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Coordinating Contracts in Value-Based Healthcare Delivery: Integration and Dynamic Incentives

Tannaz Mahootchi[a], Ignacio Castillo[b], Logan McLeod[b]

[a] *Northeastern University*
[b] *Wilfrid Laurier University*

Abstract

We study a value-based healthcare delivery system with two non-cooperative parties: a purchaser of medical services and an Integrated Practice Unit (IPU). The IPU is capable of providing all healthcare needs of patients with a specific medical condition (homogeneous patient population), is comprised of a multi-disciplinary team of providers, and is responsible for the health outcomes of the patients over the care cycle. The IPU chooses the treatment strategy, incurs the associated cost, and is paid by the healthcare purchaser. The treatment strategy critically determines the health outcomes of the patients. Assuming the existence of universal health insurance for the patient population, the healthcare purchaser's problem is to determine a payment scheme that will induce social welfare maximizing choices to the IPU. We use a dynamic continuous-time principal-agent model to capture the relationship between the purchaser and the IPU, and determine the optimal payment scheme, referred to as *dynamic outcome-adjusted payment*. The model characterizes the optimal payment scheme with a single variable. Previous value-based healthcare delivery principles suggest that the IPU should be reimbursed according to a "bundled payment." Our results suggest payment should depend on the history of health outcomes over the care cycle. The proposed payment scheme combines a bundled payment with a bonus payment for consistently producing superior outcomes. Our results suggest value could be improved by paying for health outcomes over the care cycle; thus supporting the value-based healthcare delivery objective of achieving healthier patients over time. Unlike other performance-based payment schemes, this scheme could result in a single-variable implementation.

JEL Classification: I12; I30; J44; C73

Keywords: value-based healthcare delivery; integrated healthcare delivery; universal health insurance; payment systems; coordinating contracts; dynamic incentives

1 Introduction and Motivation

A common criticism in many healthcare systems is their fragmentation, where care is delivered across specialty silos, and provided by physicians and non-physicians. Healthcare purchasers often rely on a fee-for-service payment mechanism to remunerate healthcare providers, which can result in the provision of uncoordinated and redundant services. The combination is one proposed reason for the increase in healthcare expenditures in the Organization for Economic Cooperation and Development (OECD) countries (Anderson and Hussey (2001), Anderson and Markovich (2011)). Across healthcare systems is a diverse arrangement of healthcare purchasers, varying from public single payer insurance to competing private insurance. However, common to all healthcare systems is the pressure to improve quality and access while containing expenditure growth.

To address these pressures, some healthcare systems are attempting to better integrate the delivery of healthcare. The approaches to integrated care delivery can vary in emphasis and focus. One approach entails contracts with individual providers; while another integrates care by encouraging the formation of new organizations of providers to deliver care to a defined population (Accenture (2012)). Independent of the approach, the objective of integrated care is to ensure the most appropriate and effective care is provided at the right time and in the right place, to improve the health outcomes of patients while controlling expenditures.

Central to any approach for better integration of healthcare delivery is the agency relationship between purchaser and provider. The purchaser of healthcare services (e.g. government) and a provider (e.g. single providers or teams of providers) enter into a contractual agreement where the provider delivers services to the purchaser's eligible population, and then receives reimbursement from the purchaser according to the contracted payment scheme. The purchaser and provider can have different and conflicting objectives. The healthcare purchaser's objective is to design a contract with incentives to the healthcare provider to take a set of desired actions, such as the treatment strategy to maximize the patient health outcomes.

In this paper, we focus on the value-based healthcare delivery initiative, which aims at bringing different provider types (physician and non-physician providers, across specialty silos) together to provide timely, coordinated, and seamless healthcare with the objective of improving the patient health outcomes (Porter and Guth (2012)). The tenets of value-based healthcare delivery suggest the relevant outcomes are the results of care over a disease cycle, rather than the results of a single individual intervention or visit. We assume providers are organized into teams (called an *Integrated Practice Unit*, or IPU) around specific medical conditions, and a medical condition encompasses common complications and co-occurring conditions. Thus, the IPU is able to jointly accept the responsibility for the outcomes.

Similar to Chalkley and Malcomson (2000), we use the term *contract* to refer to the payment scheme between the healthcare purchaser and the IPU. We will assume the existence of universal health insurance for the patient population; thus the healthcare purchaser's objective is to maximize health outcomes while containing expenditures. We refer to the contract that can *coordinate* the healthcare purchaser-IPU relationship as the *optimal contract* or *coordinating contract*. Thus, the coordinating contract allows each party to optimize their objective function while maximizing social welfare.

An immediate complication is the IPU's efforts are often *unverifiable* by the purchaser, since it is often not feasible for the purchaser to determine (ex ante) the type and quantity of care for every specific medical condition. And, it is often not feasible for the purchaser to determine whether the IPU met delivery specifications ex post. In this case, the IPU's actions are hidden from the purchaser.

We use a continuous-time, dynamic principal-agent model to understand the properties of the coordinating contract between a healthcare purchaser and an IPU over the care cycle under dynamic hidden action. To more clearly understand the properties, we focus on three specific research questions. First, if the purchaser is to pay a group of healthcare providers to work in coordination being accountable for patient health outcomes and expenditures, what should be the optimal payment scheme? Second, how the payment scheme would change in comparison to current payment schemes if the healthcare purchaser cared about the health outcomes over the care cycle for the patients? Finally, would a fixed fee covering the expenses over the care cycle called "bundled payment," support the objective of value provision for the patients?

Our results are relevant to a number of different types of healthcare systems. For example, the results are relevant to countries like Canada, United Kingdom, Australia, and Taiwan where there are established universal single-payer public health insurance for a specified package of benefits (Hsiou and Pylypchuk (2012); Buttigieg et al. (2015)). The results are also relevant when considering Medicare and Medicaid programs available in the Unites States. A similar reform to value-based healthcare delivery in the Unites States is the Patient Protection and Affordable Care Act of 2010, in which an Accountable Care Organization (ACO), a group of providers, accepts greater accountability for total costs and quality of care (Fisher et al. (2007); Afendulis and Kessler (2011)).

1.1 Outline of Model, Assumptions, and Results

The model for the purchaser-IPU system is an application of Sannikov (2008) and is presented in Section 2. It provides abstraction for the delivery of care to a patient suffering from a specific medical condition. The purchaser delegates the clinical decisions for the patient to the IPU, and the IPU specifies the treatment strategy, incurs the cost, and is paid by the purchaser according to a pre-specified agreement. The patient is not financially responsible to the IPU for the cost of treatments.

The IPU's efforts affect the health outcomes by modifying the probability of unavoidable complications for the patient. Treatments are costly and unverifiable to the purchaser. To motivate the IPU to take the actions desired by the healthcare purchaser, the purchaser must link the payments to the observed health outcomes, which are the stochastic signal of the IPU's actions. Furthermore, to incentivize the IPU to be accountable for the health outcomes over the disease cycle, the optimal payments to the IPU should be a function of the entire history of health outcomes.

Our main contribution is capturing the health outcomes over the care cycle and linking the payments to the history of health outcomes by using a continuous-time, dynamic principal-agent model. Using a continuous-time, dynamic principal-agent model, we are able to summarize this complex history dependence by one state variable: *continuation value* of the IPU. The continuation value reflects the likelihood of future payments to the IPU. Using the continuation value can arguably ease the implementation of the optimal contract since its evolution is the mirror of the health outcome dynamics. As a result, the continuation value could serve as the IPU's track record.

The analysis of the purchaser's problem, presented in Section 3, identifies the optimal contract referred to as *dynamic outcome-adjusted payment*. The results suggest that the purchaser can motivate the IPU by promising a lump sum money transfer after a good performance record and also by threatening to reduce his continuation value after failures.

The magnitude of the reduction in the IPU's continuation value depends on how serious the hidden action problem is. The more serious the hidden action problem is, the greater the reduction in the continuation value. With this mechanism, the IPU's continuation value will be sensitive to the failures. The optimal payment derived in this paper is different than a *bundled payment*, the payment model that the value-based healthcare delivery suggests can align the incentives to increase value of health outcomes, where a bundled payment is a single payment that covers all the procedures, tests, drugs, services during inpatient, outpatient, and rehabilitative care for a patient's medical condition (Porter and Kaplan (2014)).

1.2 Research Themes

This research relates to the literature on contract theory, healthcare contracting, and dynamic principal-agent models. There are two streams of research in contract theory. The first one focuses on hidden information, also known as adverse selection, where one party has better information than the other. An example of hidden information in the healthcare delivery context is when the distribution of risk categories in a heterogeneous population is not observable by the healthcare purchaser. Hidden information studies in healthcare aim at finding incentive compatible contracts to reduce inefficiencies (Boadway et al. (2004); Jack (2005); Zweifel and Tai-Seale (2009)). The second stream of research concentrates on the inefficiencies caused by hidden actions where one party's efforts are not verifiable by the other party.[1] Hidden action occurs when monitoring the actions of providers is either too costly or not possible; thus the healthcare purchaser cannot observe the provider's actions, treatment intensity, or the quality of the delivered care (Ma (1994); Ma and McGuire (1997); Fuloria and Zenios (2001); Jack (2005); Kaarboe and Siciliani (2011)). When one party hires another party to take some action for her as her agent, there should be a contract among the entities that can mitigate difficulties cause by hidden action or hidden information. The contract design problem is known as *principal-agent problem* (Mas-Colell et al. (1995)). The problem of hidden action can be tackled by a contract that links the agent's performance to the output of his work. Inefficiencies can arise when the agent's performance measure is distorted, for example when it cannot incorporate time lags and interdependency.

Several payment options have been proposed and implemented for healthcare systems over the past few decades (Ma (1994); Newhouse (1996); Ma and McGuire (1997); Rosenthal et al. (2004)). These payment systems affect physicians behavior, the quality of care received by patients, and healthcare costs.

A payment scheme, such as fee-for-service, is easy to implement and manage, but can be a source of inefficiency in the system since the scheme only rewards the volume of care and not the health outcomes associated with it. Empirical evidence suggest that physicians that are paid by fee-for-service provide more consultation and order more diagnostic tests than the physicians that are not paid by fee-for-service (Gosden et al. (2000); Allard et al.

[1] In the contract theory literature, the term "moral hazard" has been used extensively to describe the problem where the efforts are not verifiable (Grossman and Hart (1983); Mas-Colell et al. (1995); Bolton and Dewatripont (2005); Eisenhauer (2006)). Here, we will use the term hidden action to indicate the same problem.

(2014)). An alternative payment system that can control the costs is capitation. While a capitation payment scheme encourages physicians to keep their patients healthy, it creates incentives for physicians to systematically select patients who are healthier and require less care in the future (Léger et al. (2011)). Moreover, capitation payments mainly cover primary care services and exclude specialty or hospital care. As a result, if a primary care physician refers a patient to a specialist or to a hospital, the primary care physician can keep the capitation fee and without needing to provide the care. In addition, physicians may underreport patients' illness to them or even not reveal all possible treatments (Ellis and McGuire (1986, 1990); Hauck et al. (2002); Allard et al. (2014)). With a capitation payment scheme, the provider's income depends on the assigned patient population's healthcare usage, consequently capitation might result in less accessible care or less than efficient quality of care (Léger et al. (2011)). None of these two payment schemes, i.e. fee-for-service and capitation, motivate physicians to improve health outcomes and reduce the costs simultaneously, which is generally what patients and policy-makers desire. Not surprisingly, the issues of poor health outcomes are ample in healthcare systems. Unacceptable health outcomes and increasing healthcare expenditures are pushing governments to examine quality and provide suggestions for its improvement (Institute of Medicine (2001); CIHI (2013)).

In response to quality issues, changes to the payment schemes have been proposed to reward appropriate and high-quality care (Institute of Medicine (2007)). This type of payment scheme is known as pay-for-performance. Proposals for implementing pay-for-performance payment schemes vary from rewarding the providers for their processes Lee and Zenios (2012) (how things are done) to the patients' health outcomes (the effectiveness of treatments). Despite the promising benefits of pay-for-performance schemes, their implementation faces several significant challenges (Rosenthal et al. (2004); Maynard (2012)). Among these challenges is the problem of "multitasking;" that is if the providers face several tasks and their resources are limited, then their effort will be allocated toward explicitly rewarded tasks. Tying remuneration to processes is administratively easy to implement, but might create unwanted results by encouraging the providers to concentrate on the processes that are targeted and ignore the processes that are not. On the other hand, pay-for-performance schemes tied to patients' outcomes are not easy to implement. First, measuring health outcomes is not trivial. Second, in the current healthcare delivery structure, there is no way to isolate the individual provider's contribution to the patients' health outcomes (Léger et al. (2011)).

To implement The Patient Protection and Affordable Act of 2010, Centers for Medicare & Medicaid Services (CMS) is encouraging the providers to join together and form ACOs and changing how they reimburse providers. However, an ACO could implement a diverse range of delivery and payment models including capitation, bundled payment, and shared saving (McClellan et al. (2010)). Also, still it is unclear how the Accountable care Organizations should be structured and implemented to deliver quality care and control expenditures (Shields et al. (2011)). A recent agent-based simulation study identifies the different aspects and challenges in implementing ACOs using shared savings model (Liu and Wu (2014)). What Liu and Wu (2014) shows is the success of an ACO is related to the payment model design, provider characteristics, and cost and effectiveness of healthcare interventions.

This research contributes to the body of healthcare contracting by designing a dynamic contract between the healthcare purchaser and the team of providers, whom are collectively responsible for the health outcomes of patients over the care cycle. Several authors have captured the importance of using dynamic contracts. Among these, Radner (1985) shows that it is possible to achieve efficiency in long-term contracts by aggregating outcomes over several periods. The aggregation would allow to form better statistics about the agent's efforts, only if the agent becomes more patient. In another study, Fudenberg et al. (1990) show in several settings that it is possible to use agent's wealth as a proxy for agent's performance history in order to implement the optimal contract. The insight from these studies suggest that a firm's financial slack can summarize past performance. The firm's management team is typically modeled as one agent. Our study similarly models the IPU as one agent in the principal-agent model.

The characterization of the optimal contracts in dynamic settings is a challenging task. Describing the state of the problem is complex. The agent's compensation can be a function of the entire performance history. Additionally, the principal-agent problem is composed of one dynamic optimization problem embedded in another. The principal is optimizing her objective, realizing that the agent is looking for the optimum dynamic effort strategy to maximize his objective as well. Our research belongs to the growing literature on dynamic hidden action (moral hazard) problems that employs recursive techniques.

Solving a discrete-time dynamic principal-agent model problem is a daunting task and requires several assumptions to derive tractable results. In the context of healthcare delivery, Fuloria and Zenios (2001) find an outcome-adjusted payment that maximizes societal welfare. Such payment schemes can potentially make significant improvements, however the implementation of the resulting contract requires accurate information about the treatment technology, patient characteristics, and the provider preferences (Fuloria and Zenios (2001)). Fuloria and Zenios (2001) assume the patient will be treated out of the system for any occurrences of complications; that is, the provider is *not* responsible for the health outcomes. Moreover, to derive a tractable solution they make several strong assumptions, such as unrestricted access to a bank for the provider and the use of an exponential utility function. In contrast, the method we use to characterize the optimal value-based dynamic contract between the healthcare purchaser and the team of providers, whom are collectively responsible for the health outcomes of patients over the care cycle, originates from the literature on continuous-time contracting, mainly Sannikov (2008) and Schaettler and Sung (1993). In continuous-time, the solution can be characterized by ordinary differential equations using optimal stochastic control. This method benefits from tractability, due to the differential equation that characterizes the optimal contract, and computing power.

The continuous-time principal-agent model has been extensively studied in corporate finance applications, for examples see DeMarzo and Sannikov (2006); Biais et al. (2007, 2010); DeMarzo et al. (2012).

The remainder of this paper is organized as follows. We detail the model and formulate a principal-agent model to determine a set of incentive-compatible coordinating contracts to be offered to the IPU in Section 2. We characterize the optimal contract and explain its implementation in Section 3, and discuss future extensions and conclusions in Section 4.

2 The Model

Our health could be broadly defined as longevity and illness-free days in a given year (Grossman (2000)). Good health has positive social value for two reasons. First, health provides positive utility for patients. Second, better health increases the total amount of time available for market and nonmarket activities (Grossman (2000)). Health outcomes depend on many factors, including medical care. Grossman defines "The Human Capital Model" to demonstrate the importance of many inputs that go into the production of health along with medical care. He relates the output of health to choice variables like diet, exercise, medical care utilization, healthy habits, education, and also the medical care the patient receives from the providers (Grossman (2000)).

In our model, we will control for the patient risk factors. We assume the IPU is treating a homogeneous patient population for a specific medical condition. We also assume the existence of universal health insurance for the patient population. Hence, if the patients need care there are no monetary obstacles for utilizing the health services. Therefore, we can assume the health outcomes critically depend on the appropriateness or quality of the care provided. Appropriateness of care can have many aspects, including receiving the right medical treatment and being treated in an understanding way (Chalkley and Malcomson (2000)). In the healthcare literature, terms like intensity or quality have been used to capture the concept of appropriateness. We will refer to all these aspects of care as quality of service. Quality of service is defined as any aspect of service that benefits the patients whether during the process of treatment or after the treatment.

There are two players in this context, the healthcare purchaser and the IPU. Recall that an IPU is a team of providers formed around medical conditions to provide all the necessary care and is accountable for the health outcomes of a patient during the disease care cycle. A medical condition is an interrelated set of patient medical circumstances that includes common co-occurring conditions and complications, and requires multiple specialties and services to best address the disease from the patient's perspective. We will assume that an IPU has unique necessary skills to treat the patients. However, treatments are costly and the IPU has limited liability. By contrast, under universal health insurance, the healthcare purchaser has unlimited liability and is able to cover the costs. The two players are assumed to be risk-neutral. Time is continuous and treatments are provided over the care cycle, T. The purchaser discounts the future payoffs at rate r and the IPU discounts the future payoffs at rate $\gamma > r$, i.e. the IPU is less patient than the purchaser. This assumption rules out the possibility of indefinitely postponing the payments to the IPU. Without loss of generality, we normalize the fixed cost of forming an IPU to 0.

Health outcomes are the result of care in terms of patients' health over time. Health outcomes have been defined as survival, prevention of illness, early detection, right diagnosis, right treatment to the right patient, fewer avoidable complications, greater functionality, slower disease progression, and less care induced illnesses (Porter (2010)).

Although we are aware of the multi-dimensionality of the health outcomes (Dowd et al. (2014)), in this research we will focus on one of its dimensions to demonstrate the dynamic coordinating contract between the purchaser and the IPU that can improve value provision. Similar to Grossman (2000), we will use the "number of illness-free days in a given year" as the indicator of health outcomes.

As mentioned before, we assume the IPU is treating a homogeneous patient population with similar risk factors and thus we can fairly assume the value of functional days per

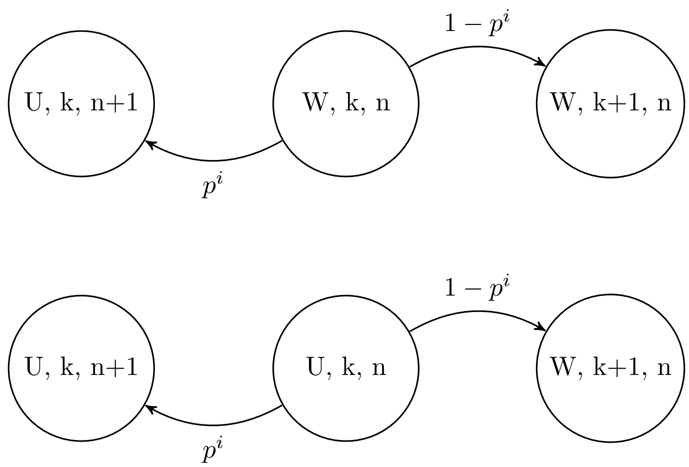

Figure 1: Problem state: patient status (W or U), number of successes (k), and number of failures (n); probability of failure is denoted by p^i

unit of time for each patient is μ, where $\mu > 0$ is a constant. We define the health status of a patient either as being "well" or "unwell." The success of the IPU is defined as keeping the patient in the "well" state or bringing them back to the "well" state and the failure as being in the "unwell" state or transitioning to the "unwell" health status.

The IPU can mitigate the risk of failures by choosing the quality of treatment, a_t. For simplicity, we will only consider two levels of quality, high and low, respectively denoted by $a^H$and a^L. When high quality care is provided, the probability of failure is denoted by p^H and when low quality treatment is provided the probability of failure is denoted by p^L.

Assuming that attentive care reduces the probability of failure, then $p^H < p^L$.

The transition between problem states is shown in figure 1. The problem state is comprised of the patient health status (being "well" or "unwell" denoted by W or U, respectively), the number of successes is denoted by k, and the number of failures is denoted by n. The probability of success and failure for the IPU is denoted by $1 - p^i$ and p^i, respectively where $i \in \{H, L\}$.

As mentioned, we use the number of illness-free days as the health outcome success indicator. From a modeling perspective, we will reduce the problem state to the number of failures for the IPU. The occurrence of failures is modeled as a point process $N = \{N_t\}_{t \geq 0}$, where for each t, N_t is the number of failures up to and including time t. The healthcare delivery failures impose two types of costs. First, any complication and illness needs to be treated by the providers, whom will use valuable resources and capacity to serve the patients suffering from complications. Second, there are costs tied to the lost working days. As a result, the number of complications is directly connected to the inefficiencies in the healthcare system. We will denote the cost of health failure with C. As a result of The Patient Protection and Affordable Care Act of 2010 (ACA) reform in the U.S., reducing avoidable readmission has been of interest to the hospitals and providers as well the policy makers.

To estimate the potential savings for the hospitals, in a recent study, the cost of readmission has been estimated using the case of Veterans Administration Carey and Stefos (2015). The findings of the paper emphasize the importance of reducing the avoidable readmission from the perspective of the providers.

Throughout we assume that

$$\mu - p^H C > 0 \tag{1}$$

The left-hand side of (1) is the net expected health outcome value when the IPU exerts high quality treatment. Condition (1) implies that a high quality treatment has positive net present value.

Using time-driven activity-based costing (Kaplan and Anderson (2004)), we require estimates for two parameters: (1) the unit cost of supplying capacity and (2) the time required to perform treatments. We assume the IPU incurs a constant cost per unit of time, h. Since we are considering two levels of quality a^H and a^L, the total cost for treatments will be denoted with ha^H and ha^L for providing high quality and low quality treatments, respectively. The IPU can save $h(a^H - a^L)$ if he choose low quality treatments over high quality treatments. Also we assume that

$$(p^L - p^H)C > h(a^H - a^L) \tag{2}$$

The left-hand side of (2) is the expected social cost of increased risk when the IPU provides low quality treatment instead of high quality treatment. The right-hand side of (2) is the cost savings from providing low quality treatment. Condition (2) implies that in the absence of the hidden action problem, it is socially optimal to require the IPU to provide high quality treatment.

We will focus on the case when the IPU's treatment choice is not verifiable but the health outcomes and costs are common information. Hence we are dealing with the hidden action problem. The key parameters of the hidden action problem are $h(a^H - a^L)$ and $p^L - p^H$. The larger the cost savings from providing low quality treatment $h(a^H - a^L)$, the more attractive it is for the IPU to shirk. The lower $p^L - p^H$ is, the more strenuous it is to detect shirking. The contract between the healthcare purchaser and IPU is designed and agreed on at time 0. The IPU then chooses the treatment strategy process $A = \{a_t\}_{t \geq 0}$. We assume both purchaser and IPU can fully commit to a long-term contract. Because of the limited liability, the IPU cannot be held responsible for costs exceeding his wealth. As a result, the purchaser incurs the complication costs and the net value of health outcome during the infinitesimal time interval $(t, t+dt]$: $\mu dt - CdN_t$. Our assumption about limited liability is in line with DeMarzo and Sannikov (2006), Sannikov (2008), and Biais et al. (2010) where limited liability reduces the ability to punish the agent. This encourages the prinicipal to replace punishments by actions. In this problem, we will assume the contract can be terminated as a result of steady adverse health outcomes. The termination time will be denoted by τ. We allow $\tau \leq T$, where T is the care cycle.

A contract specifies payments to the IPU and the termination criteria as functions of the history of past health outcomes. The cumulative value of money transfers to the IPU is nonnegative and increasing. The money transfers will be denoted by the process

$S = \{s_t\}_{t \geq 0}$ and $s_t = 0$ for all $t > \tau$.

At anytime t prior to termination, the sequence of events during the infinitesimal time interval $(t, t + dt]$ can be described as follows:

1. The IPU takes her treatment strategy decision a_t^i, where $i \in \{H, L\}$.
2. With probability $p^i dt$, there is a failure, in which case $dN_t = 1$; otherwise $dN_t = 0$.
3. The IPU receives a nonnegative money transfer ds_t.
4. The treatments are either terminated or continued.

According to this timing, the IPU's treatment decisions A are taken before realizing the current health outcomes. Formally, the process A is $\mathcal{F}^N$-predictable, where $\mathcal{F}^N = \{\mathcal{F}_t^N\}_{t \geq 0}$ is the filtration generated by N. [2] Informally, the filtration $\mathcal{F}_t^N$ contains all the information generated by N up to time t in an increasing sequence. In contrast, the purchaser's payment and termination decisions are taken after observing the health outcomes. Thus S is $\mathcal{F}^N$-adapted and τ is $\mathcal{F}^N$-stopping time, A random variable S is called adapted to $\mathcal{F}^N$ if it "casually" depends on N (Brémaud (1981)). This means that at each time t, S depends on the observation of the process N at time t. Lastly, τ is called an $\mathcal{F}^N$-*stopping time* if the decision to terminate the process or not depends on the information available from N at time t.

An effort process A will generate a unique probability distribution P^A over the path of process N. Denote by $\mathbb{E}^A$ the corresponding expectation operator. We will use the expected payoffs for each player to demonstrate the dynamic principal-agent model. Next we will explain the objective function for the IPU and healthcare purchaser.

[2] For definitions of these concepts, see Dellacherie and Meyer (1978) Chapter IV, Definitions 12, 49, and 61.

2.1 Objective Functions and the Contract Space

Given a contract $\Gamma = (S, \tau)$ and a treatment process A, the expected discounted payoff for the IPU is

$$\mathbb{E}^A \left[\int_0^\tau e^{-\gamma t}(ds_t - ha_t dt) \right] \tag{3}$$

while the expected discounted payoff of the purchaser is

$$\mathbb{E}^A \left[\int_0^\tau e^{-rt}(\mu dt - CdN_t - ds_t) \right] \tag{4}$$

Treatment strategy A is incentive compatible with respect to contract Γ if it maximizes the IPU's expected payoff (3). The healthcare purchaser's problem is to find a contract Γ and an incentive compatible treatment strategy A that maximizes the expected discounted payoff (4), subject to fulfilling the IPU's required expected discounted payoff level. We will focus on the contracts Γ where the present value of payments to the IPU is finite, that is

$$\mathbb{E}^A \left[\int_0^\tau e^{-\gamma t} ds_t \right] < \infty \tag{5}$$

Constraint (5) assures the purchaser's expected discounted payoff (4) is not infinitely negative.

2.2 Incentive Compatibility

Not unlike Sannikov (2008), we will employ martingale techniques to characterize the incentive compatibility constraint. Recall that we are to capture the health outcomes over the care cycle and link the payments to the history of health outcomes using the notion of *continuation value* for the IPU. The continuation value reflects the likelihood of future payments to the IPU. Using the agent's continuation value as a state variable is common technique in dynamic principal-agent models, see e.g. Spear and Srivastava (1987) for an illustration.

The IPU will evaluate how the treatment strategy will affect her continuation value when taking a decision at time t. The IPU's continuation value is defined as

$$w_t(\Gamma, A) = \mathbb{E}^A \left[\int_t^\tau e^{-\gamma(u-t)}(ds_u - ha_u du)|\mathcal{F}_t^N \right] \tag{6}$$

Denote by $W(\Gamma, A) = \{w_t(\Gamma, A)\}_{t\geq 0}$ the IPU's continuation value process. Since $W(\Gamma, A)$ reflects whether there was a failure at time t, it is $\mathcal{F}^N$-*adapted*. To characterize the evolution of the IPU's expected value, we will first consider his lifetime expected payoff, evaluated conditionally on the information available at time t, that is

$$\begin{aligned} v_t(\Gamma, A) &= \mathbb{E}^A \left[\int_0^\tau e^{-\gamma(u)}(ds_u - ha_u du)|\mathcal{F}_t^N \right] \\ &= \int_0^t e^{-\gamma u}(ds_u - ha_u du) + e^{-\gamma t} w_t \end{aligned} \tag{7}$$

Since $v_t(\Gamma, A)$ is the expectation of a random variable conditional on $\mathcal{F}_t^N$, the process $V(\Gamma, A) = \{v_t(\Gamma, A)\}_{t\geq 0}$ is an $\mathcal{F}^N$-martingale. [3] To offer another representation of $V(\Gamma, A)$, we will introduce a notation M_t^A that could be interpreted as the number of failures up to and including time t, minus its expectations, if the effort process A were a constant process. Thus

$$M_t^A = N_t - \int_0^t p^i du \tag{8}$$

Since the occurrence of failures is modeled as a point process, according to a basic result from the theory of point processes, M^A is an $\mathcal{F}^N$-martingale under P^A. Changes in the treatment strategy A induce changes in the distribution of failures P^A. The martingale representation theorem for point processes then implies the following lemma.

Lemma 1. *The martingale $v_t(\Gamma, A)$ satisfies*

$$v_t(\Gamma, A) = v_0(\Gamma, A) - \int_0^t e^{-\gamma u}\psi_u(\Gamma, A) dM_u^A \tag{9}$$

for all $t \geq 0$, for some $\mathcal{F}^N$-predictable process $\Psi = \{\psi_t(\Gamma, A)\}_{t\geq 0}$.

[3] Informally, martingale is a stochastic process defined on a probability space whose predicted value at any future time $u > t$ is the same as its present value at time t of prediction.

Lemma (1) along with (8) suggest that the lifetime expected value of the IPU evolves in response to the jumps of the process N. Lemma (1) reflects the fact that, at any time t, the change in $v_t(\Gamma, A)$ is equal to the product of $\mathcal{F}^N$-predictable function of the past $-e^{-\gamma t}\psi_t(\Gamma, A)$ and a term $-dM_t^A$ that reflects the failures occurring at time t. In essence, $-dM_t^A$ is the difference between the instantaneous probability of a failure $p^i dt$ and the instantaneous change in the total number of failures dN_t, which is equal to 0 or 1. As a result, $-e^{-\gamma t}\psi_t(\Gamma, A)dM_t^A$ can be interpreted as a function of the past, in which $\psi_t(\Gamma, A)$ is the sensitivity of the IPU's continuation value to the failures. Equations (7) and (9) imply that the IPU's continuation value evolves according to

$$dw_t(\Gamma, A) = \left(\gamma w_t(\Gamma, A) + ha_t^i\right) dt + \psi_t(\Gamma, A)(p^i dt - dN_t) - ds_t \tag{10}$$

for all $t \in [o, \tau)$. Equation (10) explains the expected instantaneous change in the IPU's continuation value. Since the parameter ψ_t is measuring the sensitivity of the IPU's continuation value to the failures, whenever the health outcomes features an unexpected failure dM_t, the IPU's continuation value changes by $\psi_t dM_t$. We can think of w_t as what the purchaser owes to the IPU. Using analysis not unlike that of Sannikov (2008), we have the following proposition.

Proposition 1. *Given the contract $\Gamma = (S, \tau)$, a necessary and sufficient condition for the treatment strategy a^H to be incentive compatible is that*

$$\psi(\Gamma, A) \geq \ell \tag{11}$$

for all $t \in [0, \tau)$, P^A almost surely, where $\ell = h\frac{a^H - a^L}{p^L - p^H}$.

Equation (10) shows that the IPU's continuation value will be instantaneously reduced by an amount $\psi_t(\Gamma, A)$ if there is an unanticipated failure. With this explanation, Proposition 1 states that to induce high quality treatments, the reduction in the IPU's continuation value should be greater than the cost savings that the IPU can generate by shirking. Furthermore, because of the limited liability constraint, the IPU's continuation value must remain nonnegative. The continuation value of the IPU before observing the events at time t, $w_{t^-}(\Gamma, A)$ should be greater than the loss in case of failure $\psi_t(\Gamma, A)$, therefore

$$w_{t^-}(\Gamma, A) \geq \psi_t(\Gamma, A) \tag{12}$$

for all time $t \in [o, \tau)$, where $w_{t^-}(\Gamma, A)$ is left-hand limit of the process $W(\Gamma, A)$ at time $t > 0$. While $w(\Gamma, A)$ is the continuation value of the IPU after observing the health outcomes, $w_{t^-}(\Gamma, A)$ is the continuation value before observing the health outcomes. To simplify the notation, we drop the arguments Γ and A in the remainder of the paper.

3 The Coordinating Contract

In the previous section, we considered general treatment strategies. In this section, we characterize the optimal contract that induces high quality treatment, that is $A = a^H$ for all $t \in [0, \tau)$. This optimal contract maximizes the expected value for the purchaser from an incentive compatible contract to implement a high quality treatment strategy.

This section will offer more precise insights on how to induce high quality treatments that will result in better health outcomes at minimal cost. The contract that we derive can be described by the continuation value of the IPU, which reflects the future payment decisions. the others. We will first provide the heuristic derivation of the purchaser's value function and the main properties of the optimal contract. Then we will show the formal derivation of the value function and the characteristics of the optimal contract. All the proofs are provided in the Appendix.

3.1 Properties of the Optimal Contract

In the heuristic derivation, we suppose the money transfers are continuous with respect to time and no payment is made to the IPU after a loss, that is

$$ds_t = s_t 1_{\{dN_t=0\}} dt \tag{13}$$

where $s_t \geq 0$. Here $\{s_t\}_{t\geq 0}$ is assumed to be a $\mathcal{F}^N$-predictable process that denotes the money transfer to the IPU. For incentive purposes, it might be necessary to reduce the IPU's continuation value after each loss by an amount that is proportional to his savings from providing less than optimal quality of care. Later we will verify that this conjecture is correct at the optimal contract.

We will first characterize the healthcare purchaser's continuation value $J(w)$ which is a function of the state of the problem, the IPU's continuation value w. Since the purchaser discounts the future payoffs at rate r, the expected flow of value at time t is given by

$$rJ(w) \tag{14}$$

This should be equal to the sum of the expected instantaneous value of health outcomes and the expected rate of change in the principal's continuation value. The former is the expected health outcomes minus the expected payments to the IPU, which is

$$\mu - p^H C - s_t(1 - p^H dt) \tag{15}$$

To construct the expected rate of change in the purchaser's continuation value, we use the dynamics of the IPU's continuation value (10) and set $p^i = p^H$ and $A = a^H$. Applying the change of variable formula for jump processes with bounded variation, which is the equivalent of Ito's formula for these processes, yields

$$\begin{aligned} &\left[\gamma w_{t^-} + ha^H + p^H \psi_t - s_t\right] J_w(w_{t^-}) \\ &\quad - p^H \left[J(w_{t^-}) - J(w_{t^-} - \psi_t)\right] \end{aligned} \tag{16}$$

The first term is associated with the drift in w_{t^-} and the second term corresponds to the possibility of jumps in the IPU's continuation value due to losses. Adding (16) and (15), and letting dt go to 0, we obtain the purchaser's continuation value, which satisfies the

Hamilton-Jacobi-Bellman equation.

$$
\begin{aligned}
rJ(w) = \sup_{s_t,\psi_t} \{ & (\mu - p^H C - s_t) \\
(17) \qquad & + [\gamma w_{t^-} + h a^H + p^H \psi_t - s_t] J_w(w_{t^-}) \\
& - p^H [J(w_{t^-}) - J(w_{t^-} - \psi_t)] \}
\end{aligned}
$$

where the maximization is over the set of controls (s_t, ψ_t) that satisfy constraint (11). The first term arises since the purchaser is maximizing the current payoff, the second term corresponds to the drift of the IPU's continuation value, and the third term reflects the possibility of jumps in the purchaser's continuation value due to the failures. In this part, we require J to be globally concave. The economic interpretation of this property, which will be formally establish in Proposition 2, is as follows. While termination is inefficient in the first-best case, it is necessary to provide incentives to the IPU when the continuation value w_t is low. When bad performance persists, the purchaser's value function reacts strongly. However, when w_t is large bad performance has limited impact on the purchaser's value function.

We can derive several properties of the optimal control using the Hamilton-Jacobi-Bellman equation (17). The purchaser can compensate the IPU with either cash payments or by promising a continuation value (the prospect of cash payments in future). The optimal contract uses whichever form that is least expensive to the purchaser. Paying one dollar to the IPU in cash costs the purchaser one dollar. Lump sum money transfers will be used if the slope of continuation value for the purchaser is below -1, i.e. if paying the IPU in future cost the IPU more than one dollar. Optimizing Hamilton-Jacobi-Bellman equation (17) with respect to s_t yields

$$(18) \qquad J'(w) \geq -1$$

where equality occurs at $s_t > 0$. Intuitively, $J'(w)$ is the increase in the purchaser's continuation value due to a marginal increase in the IPU's continuation value, while the right-hand side of (18) is the marginal cost for the purchaser to make an immediate money transfer to the IPU. Thus it is optimal to delay the payments as long as inequality (18) strictly holds. This reflects that the purchaser will benefit more from increases in w than transferring immediate money to the IPU. The concavity of $J(w)$ implies that condition (18) will hold when w_t is below a given threshold. We will denote this threshold with w^p. As a result, the optimal contract satisfies the next property.

Property 1. *The payments to the IPU are made only if w_t exceeds the threshold w^p, which satisfies the following condition*

$$J'(w) = -1 \tag{19}$$

This threshold and the concavity of $J(w)$ suggest that the purchaser will delay payments to the IPU and make them contingent on the record of persistent good performance. The money transfers to the IPU will begin as soon as w hits the threshold w^p, where the social value is at its maximum $J(w^p) + w^p$. The optimal contract includes a lump sum payment of $w - w^p$, when $w > w^p$. Thus the money transfers are

$$\max(w - w^p, 0) \tag{20}$$

The concavity of J also implies that it is optimal to let the IPU's sensitivity to failures ψ_t be as low as possible in (17). Consequently, including the incentive compatibility condition for the IPU (11) leads to another property of the optimal contract.

Property 2. *The sensitivity to failures of the IPU's continuation value is given by*

$$\psi_t = \ell \tag{21}$$

Based on the concavity of the purchaser's continuation value, condition (21) reflects that it is optimal to expose the IPU to the minimal risk $\psi_t = \ell$. As a result, by substituting $\psi_t = \ell$ in 10, the change in the IPU's continuation value can be described as

$$dw_t = \left(\gamma w_t + ha^H + \ell p^H\right) dt - \ell dN_t - ds_t \tag{22}$$

In other words, the IPU's continuation value will be reduced by an amount that is proportional to the cost savings from shirking. To clarify this, suppose at the beginning of time t the continuation value of the IPU is w_{t^-}. If there is a failure at time t, the IPU's continuation value should be reduced from w_{t^-} to $w_t = w_{t^-} - \ell$. Resulting in the followting property of the contract.

Property 3. *Whenever the continuation value w_t drops to zero, the contract will be terminated.*

Next, we will show that the above properties are consistent with the formal derivation of the optimal contract. First, we will establish there is a function J that fits the properties discribed above, then we will characterize the optimal contract and discuss its possible implementation.

Proposition 2. *The Hamiltonian-Jacobi-Bellman equation*

$$\begin{aligned} rJ(w) &= \mu - p^H C + (\gamma w + p^H \ell + h a^H) J'(w) \\ &\quad - p^H [J(w) - J(w - \ell)] \end{aligned} \tag{23}$$

with the threshold w^p, which is endogenously determined according to

$$J'(w) = -1$$

has a concave solution and equals the purchaser's optimal value function.

The concavity of $J(w)$ was essential in characterizing the properties of the optimal contract. The proofs can be found in the Appendix. The next step is to show that the function formulated in Proposition 2 will lead to the maximal value for the purchaser and also implement the optimal contract. For this, we will fix the initial expected continuation value for the IPU to w_0 and consider the continuation value of the IPU $\{w_t\}_{t \geq 0}$ and the cumulative money transfers $\{s_t\}_{t \geq 0}$ up to and including time t, respectively, to be solutions to [4]

[4] For each x and y, we denote by $x \vee y$ the maximum of x and y.

(24) $$w_t = w_0 + \int_0^{t^-} (\gamma w_u + ha^H + \ell p^H)du - \ell dN_u - ds_u,$$

(25) $$s_t = (w_0 - w^p) \vee 0 + \int_0^{t^-} (\gamma w^p + ha^H + \ell p^H)\mathbf{1}_{\{w_{u^+}=w^p\}}du$$

for all $t \geq 0$, where w_0 is the initial expected value for the IPU and w^p is defined in Proposition 2. Observe from (24) and (25) that $w_{t^+} = w^p$ if and only if $w_t = w^p$ and there is no failure at time t.

Proposition 3. *The optimal contract $\Gamma = (S, \tau)$ that motivates high quality treatments and delivers the IPU the initial expected discounted value w_0 satisfies properties (1-3). At any time t,*

- *i. If $w > w^p$ a lump sum transfer of $w - w^p$ is paid to the IPU.*
- *ii. As long as $w_t = w^p$ and no failure occurs, money transfers to the IPU equal the increase in the continuation value $\gamma w^p + ha^H + \ell p^H$.*
- *iii. Occurrence of failure will reduce the IPU's continuation value by ℓ.*
- *iv. The IPU will be terminated when the continuation value is $w_t = 0$, which is stochastic and unpredictable.*

The features of the optimal contract are in line with the properties described before. To keep the social value at its maximum $J(w^p) + w^p$, lump sum money transfer will occur if $w_0 > w^p$. The purchaser will transfer $\gamma w^p + ha^H + \ell p^H$ to the IPU as long as $w_t = w^p$ and no failure occurs. This term can be seen in equation (10) and (24). The amount of money transfer is equal to the increase in the IPU's continuation value when $dN_t = 0$.

We now explain how the optimal contract could be implemented in the context of value-based healthcare delivery. Before proceeding with the explanation of the optimal contract, it is worth noting that the value-based healthcare delivery tenets advocates for a bundled payment model that reimburses providers with a fixed amount of money for delivering all the services required to provide a complete cycle of patient care for a special clinical condition. For example, if a patient receives a hip replacement, the hospital, the orthopedic surgeon, and the physical therapist would all fall under the same bundled payment. Even though bundled payments have the potential to reward the providers that deliver more value to their patients (that is, better outcomes at lower costs) we show here they are not optimal. In practice, the bundled payments have struggled to gain popularity due to concerns about the accuracy of bundle price estimation, timing of the payments, and the level of support that current IT systems can provide (Porter and Kaplan (2014)). We assume the providers involved in an IPU have delegated the responsibilities of care coordination to a care manager.

Other than the factors mentioned above, the optimal payment model should provide the providers with enough flexibility to build a program that makes clinical and economic sense. In addition, the optimal payment should pay the providers enough to achieve the health outcomes and also encourage improvement of patient health outcomes through accountability and quality measures. As mentioned in Section 2, we assume the purchaser and IPU use time-driven activity-based costing to measure the costs across the full cycle of care. As a result, the IPU has confidence in the budgeting process. Furthermore, we assume the contract is set for a homogeneous patient population and the total number of patients assigned to the provider will not change for a given duration of time. Using our results, we will now discuss one of the possible contract implementations.

Recall that w can be interpreted as the amount of money the purchaser owes to the IPU. Starting at time 0, the purchaser and the IPU agree on a contract based on the initial expected value for the IPU, w_0. Assuming w as the amount of credit the IPU has with the purchaser, the IPU can withdraw money from the credit line up to w.

According to (22), if no failures occur, during the infinitesimal time interval $(t, t+dt]$, the change in the continuation value is given by $\gamma w_t + ha^H + \ell p^H$. This is similar to the fixed amount of money the purchaser pays to the IPU in the bundled payment. However, unlike the bundled payment definition, the amount the purchaser owes to the IPU w in the optimal contract is dynamic and depends on the IPU's performance. Good performance record increases w. As explained before, the threshold w^p is where the social value is maximized, the maximum of $J(w) + w$, and thus the purchaser wants to keep the continuation value at w^p. Good performance will increase w by $\gamma w + ha^H + \ell p^H$. When a failure happens the continuation value will be reduced by ℓ which itself depends on the IPU's cost savings from providing less than optimal quality of care. If w exceeds w^p, the IPU will be paid the lump sum money transfer of $w - w^p$ as bonus payment for consistent superior performance.

In other words, the IPU could receive bonus payments if they can successfully minimize avoidable complications. Furthermore, the IPU is incentivized to innovate the care process and minimize the costs while providing high quality treatments. This can be seen in how w evolves. If the IPU can innovate the care process, they can reduce the amount of money that will be withdrawn from w, and hence w will increase. An increase in the continuation value w is optimal for both parties up until the threshold w^p, in which the bonus payment will be paid to the IPU.

The use of the credit line concept to execute the optimal contract will solve one of the bundled payment's implementation challenges, which is the timing of payments to the IPU (Witkowski et al. (2013)).

The possibility of punishment by decreasing the continuation value is another source of incentive for the IPU to provide high quality treatments to the patient. Any adverse health outcomes will decrease w by ℓ and the the contract will be terminated when the IPU maxes out its credit limit w, i.e. when $w = 0$.

4 Conclusions

Resolving issues of fragmentation in health care delivery as a way to potentially address concerns of containing health care expenditures is a non-trivial problem. One approach to resolving fragmentation is to reform provider payment schemes to move away from fee-for-service and towards payments for desired health outcomes. Our approach here focuses on value-based healthcare delivery as proposed by Porter and Guth (2012). We studied the coordinating contracts between the healthcare purchaser and the provider organization (IPU) in the context of value-based healthcare delivery. The coordinating contract allows the IPU to optimize its objective while maximizing societal welfare. We also consider the hidden action problem, where the IPU's treatment strategy is unverifiable to the purchaser. To capture the dynamics of health outcomes over the care cycle we used a continuous-time dynamic principal-agent model to derive the optimal contract, which allows us to link payment to the history of health outcomes.

Failing to transition patients to a healthy state is expensive, not only because patients receive costly avoidable treatments but also because patients lose functional days. Accountability for avoidable complications is one of the ways in which value-based healthcare delivery is intending to reduce inefficiencies in the healthcare system. Our analysis suggests to prevent healthcare failures, compensation policies should be made contingent on the accumulated performance of the provider (IPU). We used the concept of *continuation value* and interpret it as representing the IPU's track record.

Based on the continuation value, accumulated good performance results in positive monetary transfers to the IPU, while failures reduce the IPU's compensation. This is the cornerstone of our *dynamic outcome-adjusted payment* to characterize the optimal contract between the healthcare purchaser and IPU, who is collectively responsible for the health outcomes of their patients over the care cycle.

Our research contributes to the literature of healthcare contracting in several ways. First, it closes the gap in designing a dynamic incentive contract between healthcare purchasers and providers. A common payment mechanisms (fee-for-service) reimburses providers for discrete services and can encourage providers to over provide services. However, to add value for the patients, the providers should evaluate whether additional tests or treatments can improve a patient's health outcomes. Alternative payment mechanisms (like capitation) may control healthcare expenditure growth, but might incentivize providers to under provide services or cream-skim healthier patients who require less care. Additionally, the current fragmented healthcare delivery structure does not allow providers to leverage the expertise of other providers. Value-based healthcare delivery brings all relevant providers together determine the well-being of a patient with a certain medical condition together in an IPU.

Since the IPU's treatment strategy stochastically affects patient health outcomes over time, a payment model that considers the health outcomes over the care cycle and remunerates the IPU based on outcomes is needed. We determined a payment arrangement to encourage the IPU to provide high quality treatments to patients with a given budget. A good performance record for the IPU is compensated with a bonus payment. This is a significant contribution because many existing payment schemes linking payment to performance, pay for fulfilling some targeted processes, which might not result in better health outcomes. Additionally, pay-for-performance schemes that directly target better health outcomes are often challenging to implement within a fragmented delivery structure. An individual healthcare providers cannot be held accountable for a patient's health outcomes since each provider can argue the other providers involved did not provided high quality care.

Second, our research mathematically demonstrates the optimal payment system for value-based delivery. It has been argued a bundled payment should coordinate the relationship between the healthcare purchaser-IPU relationship (Porter and Guth (2012)). Aside from the bundled payment, we find the IPU should be compensated with a bonus when they achieve superior performance. Essentially the payment to the IPU should be adjusted based on the health outcomes.

Third, the way we characterize the optimal contract can arguably result in a single-variable implementation. The use of a continuous-time principal-agent model helps us model the problem with minimal assumptions and provided a way to summarize the IPU's track record over the care cycle. Cost-reducing efforts and value-adding treatments increase the IPU's *continuation value*, which can eventually result in a bonus payment if the IPU exceeds a certain threshold for the continuation value. Thus, our proposed payment scheme can fulfill the tenets of value-based healthcare delivery by acting as the source of incentive for the IPU to improve the health outcomes and minimize the costs at the same time.

Our model can be extended to include the possibility of IPU learning throughout time. Learning could provide cost-reducing opportunities and thus more efficiently provide patient care. The implications of learning in value-based healthcare delivery on the payment scheme is interesting to study. Further, the model could be modified for specific diseases. Particularly for terminally ill patients, who have a distinct health evolution. Alternatively, the optimal design could be extended to look at of non-financial incentives among different IPUs. If different IPUs could be rated in comparison to their peers, they might behave differently. As a result, the healthcare purchaser may benefit from building in social comparisons or peer pressure into their mechanisms.

We acknowledge the optimal payment system is one of many challenges purchasers and providers might face in implementing value-based health care reforms. Other challenges include correctly measuring the relevant health outcomes to patients and the design of IT systems.

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Appendix

Proof. Proof of Lemma 1. Condition (9) is the predictable representation of martingale $v_t(\Gamma, A)$, following Brémaud (Chapter III, Theorems T9 and T17) Brémaud (1981). □

Proof. Proof of Proposition 1. Let v'_t represent the IPU's lifetime expected value, given the information available at time t, when he uses and alternative treatment strategy $A' = \{a'_t = a^L\}_{t\geq 0}$ until time t and then changing the treatments to $A = \{a_t = a^H\}_{t\geq 0}$, as a result

$$v'_t(\Gamma, A') = \int_0^t e^{-\gamma u}(ds_u - ha'_u du) + e^{-\gamma t} w_t(\Gamma, A) \tag{26}$$

Not unlike Sannikov (2008) and Biais et al. (2010), it is straightforward to show that if $\psi \geq \ell$, where $\ell = h\frac{a^H - a^L}{p^L - p^H}$, the drift of the process is going to be nonpositive for all t and thus v'_t is supermartingale for any alternative strategy A'. As a result, the strategy A is at least as good as the alternative strategy A'. □

Proof. Proof of Proposition 2. First, we will establish the existence of a twice differntiable solution to the Hamiltonian-Jacobi-Belllman (HJB) equation (17). Assumption (1) implies that the purchaser wants to avoid health failures at the first best solution. Using (17), and setting $\psi = \ell$, the HJB equation is given by

$$rJ(w) = \mu - p^H C + (\gamma w + ha^H)J'(w) + p^H[J(w) - J(w - \ell)] \tag{27}$$

Let's define function H as

$$\begin{aligned} H(w, u, \beta) = -\min\big[&ru - \mu + p^H C - \beta(\gamma w + ha^H) \\ &- p^H(u(w) - u(w - \ell))\big] \end{aligned} \tag{28}$$

therefore, the HJB is equivalent to

$$H(w, u, \beta) = 0 \tag{29}$$

By Berge's Maximum Theorem, $H(w, u, \beta)$ is jointly continuous in its parameters. This implies that for any slope m, the initial value problem with boundary conditions $J(0) = 0$ and $J'(w) = m$ has a continuous differentiable solution on its domain. Furthermore, since the HJB equation is the sufficient condition for optimality any candidate function that solves the HJB, is indeed optimal.

Denote by $J(w)$ the purchaser's highest value from a contract that provides the IPU the continuation value of w. Since the purchaser has the option of providing w to the IPU by paying a lump-sum transfer of $ds > 0$. In that case, $ds > 0$, the IPU's expected continuation value will be $w - ds$. As a result of this payment, purchaser's continuation value moves to the $J(w-ds)$. For $J(w)$, to be the purchaser's highest value, the following condition must hold

$$J(w) \geq J(w-ds) - ds \tag{30}$$

The above equation is equivalent to

$$J'(w) \geq -1 \tag{31}$$

for some w. Condition (31) implies that there exists w for which it is optimal for the purchaser to let the IPU's continuation value grow instead of making payments $ds > 0$. Condition (31) along with the fact that $rJ(w) < \mu - p^H C - (\gamma w + p^H \ell + ha^H)$ imply that $J''(w) < 0$. Therefore, to the left of threshold w^p with boundary condition $J'(w^p) = -1$ and

$$rJ(w^p) = \mu - p^H C - (\gamma w^p + p^H \ell + ha^H)$$

function $J(w)$ is concave. □

Proof. Proof of Proposition 3 This proof uses propositions (1 & 2) and equations (24 & 25).

i. According to the definition of boundary condition and because of the concavity of $J(w)$, when the continuation value exceeds w^p, $J'(w) < -1$. In another words, $J(w) < J(w-ds) - ds$. As a result, the purchaser is better off to pay a lump sum money $ds = w - w^p$ to the IPU. This money transfer will maximize the total continuation value $J(w) + w$.

ii. When $w = w^p$ and no failure occurs, according to (24) during $[t, t+dt)$ the continuation value increases by $\gamma w^p + ha^H + \ell p^H$. To keep the IPU's continuation value at the optimal level w^p, the purchaser will transfer $s_t = \gamma w^p + ha^H + \ell p^H$ to the IPU.

iii. Proposition 1 along with Proposition 2 ensures that the sensitivity of IPU's continuation value is set to the minimum level, therefore $\psi_t = \ell$.

iv. By each failure, the continuation value will be reduce by $\psi = \ell$. Since the process w is $\mathcal{F}^N$-adapted and the stopping time τ is $\mathcal{F}^N$-*stopping time*, the decision to terminate the process or not depends only on the information from N at time t. Thus, it is stochastic and unpredictable when continuation value hits 0. When $w = 0$, the purchaser would prefer to terminate the contract.

□