta+u\eta+t-u)+2\beta_{\mathrm{T}}t(u+t))}{\Delta_0}$	$\frac{\theta(\theta\delta^2r(t\eta+u\eta+3t-u)+2\beta_{\mathrm{I}}t(t-u))}{\Delta_0}$	—
AY	$\frac{\theta\delta(r\theta\gamma\Delta_1-\alpha^2\theta^2+2\gamma t\beta_{\mathrm{T}}(u+t-\alpha))}{\gamma\Delta_0-\alpha^2\theta^2(\beta_{\mathrm{I}}+\beta_{\mathrm{T}}\delta^2)}$	$\frac{\theta(\theta\delta^2(r\gamma(\Delta_1+2(1-\eta)t)-\alpha^2\theta)+2\gamma t\beta_{\mathrm{I}}(\alpha+t-u))}{\gamma\Delta_0-\alpha^2\theta^2(\beta_{\mathrm{I}}+\beta_{\mathrm{T}}\delta^2)}$	$\frac{\alpha\theta^2(\beta_{\mathrm{I}}(u-t-\alpha)+\delta^2(\beta_{\mathrm{T}}(u+t-\alpha)-r\theta(1-\eta)))}{\gamma\Delta_0-\alpha^2\theta^2(\beta_{\mathrm{I}}+\beta_{\mathrm{T}}\delta^2)}$

where $\Delta_0 = 4tr\theta(\eta\beta_{\mathrm{I}} + \beta_{\mathrm{T}}\delta^2) + 4t^2\beta_{\mathrm{I}}\beta_{\mathrm{T}} - (r\delta\theta(\eta-1))^2$ and $\Delta_1 = (1+3\eta)t + (\alpha-u)(1-\eta)$.

4.1. Case BN

In this subsection, we focus on analyzing the case in which the hospital can only offer in-person treatment and no pandemic emerges. In this context, the medical consumption difference, which has a one-to-one correspondence with the medical consumption cost of the in-person service, should be considered by the hospital when making decisions. However, the medical consumption cost of the in-person service has a complex influence on the hospital's decision. On the one hand, it has a negative impact on the patient demand for in-person services. A high value of the medical consumption cost will persuade some patients to balk since they suffer disutility from seeking care. On the other hand, the medical consumption cost has a positive impact on the hospital's marginal profit, which may help it to benefit substantially from serving patients. By taking the first-order condition of the optimal in-person capacity $\mu_{\mathrm{I}}^{\mathrm{BN}}$ with respect to the medical consumption difference δ, we obtain the change trend of the in-person capacity $\mu_{\mathrm{I}}^{\mathrm{BN}}$ as the medical consumption difference increases and summarize the result in the following lemma.

Lemma 1. *In* Case BN, *the optimal in-person capacity* $\mu_{\mathrm{I}}^{\mathrm{BN}}$ *first increases then decreases in the medical consumption difference* δ*.*

Lemma 1 illustrates that under Case BN, the optimal in-person capacity first increases then decreases as the medical consumption cost rises up. This result originates from the complex influence of the medical consumption difference on the hospital operations, as discussed before. When the medical consumption cost is low, the demand for healthcare service is relatively high, under which context the hospital can appropriately increase its capacity to increase patients' consumption of medical resource, and then profit more from such consumption to recoup some of its input costs. However, as the medical consumption cost increases to a certain value, increasing capacity will lead to a significant reduction of the demand. As such, to attract patients, the hospital responds by decreasing its capacity to better serve these patients.

4.2. Case BY

This subsection considers the situation in which the hospital can offer only in-person treatment for patients and the pandemic is present. Different from Case BN in which there is no pandemic, patients seeking care from the hospital suffer a risk of infection, and the hospital should invest effort to decrease such a risk in this case. When making decisions, it is natural that the hospital will take the effort cost of reducing infection into account, which represents the difficulty of reducing patients' infection risk, in addition to the medical consumption difference. Reducing infection will help the hospital attract some patients, who balk from attending due to the pandemic, to seek care in person, which subsequently leads to the formation of a new tradeoff for the hospital between in-person capacity and infection-reduction effort. To investigate the impact of the medical consumption difference and the infection-reduction effort cost on the hospital's in-person capacity and effort decisions, we conduct a sensitivity analysis and summarize results in the following lemma.

Lemma 2. *In* Case BY*, the sensitivities of the hospital's optimal in-person capacity* $\mu_{\mathrm{I}}^{\mathrm{BY}}$ *and optimal effort* e^{BY} *with respect to the medical consumption difference* δ *and the infection-reduction effort cost* γ *are as follows:*

(1) $\mu_{\mathrm{I}}^{\mathrm{BY}}$ *is increasing in* δ *if* $\gamma < \frac{\alpha^2\theta}{2tr}$ *and first increases then decreases in* δ *otherwise, while* e^{BY} *is increasing in* δ*,*

(2) *both* $\mu_{\mathrm{I}}^{\mathrm{BY}}$ *and* e^{BY} *are decreasing in* γ*.*

One interesting implication can be inferred from Lemma 2. That is, under Case BY, the sensitivity of the optimal in-person capacity with respect to the medical consumption difference is non-monotonic, when the infection-reduction effort cost is high. Such a result is quite different from that in Case BN. This is because in the presence of the pandemic, the magnitude of the infection-reduction effort cost determines how much effort the hospital can exert to reduce infection, which subsequently decides the size of patient demand and finally has an impact on the in-person capacity. Specifically, when the effort cost is high, the optimal in-person capacity first increases then decreases with the medical consumption cost. The reason behind this result is that the high cost of effort discourages the hospital to exert enough effort, which means that more patients are persuaded to retreat by the pandemic. When the medical consumption cost is relatively low, the hospital chooses to set a larger capacity for in-person modality to increase its marginal revenue, so as to obtain greater benefits from serving patients and finally recoup some of its input costs. However, as the medical consumption cost increases above a threshold, the demand for service is significantly reduced. Reducing capacity to increase demand becomes the best strategy for the hospital.

4.3. Case AN

In this configuration, the hospital decides to adopt telemedicine, and no pandemic emerges. Thus, the hospital will set capacities for both in-person and telemedicine modalities, and then patients decide which modality to seek care with. Different from Case BN in which there is no telemedicine, to minimize the total costs, the hospital under Case AN should take not only the medical consumption difference but also the reimbursement difference between the two modalities into consideration. We conduct a sensitivity analysis to investigate how the capacity decisions on in-person and telemedicine modalities are affected by such two differences in this context, and summarize results in Lemma 3.

Lemma 3. *In* Case AN*, the sensitivities of the hospital's optimal in-person capacity* $\mu_{\mathrm{I}}^{\mathrm{AN}}$ *and optimal telemedicine capacity* $\mu_{\mathrm{T}}^{\mathrm{AN}}$ *with respect to the medical consumption difference* δ *and the reimbursement difference* η *are as follows:*

(1) $\mu_{\mathrm{I}}^{\mathrm{AN}}$ *first increases then decreases with* δ*, while* $\mu_{\mathrm{T}}^{\mathrm{AN}}$ *is increasing with* δ*,*

(2) $\mu_{\mathrm{I}}^{\mathrm{AN}}$ *is increasing in* η*, whereas* $\mu_{\mathrm{T}}^{\mathrm{AN}}$ *first decreases then increases in* η *if* $\delta < \delta_1$ *and is increasing in* η *otherwise.*

As shown in Lemma 3, under Case AN, the hospital's optimal telemedicine capacity is not always monotonically decreasing in the reimbursement difference, which goes against public's expectations, given that a large reimbursement difference will discourage patients to seek care via telemedicine. Instead, we find that the telemedicine capacity decreases with the reimbursement difference only if the differences in medical consumption and reimbursement are both small, and increases under the other two conditions. One condition is when the medical consumption difference is small and the reimbursement difference is large, and another is when the medical consumption difference is large. Under the former condition, patient demand for telemedicine service is significantly reduced by the small medical consumption difference and the large reimbursement difference. Faced with this, the hospital will increase the capacity for telemedicine modality to increase its marginal revenue so as to gain more profits to cover its input costs (similar to the High Price Strategy). However, under the latter condition, patient demand for telemedicine service is still high because patients seeking care via telemedicine can enjoy the benefit of low medical consumption, which offsets the negative impact of reimbursement difference. Confronting this situation, the hospital can accordingly increase the telemedicine capacity (without generating drastic influence on patient demand) to gain more benefits from serving patients, as the reimbursement difference increases.

4.4. Case AY

In this case, the hospital can offer two service modalities, in-person and telemedicine, and the pandemic is present. As a result, the hospital should make decisions on the capacities of both modalities as well as the infection-reduction effort. And due to the emergence of the pandemic, the hospital has to take the infection-reduction effort cost into consideration, in addition to the differences in medical consumption and reimbursement. How these three key factors affect the hospital's optimal decisions under Case AY is summarized in the following lemma.

Lemma 4. *In* Case AY*, the sensitivities of the hospital's optimal in-person capacity* $\mu_{\mathrm{I}}^{\mathrm{AY}}$*, optimal telemedicine capacity* $\mu_{\mathrm{T}}^{\mathrm{AY}}$*, and optimal effort* e^{AY} *with respect to the medical consumption difference* δ*, the reimbursement difference* η*, and the infection-reduction effort cost* γ *are as follows:*

(1) $\mu_{\mathrm{I}}^{\mathrm{AY}}$ *is non-monotonic in* δ *if* $\gamma < \frac{\alpha^2\theta^2}{4t(\eta r\theta + t\beta_{\mathrm{T}})}$ *or* $\gamma > \frac{\alpha^2\theta^2\beta_{\mathrm{T}}}{r\theta(4t\beta_{\mathrm{T}} - r(1-\eta)^2\theta)}$ *and monotonic in* δ *otherwise, while* $\mu_{\mathrm{T}}^{\mathrm{AY}}$ *and* e^{AY} *are both monotonic in* δ*,*

(2) $\mu_{\mathrm{I}}^{\mathrm{AY}}$ *and* $\mu_{\mathrm{T}}^{\mathrm{AY}}$ *are both monotonic in* η*, whereas* e^{AY} *is not necessarily monotonic in* η*,*

(3) $\mu_{\mathrm{I}}^{\mathrm{AY}}$ *and* e^{AY} *are both monotonically decreasing in* γ*, whereas* $\mu_{\mathrm{T}}^{\mathrm{AY}}$ *is monotonically decreasing in* γ *if* $\delta < \sqrt{\frac{\beta_{\mathrm{I}}(\alpha+t-u)}{\beta_{\mathrm{T}}(t+u-\alpha) - \theta r}}$ *and* $\eta < \min(1 + \frac{\beta_{\mathrm{I}}(\alpha+t-u) - \delta^2\beta_{\mathrm{T}}(t+u-\alpha)}{r\theta\delta^2}, \frac{1}{r})$ *and is monotonically increasing in* γ *otherwise.*

One can observe from Lemma 4 that whether the in-person capacity is monotonic with respect to the medical consumption difference largely depends on the infection-reduction effort cost, which is different from results in Case AN. This is because the magnitude of the infection-reduction effort cost has a remarkable influence on the competition between the two modalities when the pandemic prevails. Furthermore, we find that the hospital will decrease its telemedicine capacity as the infection-reduction effort cost increases, when the differences in medical consumption and reimbursement are both relatively small. This result is somewhat counterintuitive, and we explain it as follows. In this situation, the large consumption difference and the small reimbursement difference jointly lead to a not low demand for telemedicine services, especially when the health insurer encourages patients to seek care via telemedicine by easing restrictions on reimbursement (i.e., $\eta < 1$). Moreover, as the effort cost increases, patient infection risk cost increases, since the infection-reduction effort exerted by the hospital decreases (i.e., $\frac{\partial e^{\mathrm{AY}}}{\partial\gamma} < 0$), which further raises patient demand for telemedicine services. Faced with such demand for telemedicine service, the hospital chooses to attract more patients by accordingly decreasing its capacity, which is linked to patient consumption cost, so as to achieve the economies of scale.

5. Equilibrium Strategy on Telemedicine

Using the optimal solutions of the different cases obtained in the previous section, we now come to explore the equilibrium strategy of the hospital under different market conditions, that is, without and with the pandemic. We first ascertain the best choice of the hospital on whether to introduce telemedicine by comparing the case with telemedicine to the case without telemedicine in the time of no pandemic (i.e., Case AN vs. Case BN). We summarize the equilibrium strategy of the hospital on telemedicine with no pandemic prevailing in the market in the following proposition. The specific expressions of thresholds used in this paper are summarized in Appendix A.

Proposition 1. *In the absence of the pandemic, the hospital prefers to introduce telemedicine if the differences in medical consumption and reimbursement are both small (i.e.,* $\delta < \hat{\delta}$ *and* $\eta < \hat{\eta}$*); otherwise, it delivers service to patients in person only.*

Proposition 1 illustrates the equilibrium strategy of the hospital regarding telemedicine in the absence of the pandemic. We can see that with no pandemic, the hospital will achieve its objective to reduce total costs by introducing telemedicine if the differences in medical consumption and reimbursement are both relatively small; otherwise, it will suffer an increase in its total costs. The reason for this result is as follows. From the perspective of patients, the small medical consumption difference encourages them to seek care in person, whereas the small reimbursement difference discourages them from doing so, which jointly mean that the demand for telemedicine is not low. Recall that the small medical consumption difference implies that the telemedicine modality is more profitable for the hospital than the in-person modality. As a result, in such a context, the hospital prefers to introduce telemedicine, which can reap substantial benefits. However, in other cases, the in-person modality dominates telemedicine in terms of the profitability. Consequently, it is better for the hospital not to introduce telemedicine here. This result is consistent with the fact observed in practice that telemedicine is not widely adopted by hospitals in the absence of the pandemic due to the differences in medical consumption and reimbursement. Proposition 1 contributes to explaining such a fact and providing theoretical support for the hospital's strategy on whether to introduce telemedicine in the absence of the pandemic.

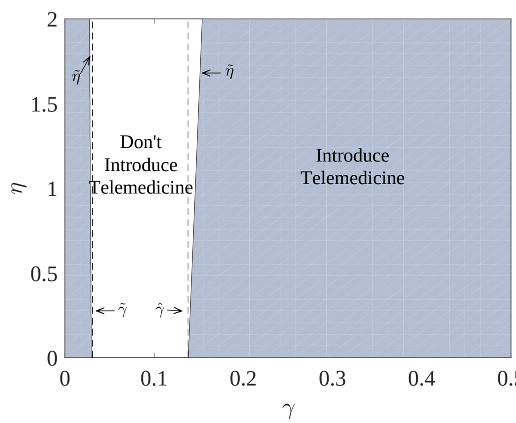
Next, we investigate the equilibrium telemedicine strategy of the hospital to respond to the outbreak of the pandemic. Before that, we explore the impact of the pandemic on the hospital's total costs by comparing the case with the pandemic to the case without the pandemic in the context of no telemedicine (i.e., Case BY vs. Case BN), results of which are summarized in Proposition 2.

Proposition 2. *Before the introduction of telemedicine, if the infection-reduction effort cost* $\gamma > \frac{\alpha\theta(v+u)^2}{2rt(2v+2u-\alpha)}$, *or* $\gamma < \frac{\alpha\theta(v+u)^2}{2rt(2v+2u-\alpha)}$ *and the medical consumption difference* $\delta < \sqrt{\frac{\gamma\beta_I t^2(2v+2u-\alpha)}{\theta(\alpha\theta(v+u)^2-2rt(2v+2u-\alpha)\gamma)}}$, *the outbreak of the pandemic increases the total costs of the hospital (i.e.,* $C^{\mathrm{BN}} < C^{\mathrm{BY}}$*); otherwise, it decreases the total costs of the hospital (i.e.,* $C^{\mathrm{BN}} \geq C^{\mathrm{BY}}$*).*

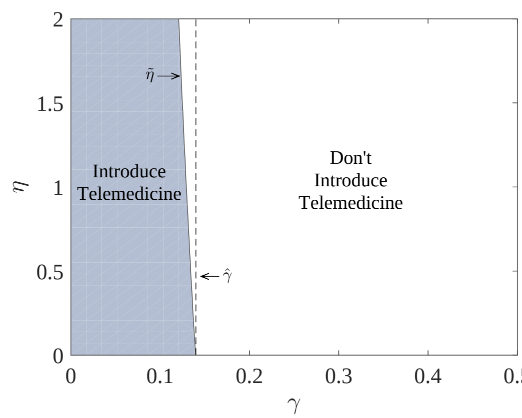
As shown in Proposition 2, when the effort cost is high, the presence of the pandemic always leads to an increase in the hospital's total costs. This is because in this situation, the hospital is unwilling to exert effort to recover the demand for in-person services. Instead, it is more likely to decrease its in-person capacity as the pandemic emerges. Such behavior by the hospital decreases the revenue generated from medical consumption, which consequently, cannot cover the increased input costs and leads to an increase in the total costs. However, when the effort cost is relatively low, the emergence of the pandemic does not necessarily lead to an increase in the total costs for hospitals, which depends on the magnitude of the medical consumption difference. To be specific, when the pandemic arises, the hospital with a small medical consumption difference will suffer increased total costs, whereas the hospital with a large difference will have decreased total costs. The underlying logic behind this is that the large medical consumption difference allows the hospital to gain more revenue from serving patients by adjusting its in-person capacity, helping recoup more input costs, especially when the effort cost is low. Proposition 2 theoretically contributes to providing insights for hospital managers on how to survive the pandemic without introducing telemedicine. For example, the hospital could take more effective measures to reduce infection of in-person patients.

Then, we turn our attention to explore the equilibrium strategy of the hospital on telemedicine when the pandemic is prevailing in the market. By comparing the case with telemedicine to the case without telemedicine under the setting with the pandemic (i.e., Case AY vs. Case BY), we can specify the following results, listed in Proposition 3 and shown in Fig. 1.[8]

Proposition 3. *In the presence of the pandemic, the hospital prefers to introduce telemedicine (i.e., $C^{\mathrm{AY}} < C^{\mathrm{BY}}$) if the medical consumption difference δ, the infection-reduction effort cost γ, and the reimbursement difference η satisfy:* (1) $\delta < \tilde{\delta}$, $\gamma < \tilde{\gamma}$ *or* $\gamma > \hat{\gamma}$, *and* $\eta < \tilde{\eta}$, *or* (2) $\delta > \tilde{\delta}$, $\gamma < \hat{\gamma}$ *and* $\eta < \tilde{\eta}$, *respectively; otherwise, it will not introduce telemedicine (i.e.,* $C^{\mathrm{AY}} > C^{\mathrm{BY}}$*).*



(a) Low medical consumption difference ($\delta = 0.4$)



(b) High medical consumption difference ($\delta = 1.5$)

Fig. 1. The equilibrium strategy of the hospital on telemedicine in the presence of the pandemic.

When the pandemic is present in the market, we find that introducing telemedicine is not always the best choice for the hospital, as shown in Proposition 3 and Fig. 1. Instead, only when one of the following two conditions holds will the hospital deliver services to patients via telemedicine. *The first condition* is when the medical consumption difference is small, the effort cost is sufficiently low or significantly high, and the reimbursement difference is small (i.e., $\delta < \tilde{\delta}$, $\gamma < \tilde{\gamma}$ or $\gamma > \hat{\gamma}$, and $\eta < \tilde{\eta}$). As explained in Proposition 1, when the differences in medical consumption and reimbursement are both small, the demand for telemedicine is not low. However, the presence of the pandemic has a negative influence on patients' willingness to seek care in person, which ultimately affects the demand for the in-person and telemedicine modalities. Such a negative influence can be alleviated by the hospital's infection-reduction effort. When the effort cost is sufficiently low, the hospital can exert high effort to decrease the influence of the pandemic on

[8] All parameters used in Figs. 1–4 ($v = 3.2$, $u = 1.9$, $t = 3.2$, $\alpha = 2.9$, $\theta = 0.3$, $\beta_{\mathrm{I}} = 0.2$, $\beta_{\mathrm{T}} = 0.95$, and $r = 0.5$) satisfy the parametric assumptions in the problem description and have practical significance. Indeed, the qualitative findings still hold when the parameter values change within a reasonable range.

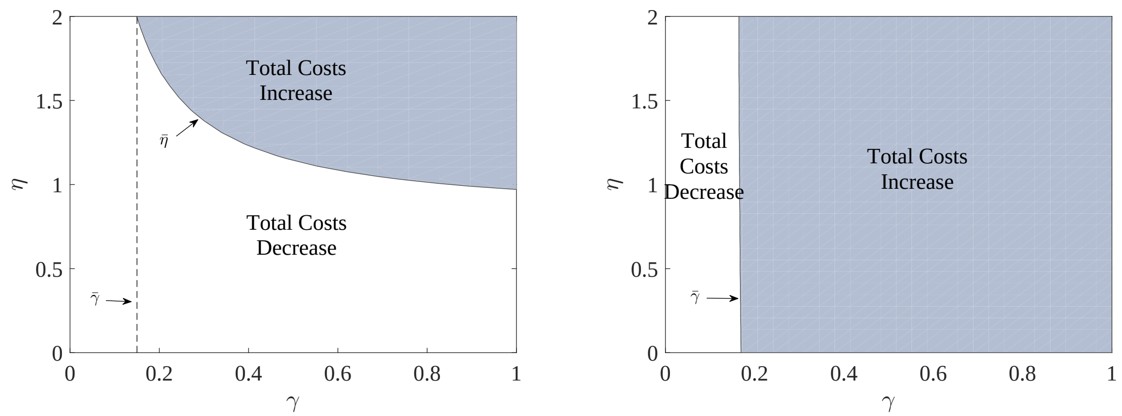
demand and thus can maintain small changes in demand for the two modalities. This in turn allows the hospital to benefit from both modalities. To be specific, the hospital, on the one hand, sets a high in-person capacity to increase its profit from serving patients in person and, on the other hand, covers all patients by introducing telemedicine to obtain extra profits. However, when the effort cost is sufficiently high, the hospital does not find it profitable to exert effort to increase the demand for the in-person modality. Furthermore, the small medical consumption difference, which implies that the telemedicine modality is more profitable for the hospital than the in-person modality, also encourages the hospital to adopt telemedicine.

The second condition is when the medical consumption difference is large, the effort cost is relatively low, and the reimbursement difference is small (i.e., $\delta > \tilde{\delta}$, $\gamma < \hat{\gamma}$, and $\eta < \tilde{\eta}$). This result is somewhat counterintuitive, given that the hospital can obtain a greater benefit from the in-person patients' medical consumption without devoting substantial effort costs. The reason for this result is that the large medical consumption difference and the small reimbursement difference jointly lead to a high demand for telemedicine. When the effort cost to reduce infection risk is low, the hospital can exert more effort to retain its in-person patients and thus can achieve economies of scale for the two service modalities. As a result, introducing telemedicine is the best choice for the hospital in response to the pandemic under such conditions. However, when the effort cost is relatively high, the hospital's effort to reduce infection is quite limited, and the demand for telemedicine is further increased to a high level. Recall that serving patients in person is more profitable for the hospital here. Faced with many patients switching to seek care via telemedicine in this situation, the hospital is incentivized to exclude the telemedicine modality and prompt as many patients as possible to seek care in person. This is also consistent with the reality that telemedicine is not widely adopted by hospitals around the world even with the COVID-19 pandemic. Proposition 3 provides managerial insights for hospitals on whether to introduce telemedicine when the pandemic emerges.

Additionally, we analyze the impact of the pandemic on the total costs of the hospital with telemedicine by comparing the case without the pandemic to the case with the pandemic under the context of introducing telemedicine (i.e., Case AN vs. Case AY), and summarize results in the following proposition.

Proposition 4. *After the introduction of telemedicine, the outbreak of the pandemic still leads to an increase of the hospital's total costs (i.e., $C^{\mathrm{AN}} \leq C^{\mathrm{AY}}$) if the medical consumption difference δ, the infection-reduction effort cost γ, and the reimbursement difference η satisfy:* (1) $\delta < \frac{\beta_{\mathrm{I}}(\alpha+2t-2u)}{2(u+t)\beta_{\mathrm{T}}-\alpha\beta_{\mathrm{T}}-2r\theta}$, $\gamma > \bar{\gamma}$ *and* $\eta > \bar{\eta}$, *or* (2) $\delta > \frac{\beta_{\mathrm{I}}(\alpha+2t-2u)}{2(u+t)\beta_{\mathrm{T}}-\alpha\beta_{\mathrm{T}}-2r\theta}$ *and* $\gamma > \bar{\gamma}$*; otherwise, the outbreak of the pandemic contributes to the reduction of the hospital's total costs.*

When the telemedicine service is available for patients, the presence of the pandemic still increases in the hospital's total costs under some conditions, as described in Proposition 4 and Fig. 2. Specifically, when the medical consumption difference is small but both the effort cost and the reimbursement difference are large, the hospital suffers an increase in its total costs. As discussed



(a) Low medical consumption difference ($\delta = 0.4$) (b) High medical consumption difference ($\delta = 1.5$)

Fig. 2. The impact of the pandemic on the total costs of the hospital with telemedicine.

above, both the small consumption difference and the large reimbursement difference can jointly prompt patients to seek care in person. However, the small consumption difference and the high effort cost mean that when serving patients in person, the hospital not only obtains low revenue but also needs to suffer more effort costs to reduce the infection risk of these in-person patients. When faced with a relatively low demand for telemedicine service, the hospital also cannot profit from serving telemedicine patients, ultimately leading to an increase in its total costs. Besides, when the medical consumption difference and the effort cost are both large, the hospital's total costs also increase. This is because the large medical consumption difference prompts more patients to seek care via telemedicine, which allows them to enjoy low medical expenses. Such patient behavior leads to low demand for in-person services but high demand for telemedicine services. That is, the hospital here has to face a situation in which the in-person modality is more profitable but has less demand, while telemedicine is less profitable but has high demand. Consequently, the hospital cannot benefit substantially from serving patients to recoup its input costs. Furthermore, the high effort cost also increases the total costs of the hospital. Proposition 4 provides managerial insights for hospitals on how to operate during the pandemic, for example, taking suitable measures to reduce infection risk for patients.

6. Analysis of Pandemic Effect and Telemedicine Option

In this section, we first explore the impact of the pandemic and telemedicine on the hospital's capacity and effort decisions. Then, we investigate how social welfare is influenced by the pandemic and telemedicine from the perspective of the social planner. Note that the term "social planner" represents organizations (e.g., the government) that care about the welfare of the whole society including all patients and the hospital. Such an investigation helps provide guidelines for these organizations to make policies for telemedicine, for example, whether they should allow telemedicine to be introduced by the hospital. Finally, we conduct a case study to evaluate the impact of the pandemic and telemedicine on the equilibrium strategy of the hospital and the social planner.

6.1. Impact on decisions of the hospital

In this subsection, we ascertain the impact of the pandemic and telemedicine on hospital's decisions making. We first explore the impact of the pandemic on the hospital's decisions in two settings, that is, without and with telemedicine. By comparing the cases with and without the pandemic in settings of without and with telemedicine (i.e., Cases BY vs. BN and Cases AY vs. AN), respectively, we obtain results about the impact of the pandemic on the hospital's decisions, which are summarized in Proposition 5.

Proposition 5. *Given the medical consumption difference δ, the reimbursement difference η, and the infection-reduction effort cost γ, the presence of the pandemic has the following impact on the hospital's optimal in-person (μ_{I}) and telemedicine (μ_{T}) capacities:*

(1) *without telemedicine, $\mu_{\mathrm{I}}^{\mathrm{BN}} \leq \mu_{\mathrm{I}}^{\mathrm{BY}}$ if $\gamma < \frac{\alpha\theta(v+u)}{2rt}$ and $\delta \geq \sqrt{\frac{\beta_{\mathrm{I}}\gamma t^2}{\alpha\theta^2(v+u)-2\gamma rt\theta}}$; otherwise, $\mu_{\mathrm{I}}^{\mathrm{BN}} > \mu_{\mathrm{I}}^{\mathrm{BY}}$,*

(2) *with telemedicine, $\mu_{\mathrm{I}}^{\mathrm{AN}} < \mu_{\mathrm{I}}^{\mathrm{AY}}$ and $\mu_{\mathrm{T}}^{\mathrm{AN}} > \mu_{\mathrm{T}}^{\mathrm{AY}}$ if $\delta > \sqrt{\frac{\beta_{\mathrm{I}}(t-u)}{\beta_{\mathrm{T}}(t+u)+\theta(1-r)}}$, $\eta > \ddot{\eta}$, and $\gamma < \ddot{\gamma}$; otherwise, $\mu_{\mathrm{I}}^{\mathrm{AN}} \geq \mu_{\mathrm{I}}^{\mathrm{AY}}$ $\mu_{\mathrm{T}}^{\mathrm{AN}} \leq \mu_{\mathrm{T}}^{\mathrm{AY}}$.*

From Proposition 5, we observe that the hospital does not necessarily decrease its in-person capacity when the pandemic arrives, regardless of whether telemedicine is introduced, which is contrary to the public's expectations. We explain this result through the following logic. From the definition of patient utility in our paper, we can infer that the demand for in-person services will be reduced in the presence of the pandemic. Faced with a smaller market, when the effort cost is sufficiently low, the hospital is encouraged to not only exert relatively high effort to recover some in-person patients but also increase the in-person capacity to raise its marginal revenue, especially when the medical consumption difference is large. As a result, the hospital gains more revenue and ultimately minimizes its total costs when the pandemic is present. However, after the introduction of telemedicine, the low effort cost and the large consumption difference are no longer sufficient to incentivize the hospital to increase its in-person capacity. An additional condition that the reimbursement difference is relatively large, is required for the hospital to do so, in addition to the two conditions. This is because the reimbursement difference can influence patients' choices regarding the two service modalities. A large reimbursement difference means that the health insurer prefers to limit the use of telemedicine, which leads to high demand for in-person services. As a result, the hospital will increase its in-person capacity in response to such a situation. Proposition 5 is intended to provide insights on hospital operation management to respond to the prevalence of the pandemic for the hospital, with or without telemedicine.

Next, we investigate the impact of telemedicine on the hospital's decisions under two settings, that is, without and with the pandemic. By comparing the cases with and without telemedicine in settings of without and with the pandemic (i.e., Cases AN vs. BN and Cases AY vs. BY), respectively, we obtain results about the impact of telemedicine on the hospital's decisions, listed in the following proposition.

Proposition 6. *Given the medical consumption difference δ, the reimbursement difference η, and the infection-reduction effort cost γ, the introduction of telemedicine has the following impact on the hospital's in-person capacity (μ_{I}) and effort (e):*

(1) *in the absence of the pandemic, $\mu_{\mathrm{I}}^{\mathrm{BN}} > \mu_{\mathrm{I}}^{\mathrm{AN}}$,*

(2) *in the presence of the pandemic,*

(a) $\mu_{\mathrm{I}}^{\mathrm{BY}} > \mu_{\mathrm{I}}^{\mathrm{AY}}$ *if one of the following conditions holds:* (i) $\delta < \delta_a$ *and* $\gamma > \gamma_a$, (ii) $\delta_a < \delta < \delta_b$, $\eta < \eta_a$ *and* $\gamma > \gamma_a$, (iii) $\delta_a < \delta < \delta_b$, $\eta > \eta_a$ *and* $\gamma_b < \gamma < \gamma_a$, *and* (iv) $\delta > \delta_b$ *and* $\gamma_b < \gamma < \gamma_a$; *otherwise,* $\mu_{\mathrm{I}}^{\mathrm{BY}} \leq \mu_{\mathrm{I}}^{\mathrm{AY}}$,

(b) $e^{\mathrm{BY}} < e^{\mathrm{AY}}$ *if* $\gamma < \gamma_c$ *and* $\eta < \eta_b$; *otherwise,* $e^{\mathrm{BY}} \geq e^{\mathrm{AY}}$.

Two important implications can be observed from Proposition 6. First, in the presence of the pandemic, the introduction of telemedicine can increase in-person capacity under certain conditions, which is somewhat counterintuitive. Among these conditions, the most surprising is that when the medical consumption difference is moderate, the reimbursement difference is large and the effort cost is high. We explain this result through the following logic. As discussed above, the high reimbursement difference will lead to relatively high demand for in-person services. The not small medical consumption difference, together with the high demand for in-person services, encourages the hospital to increase its in-person capacity, which further increases the marginal revenue of the in-person services. As such, the hospital can obtain high revenue, enough to cover the high effort cost. Second, even with the introduction of telemedicine, the hospital still chooses to exert more effort to reduce patients' infection risk when the effort cost and the reimbursement difference are both small. The reason for this result is that the low reimbursement rate causes low demand for in-person services, which prevents the hospital from achieving economies of scale for this type of services. However, the low effort cost provides incentives for the hospital to attract some in-person patients by exerting more effort. As a result, the hospital can achieve economies of scale in both services and thereby decrease its total costs. Proposition 6 provides guidelines for the hospital on how to change its capacity and effort decisions in response to the introduction of telemedicine with and without the pandemic.

Thus far, we have investigated the impact of the pandemic and telemedicine on the hospital's decisions. To provide a more intuitive presentation of the theoretical results in Propositions 5–6, we summarize these main findings in Table 3. Through horizontal comparison of the four cases in the table, we can easily obtain the impact of the pandemic on the hospital's decisions without and with telemedicine. By comparing these results on the impact of the pandemic between without and with telemedicine, we find that the hospital may reduce in-person capacity when the pandemic emerges in both settings. Through vertical comparison of the four cases in the table, we can determine the impact of telemedicine on the decisions of the hospital in the presence and absence of the pandemic. Similarly, by comparing these results on the impact of telemedicine without and with the pandemic, we find that the hospital using telemedicine may increase in-person capacity during the pandemic, which differs from the result in the absence of the pandemic. This result derives from the expansionary impact of the pandemic on in-person capacity, as mentioned above.

Table 3. Summary of the impact of the pandemic and telemedicine on decisions of the hospital.

	With no pandemic (N)	With the pandemic (Y)	Impact of the pandemic
Without telemedicine (B)	Case BN ($\mu_{\mathrm{I}}^{\mathrm{BN}}$)	Case BY ($\mu_{\mathrm{I}}^{\mathrm{BY}}$, e^{BY})	$\mu_{\mathrm{I}}^{\mathrm{BY}} > \mu_{\mathrm{I}}^{\mathrm{BN}}$ if the effort cost is low and the medical consumption difference is large, otherwise, $\mu_{\mathrm{I}}^{\mathrm{BY}} \leq \mu_{\mathrm{I}}^{\mathrm{BN}}$.
With telemedicine (A)	Case AN ($\mu_{\mathrm{I}}^{\mathrm{AN}}$, $\mu_{\mathrm{T}}^{\mathrm{AN}}$)	Case AY ($\mu_{\mathrm{I}}^{\mathrm{AY}}$, $\mu_{\mathrm{T}}^{\mathrm{AY}}$, e^{AY})	$\mu_{\mathrm{I}}^{\mathrm{AY}} > \mu_{\mathrm{I}}^{\mathrm{AN}}$ and $\mu_{\mathrm{T}}^{\mathrm{AY}} < \mu_{\mathrm{T}}^{\mathrm{AN}}$ if the differences in medical consumption and reimbursement are both large but the effort cost is low, otherwise, $\mu_{\mathrm{I}}^{\mathrm{AY}} \leq \mu_{\mathrm{I}}^{\mathrm{AN}}$ and $\mu_{\mathrm{T}}^{\mathrm{AY}} \geq \mu_{\mathrm{T}}^{\mathrm{AN}}$.
Impact of telemedicine	$\mu_{\mathrm{I}}^{\mathrm{AN}} > \mu_{\mathrm{I}}^{\mathrm{BN}}$ for any given medical consumption difference and reimbursement difference.	(1) $\mu_{\mathrm{I}}^{\mathrm{AY}} < \mu_{\mathrm{I}}^{\mathrm{BY}}$ (i) when the effort cost is high, if the medical consumption difference is small, or the medical consumption difference is moderate and the reimbursement difference is small, or (ii) when the effort cost is moderate, if the medical consumption difference is moderate and the reimbursement difference is large, or the medical consumption difference is large; under the other conditions, $\mu_{\mathrm{I}}^{\mathrm{AY}} \leq \mu_{\mathrm{I}}^{\mathrm{BY}}$, (2) $e^{\mathrm{AY}} > e^{\mathrm{BY}}$ if the effort cost and the reimbursement difference are both large, otherwise, $e^{\mathrm{AY}} \leq e^{\mathrm{BY}}$.	—

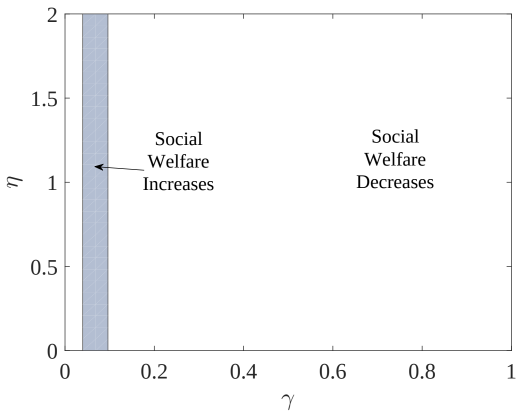
6.2. *Social welfare*

In this subsection, we turn to explore the equilibrium strategy of the social planner by investigating the impact of telemedicine on the social welfare S that takes both the total patient utility and the service accessibility into consideration (Guo et al., 2018) in addition to the hospital's total costs. That is, we model the social welfare by considering the following three factors: (i) the utility U_i ($i = \mathrm{I}, \mathrm{T}$) associated with each patient seeking care with modality i, (ii) an additional cost φ for each patient who balks, and (iii) the total costs C incurred by the hospital. Specifically,

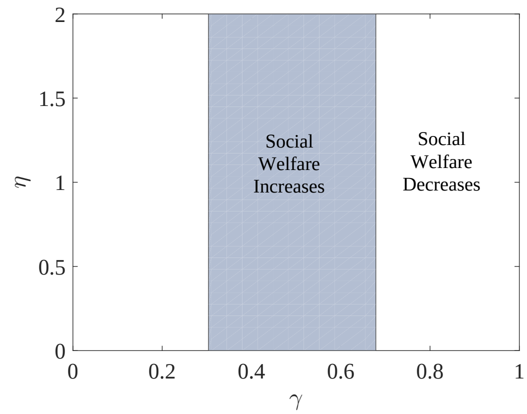
$$S = \int_0^{\lambda_{\mathrm{I}}} U_{\mathrm{I}}(x)\mathrm{d}x + \int_{1-\lambda_{\mathrm{T}}}^{1} U_{\mathrm{T}}(x)\mathrm{d}x - (1 - \lambda_{\mathrm{I}} - \lambda_{\mathrm{T}})\varphi - C. \tag{4}$$

Similarly, we first investigate the impact of the pandemic on the social welfare and then come to study the equilibrium strategy of the social planner on telemedicine. For a more intuitive presentation, we numerically investigate the impact of the pandemic and telemedicine on the social welfare S and describe results in Figs. 3 and 4 (we set $\varphi = 0.2$).

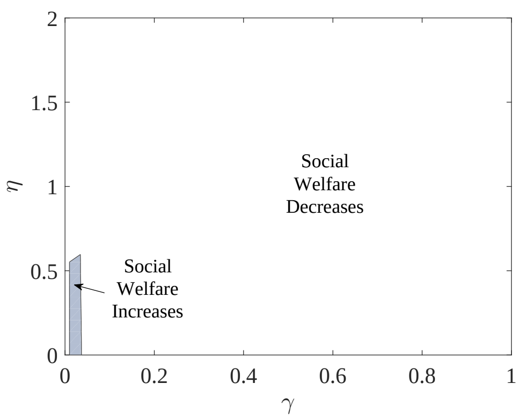
As shown in Fig. 3, the brunt of the pandemic indeed almost always produces disutility on social welfare, however, there are conditions under which social welfare can be improved as the pandemic



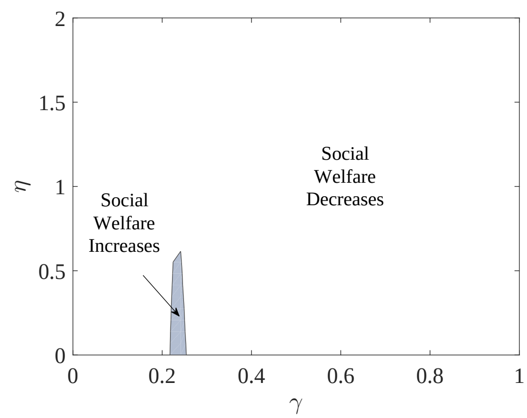
(a) Low medical consumption difference ($\delta = 0.4$) without telemedicine



(b) High medical consumption difference ($\delta = 1.5$) without telemedicine



(c) Low medical consumption difference ($\delta = 0.4$) with telemedicine

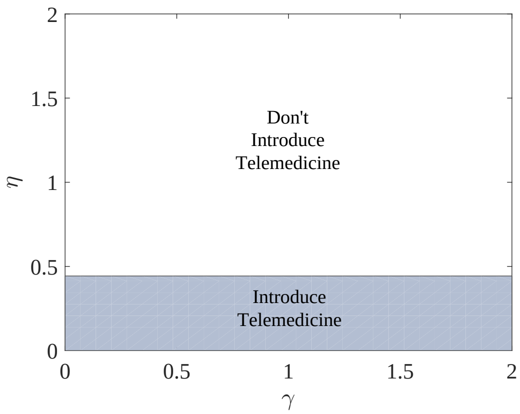


(d) High medical consumption difference ($\delta = 1.5$) with telemedicine

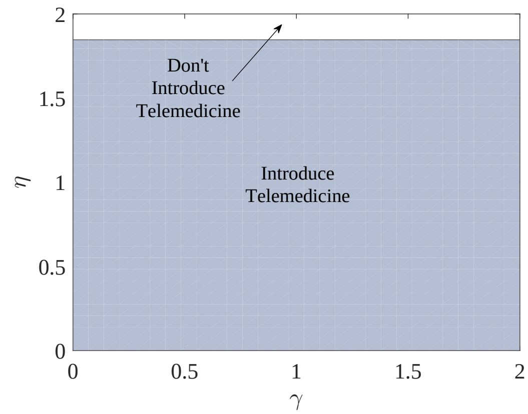
Fig. 3. The impact of the pandemic on social welfare.

arrives. To be specific, in the setting of without telemedicine, the condition is when the effort cost is in a medium size, whereas in the setting of with telemedicine, the condition changes into that when the effort cost is in a relatively medium size and the reimbursement difference is small. This is because in this situation, the hospital achieves the reduction of the total costs by adjusting its capacities and effort level (highlighted in Propositions 2 and 4), and such reduction in total costs dominates the decrease of total patient utility due to the presence of the pandemic. As a result, the social welfare increases in such conditions.

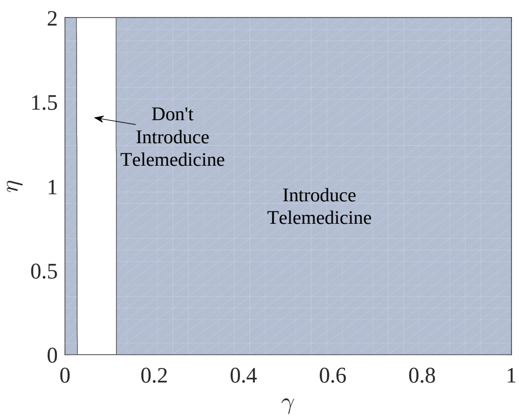
Fig. 4 articulates the equilibrium strategy of the social planner regarding whether to introduce telemedicine. A counterintuitive result is that in the presence of the pandemic, the region where the social planner is advised to introduce telemedicine is reduced as the medical consumption difference increases. This is because the large medical consumption difference represents a high marginal revenue of the in-person modality, which implies that the introduction of telemedicine will reduce the hospital's revenue and thus increase its total costs. Such an increase in the total costs of the hospital exceeds the increase in patient utility caused by the introduction of telemedicine.



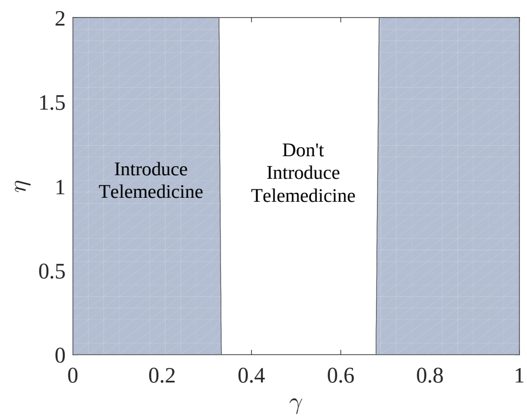
(a) Low medical consumption difference ($\delta = 0.4$) without the pandemic



(b) High medical consumption difference ($\delta = 1.5$) without the pandemic



(c) Low medical consumption difference ($\delta = 0.4$) with the pandemic



(d) High medical consumption difference ($\delta = 1.5$) with the pandemic

Fig. 4. The equilibrium strategy of the social planner on telemedicine.

Consequently, the region to introduce telemedicine becomes smaller as the medical consumption difference increases.

6.3. Case study

In this subsection, we conduct a case study using data from a cardiovascular hospital in Tianjin, China. The purpose of the case study is to verify the main analytical results and to further explore the managerial insights. Our case study examines the joint impact of the medical consumption difference δ, the infection-reduction effort cost γ and the reimbursement difference on the equilibrium telemedicine strategy of the hospital and the social planner.

Other basic parameters are set as follows: according to the data we collect from the hospital, the total investment cost for in-person capacity is CNY 1.51 million, and that for telemedicine capacity is CNY 14.9 million. Furthermore, from the data, we calculate that the average visit time of in-person patients is 30.88 minutes and that of telemedicine patients is 19.75 minutes. There are 18 physicians in the outpatient department. Though the formulation of the capacity cost $\frac{\beta_i \mu^2}{2}$, we obtain the cost factors $\beta_{\mathrm{I}} = 2468.96$ and $\beta_{\mathrm{T}} = 9965.59$. Moreover, using data from the survey, we infer that the medical consumption cost of the telemedicine modality is 1132.8/hour. As a result, we set $\rho_{\mathrm{I}} = 1132.8\delta$ and $\rho_{\mathrm{T}} = 1132.8$. According to an interview we conducted with the head of the hospital, we know that the hospital's revenue rate from medical consumption is 0.01 and its market size for chronic outpatient care is approximately $10,000$ such that we set $\theta = 0.01$ and $\Lambda = 10,000$. Furthermore, from the survey we conducted in the hospital, we determine that the reimbursement rate r for patients with chronic diseases is 50%. We use the average cost to cure an infected patient to represent the unit risk cost for in-person patients α, which is estimated to be CNY $10,234.12$.[9] Following Rajan et al. (2013) and taking the inconvenience of patients with chronic diseases into consideration, we set the unit mismatch cost to be $t = 15,000$. To satisfy the assumptions that $t > |\alpha - u|$ and the market is partially covered before the introduction of telemedicine but fully covered thereafter, we set the difference in service value $u = 1,000$ and the service value $v = 14,000$. In the analysis of social welfare, we set the additional cost for each patient who balks to be $\varphi = 2000$. Based on these parameters, after solving the models, we analyze the equilibrium telemedicine strategy of the hospital and the social planner.

As shown in Fig. 5, we find that results regarding the hospital's equilibrium strategy on telemedicine drawn from this figure are consistent with the previous statements. Specifically, in the absence of the pandemic, the hospital should introduce telemedicine when the reimbursement difference is relatively small. In the presence of the pandemic, the introduction of telemedicine is not always beneficial for the hospital. Fig. 6 shows the equilibrium telemedicine strategy of the social planner, from which we can infer that social welfare can be improved by introducing telemedicine under certain conditions both without and with the pandemic.

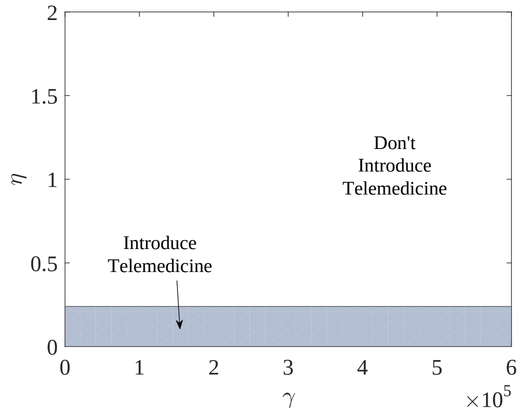
7. Extensions

In this section, we extend our results by altering some assumptions in our focal model. All proofs of the results are provided in Appendix D.

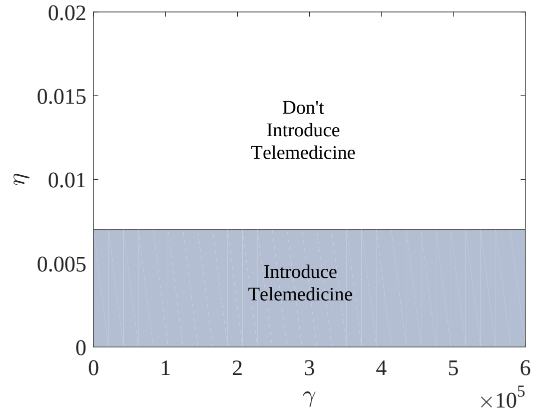
7.1. Nonlinear function for medical consumption cost

In this subsection, we extend the aforementioned expression of the medical consumption cost fell on patients to examine whether our main results remain unchanged. Concretely, we adopt $m(\mu_i) = \rho_i\sqrt{\mu_i} + F$, $i \in \{\mathrm{I}, \mathrm{T}\}$ to model the medical consumption cost, where F represents the fixed medical consumption cost afforded by each patient. The results of the analysis show that our main conclusions can still hold (see Appendix D.1). To be specific, the introduction of telemedicine may generate a loss for the hospital regardless of whether with the pandemic prevailing or not. And the hospital adopting telemedicine may increase in-person capacity but decrease telemedicine capacity as the pandemic emerges. Finally, we find that social welfare can be improved by introducing telemedicine under some conditions.

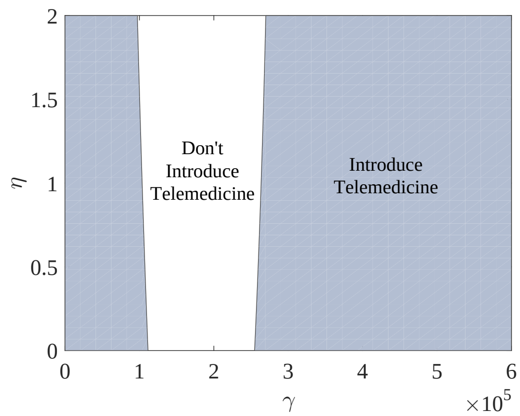
[9]Source: http://www.jlio.gov.cn/index.php/xwfb/szfxwfbh/17432-2020-02-18-03-06-33.html.



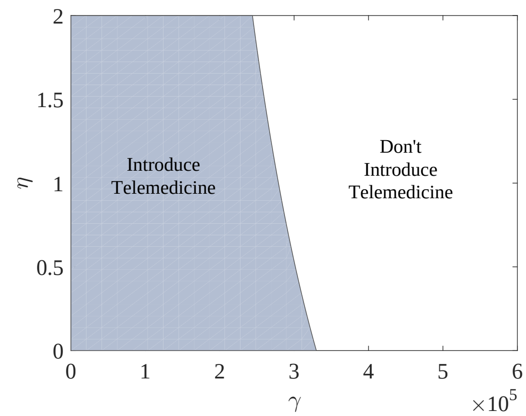
(a) Low medical consumption difference ($\delta = 0.4$) without the pandemic



(b) High medical consumption difference ($\delta = 1.5$) without the pandemic



(c) Low medical consumption difference ($\delta = 0.4$) with the pandemic



(d) High medical consumption difference ($\delta = 1.5$) with the pandemic

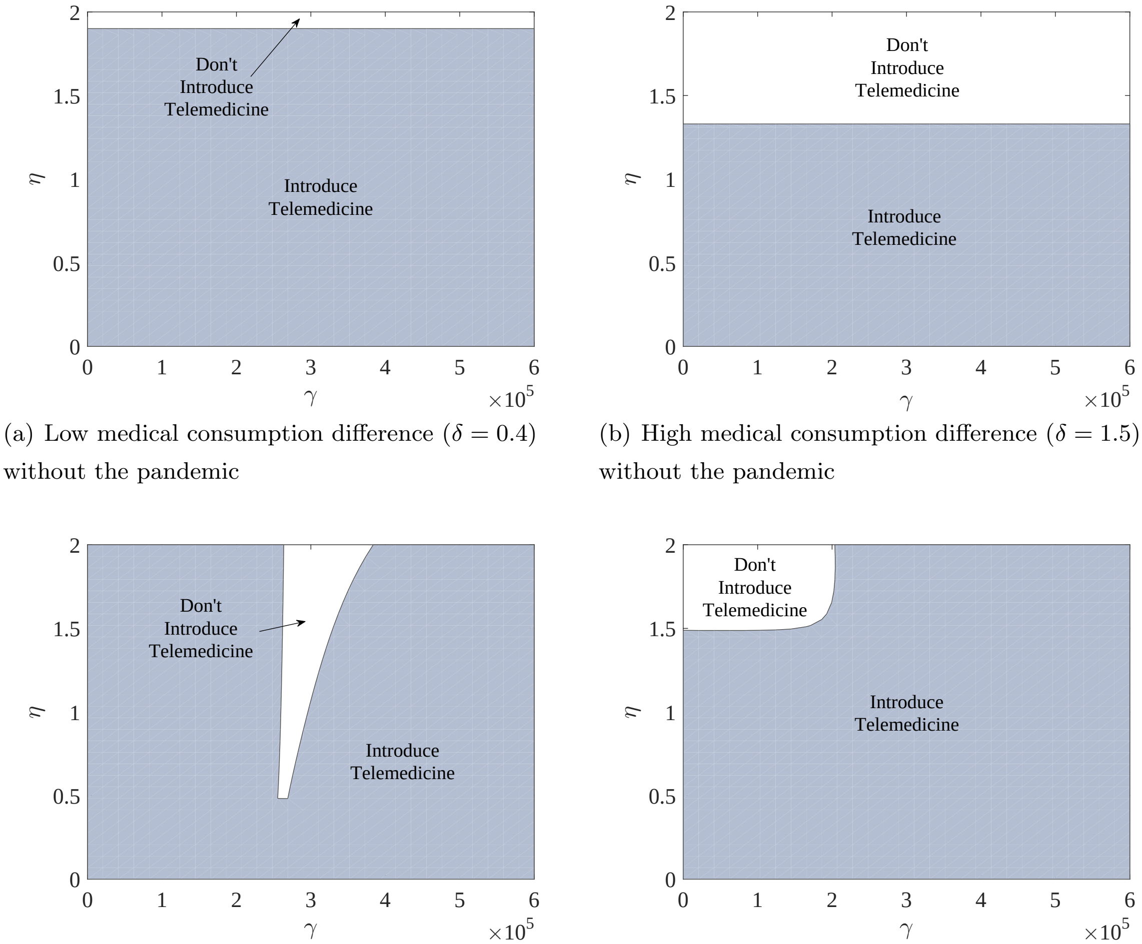
Fig. 5. The equilibrium strategy of the hospital on telemedicine.

7.2. Additional medical consumption of in-person patients in the presence of the pandemic

In this section, we take the additional medical resource consumption of in-person patients in the presence of the pandemic, for example, nucleic acid testing, into consideration. Specifically, we assume that patients seeking care in person have to consume a certain additional resource and incur a fixed monetary cost $p > 0$. We present relevant models and results in Appendix D.2, and find that our main results are robust. In addition, we find that the additional medical consumption of in-person patients enlarges the available region where the hospital is better not to introduce telemedicine. The reason behind this result is that the additional medical consumption gives the hospital another chance to increase its profits generated from serving in-person patients, which makes it no longer prefer for introducing telemedicine.

7.3. Nonlinear function for infection risk cost of patients

In the focal model, we assume that the infection risk cost of patients is linear in the hospital's infection-reduction effort. This section relaxes this assumption and examines a nonlinear function



(a) Low medical consumption difference ($\delta = 0.4$) without the pandemic

(b) High medical consumption difference ($\delta = 1.5$) without the pandemic

(c) Low medical consumption difference ($\delta = 0.4$) with the pandemic

(d) High medical consumption difference ($\delta = 1.5$) with the pandemic

Fig. 6. The equilibrium strategy of the social planner on telemedicine.

$\varphi(e) = \alpha(1 - e^2)$ to determine whether the main results are robust to the change of the function. Relevant models and solutions are presented in Appendix D.3. The results of the analysis show that our main conclusions remain intact. Specifically, in the absence of the pandemic, the hospital prefers to introduce telemedicine when the medical consumption difference is relatively small. However, in the presence of the pandemic, the introduction of telemedicine does not always benefit the hospital. And in response to the prevalence of the pandemic, the hospital may increase its in-person capacity but decrease its telemedicine capacity under certain conditions. Finally, we verify that social welfare can be improved by the introduction of telemedicine under some cases. In addition to verify the robustness of our main results, we also find that the region where the hospital should adopt telemedicine enlarges as we change the infection risk cost function into $\varphi(e) = \alpha(1 - e^2)$. This is because the infection risk cost becomes more difficult to be decreased in this setting, which means the hospital incurs more effort cost. Recall that serving patients via telemedicine does not incur such cost. As such, the hospital prefers to introduce telemedicine.

8. Conclusion and Future Research

The introduction of telemedicine has brought great changes to the operational decision-making of the medical system, and it also plays a great role in the prevention of infection for non-infected patients when a pandemic is prevailing. However, the adoption of telemedicine has not reached the expected level in practice. In this study, we develop a model to investigate the reason behind this observation and study the hospital's operation decisions in a market that may be hit by the pandemic. The hospital has to exert effort to prevent infection for their routine patients and may offer two service modalities, in-person and telemedicine, to serve these patients. Then, patients make choice between the two modalities based on their utilities including service value, mismatch cost, medical consumption cost, reimbursement, and the risk cost of infection.

By analyzing the model, we obtained the following findings. First, in the absence of the pandemic, the hospital will adopt telemedicine to serve patient when the differences in medical consumption and reimbursement are both relatively small. Second, the pandemic indeed almost always leads to an increase of the total costs of the hospital while it also has the potential to reduce the total costs under some cases. Furthermore, we find that the introduction of telemedicine is not always beneficial for mitigating the pandemic influence on the hospital's total costs as the public believes. Third, the pandemic does not necessarily prompt the hospital to shift from providing in-person services to telemedicine services. Instead, the hospital may set high effort level and high in-person capacity after the introduction of telemedicine as it takes the medical consumption difference, reimbursement difference and the infection-reduction effort cost into consideration. Fourth, we find that with the presence of the pandemic, if the infection-reduction effort cost and the reimbursement difference are both moderate, providing only in-person modality with patients is preferred by the social planner; otherwise, introducing telemedicine is beneficial for the whole society. And the region where social welfare is improved is decreasing with the medical consumption difference.

These findings provide the following managerial implications for hospital managers and social planners. We suggest that: (i) with no pandemic, the hospital can achieve its objective of reducing total costs by introducing telemedicine when the differences in medical consumption and reimbursement are both low; (ii) the hospital can benefit from the pandemic, that is, minimize its total costs, by selecting infection-reduction measures with low cost; (iii) when the medical consumption difference is small, the effort cost is sufficiently low or high, and the reimbursement difference is small, or when the medical consumption difference is large, the effort cost is relatively low, and the reimbursement difference is small, the hospital should implement telemedicine in response to the outbreak of the pandemic; (iv) the social planner should introduce telemedicine to respond to the pandemic when the infection-reduction effort cost and the reimbursement difference are both moderate; (v) the attitude of the health insurer indeed influences the hospital's choice on telemedicine, and thus, the health insurer can adjust its reimbursement rates to induce the hospital's choice regarding telemedicine.

This research can be extended in several possible directions. First, we focus on optimizing a hospital's resource allocation in a monopoly market. It would be significant to explore whether hospitals should introduce telemedicine in a duopoly market that may be affected by the pandemic. Second, we assume that patients in this healthcare market have homogeneous sensitivity to mismatch when choosing the service modalities. An interesting topic for future research would be to investigate the impact of telemedicine on hospitals' operations when some patients are loyal to either of the two service modalities, in-person or telemedicine. Third, in our paper, we focus on investigating the impact of the differences in medical consumption and reimbursement, and the infection-reduction effort cost on hospital's strategy on telemedicine, and we may omit some other elements, such as technological, organizational, human, and economic factors. Future works could take them into consideration. Fourth, our study assumes an exogenous health insurer, which can be relaxed by allowing the health insurer to strategically adjust its reimbursement rates for in-person and telemedicine patients according to the operations of the hospital.

Acknowledgements

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