The optimal payment system for hospitals under adverse selection, moral hazard and limited liability

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Abstract

This paper studies the optimal contract offered by a regulator to a partially altruistic hospital under adverse selection, moral hazard, and limited liability. We consider that the hospital privately observes the severity of illness of patients and chooses a hidden quality that influences the probability of some complications or comorbidities (CCs) occurring. We analyze the conditions under which the payment, for a given Diagnosis Related Group, should be refined according to the severity of illness and the occurrence of CCs.

Keywords Hospital regulation, adverse selection, moral hazard, limited liability, altruism.

JEL Classification Numbers I18; L3; D82

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1 Introduction

Until the 1980s, the main form of hospital payments in the United States and in most developed countries was cost reimbursement. In 1983, Medicare introduced a new form of payment, i.e. the Prospective Payment System (PPS) that sets prices prior to the period for which care is given. Under PPS, rates are determined by diagnosis related groups (DRGs). Each DRG is given a flat payment calculated in part on the basis of costs incurred for that DRG nationally. As noted by Geissler et al. (2011),

> DRG-based hospital payment systems have become the basis for paying hospitals and measuring their activity in most high-income countries, albeit to different extents (Paris et al. (2010)). However, the term DRG is widely used but with different meanings across and within countries. Some countries use DRGs mostly as a measure for assessing hospital casemix (for example, Sweden and Finland), whereas in other countries DRGs are used as a synonym for payment rates (such as in France and Germany).

The literature on providers' incentives in health care has quite extensively discussed the incentive properties and drawbacks of prospective payments. Dranove (1987) for example shows that rate setting by DRG encourages hospitals to specialize in those DRGs for which they have relatively low production costs. Ellis and McGuire (1986) introduce the physician as a utility maximizing agent for both the patient and the hospital. They demonstrate that a combination of fixed price and partial cost reimbursement is optimal when the doctor is not a perfect agent for the patient. Allen and Gertler (1991) show that some patients may receive inefficient quality under PPS when patients are heterogeneous within a given DRG.[1]

The failure to capture differences in expected costs among heterogeneous patients is probably the main drawback with DRG payment. In order to decrease the intra-DRG cost-variability, several refinements have been introduced in the DRG systems of many countries. A refinement consists in splitting a single DRG category into two or more DRG categories

[1] See also Barros (2003), Beitia (2003), Brekke and Sorgard (2007), Chalkley and Malcomson (1998a, 1998b), De Fraja (2000), Eggleston (2005), Ellis and McGuire (1990), Holmstrom and Milgrom (1991), Jack (2005), Ma (1994, 1998), McClellan (1997), Mougeot and Naegelen (2005), Pope (1989), and Shleifer (1985).

relating to the same primary diagnosis (e.g. in France many DRGs are now split into four levels of severity). However, when DRGs are refined, hospitals are usually suspected of "DRG creep", which has been narrowly regarded as reporting diagnostic and procedural codes that result in greater reimbursement. Therefore, an optimal degree of refinement should be designed. In practice, the split of a DRG is mainly based on the three characteristics below.

First, the split of a DRG can be based on exogenous variables for the hospital such as the type of the hospital and the age of the patients (e.g. as in France and Switzerland).

Second, the split can be based on exogenous variables for the hospital but that may be over-reported such as the severity of illness.

Third, the split of a DRG can be based on variables that can be chosen (or at least influenced) by the hospital, e.g. the type of treatment. Thus, Siciliani (2006) and Hafsteinsdottir and Siciliani (2010) determine the optimal payment when the DRG payment can be refined between medical and surgical treatments. The split of a DRG can also be based on the length of stay. For example, in France, Switzerland, and the United States, the hospital is paid a fixed price per DRG for most patients (inlier patients), whereas it is reimbursed by a cost sharing payment for patients (outlier patients) with exceptionally long (or short) stays. The analysis of the optimal outlier payment policy has been developed by Mougeot and Naegelen (2008 and 2009).

Another main reason for splitting DRG is whether some complications or comorbidities (hereafter "CCs") occur or not, e.g. as in Switzerland, Germany, and France. The optimal price regulation in this context is quite complex to define insofar as the occurrence of CCs depends on the level of quality of care chosen by the hospital, which is not observable by the regulator. Moreover, the severity of illness of the patients is not directly observable by the regulator. Thus, the regulator faces both moral hazard and adverse selection. In this asymmetric information context, the aim of this paper is to analyze the optimal price regulation of a hospital when payment may be refined on the basis of two characteristics: the occurrence of CCs and the reported (by the hospital) severity of illness.

Analyzing the optimal regulation of hospitals' payment systems first involves identifying the objective of hospitals. By the WHO definition, this objective is to provide the best possible quality of health service. However, it is difficult to precisely define quality and to evaluate the level of quality. Probably the best-known definition is provided by the Institute of Medicine (IOM, Washington, DC) which defines quality as "the degree to which health services for individuals and populations increase the likelihood of desired health outcomes and are consistent with current professional knowledge".[2]

However, the literature has considered a different definition of quality, insofar as quality is mainly considered as a moral-hazard variable, not observable by the regulator (it may be observable by patients), which deterministically influences the observable cost. Under this assumption, several papers have analyzed the design of optimal hospital payment rules in a context of both moral hazard and adverse selection. For instance, Chalkley and Malcomson (2002) develop a model based on Laffont and Tirole (1993) to estimate the gains from introducing cost sharing arrangements in DRG payments. Jack (2005) analyzes a context where providers have private information about their degrees of altruism. In Kantarevic and Kralja (2016), providers have private information about their costs of exerting effort.

We believe that this form of modeling (known as "false moral hazard") does not really fit the above definition of quality. Therefore, in this paper, we consider instead a model with true moral hazard insofar as quality influences the probability of CCs occurring. Formally, our model considers two states of nature, namely with or without CCs. Our normative approach aims at defining the optimal payments to be made to the hospital in both states of nature. Particularly, for a given DRG, should the payment depend on the severity of illness (reported by the hospital) or should the payment be a flat rate one? Secondly, should the payment be split into two different categories, i.e with or without CCs? If the payment is refined, is the payment in the event of CCs higher than the payment without CCs? These are the main questions we address in this paper.

Formally, we consider that the regulator observes neither the quality of care (chosen by the hospital) nor the severity of illness.[3] Therefore, the optimal payment must be structured to satisfy the incentive constraint, the no shun constraint, and the overall limited liability constraint. The first constraint implies that the hospital is honest when reporting the severity

[2]Cf. IOM (Institute of Medicine), "To Err Is Human: Building a Safer Health System", Washington, DC: National Academy Press 2000.

[3]Thus, in terms of incentives theory, we analyze a mixed model with true moral hazard, see Gottlieb and Moreira (2017) or Ollier and Thomas (2013) for theoretical developments.

of illness and obedient when choosing the level of quality. The second constraint ensures that the hospital has no incentives to shun unprofitable patients. Due to the latter, the hospital cannot end up with a negative payoff either in the worst case where all the patients suffer CCs or in the most favorable case where no patients suffer CCs. Moreover, we take the shadow cost of public funds into account in the design of the optimal regulation. Thus, financing hospital rents implies a deadweight loss. The design of an optimal payment rule should also take into account the fact that the incentives of the regulator and the hospital do not necessarily work in opposite directions since we consider a partially altruistic hospital that cares about patients' surplus. Besides, we assume that the utilitarian regulator maximizes the social welfare, which is the sum of the social benefit of health care and the utility of the risk-neutral hospital.

Given the specifications of our model, it should be noted that the paper closest to ours is Wu et al. (2018). They consider that the probability of the patient recovering, upon receiving hospital treatment, depends on both the hospital's level of effort and its ability type. However, our model differs from Wu et al.'s (2018) in several respects. First, in our model, the probability of occurrence of CCs depends exclusively on the level of quality (the moral-hazard variable). Second, in Wu et al. (2018), the adverse-selection problem between the hospital and the payer arises since the hospital's ability is unknown to the payer. Patients are also assumed to be homogenous in terms of illness severity and receive a constant benefit from treatment. Our model considers instead heterogeneous patients in terms of severity (which constitutes the adverse-selection variable) and we assume that the regulator values more highly the treatment of patients with more severe illnesses. Third, Wu et al. (2018) consider that the health provider is self-interested whereas we allow this provider to be altruistic. This is a key difference since we show that the optimal regulation strongly depends on the level of altruism.

In this paper, as a first benchmark case, we consider a simple context of moral hazard, i.e. when the regulator does not observe the quality of care but observes the patient severities and ignores the hospital's limited liability constraint. In this case, the first-best level of quality can be achieved by a fixed payment which depends on the level of severity. Thus, the refinement with our without CCs is not optimal.

If limited liability is added to moral hazard, the regulator must then leave a rent to the hospital since the latter cannot end up with a negative profit. The cost of this limited liability rent can be reduced by giving the hospital a higher payment when CCs occur than when they do not. This induces the hospital to provide a lower level of quality than the first-best level. Thus, under moral hazard and limited liability, both refinements in terms of CCs and in terms of severity are optimal.

When adverse selection is added to moral hazard and limited liability, we find that the optimal regulation contract depends on the level of altruism of the hospital, namely whether altruism is low, moderate, or high.[4]

When altruism is low, we show that both refinements in terms of the occurrence of CCs and in terms of severity are optimal. However, somewhat counterintuitively, the optimal payment in the event of CCs has to be lower than without CCs. The intuition for this result is the following. To elicit truthful information from the hospital, the regulator must leave a rent to the hospital. In order to reduce this information rent (as in a model with adverse selection alone), the regulator induces upward distortions of the quality provided in comparison with the first-best quality level. This distortion can only be achieved by setting a payment with CCs lower than without CCs.

When altruism is high, we find that the payment should be refined in terms of the occurrence of CCs, with a higher payment when CCs occur than when not. However, it should not be refined in terms of severity of illness. This result can be interpreted. Under high altruism, the dominant purpose of the regulator is to reduce the limited liability rent. Thus, the regulator faces, a priori, the same trade-offs as under moral hazard and limited liability. Therefore, the cost of the limited liability rent is reduced by giving the hospital a higher payment when CCs occur than when not and the hospital provides a lower level of quality than the first-best level. Nevertheless, this payment structure is not compatible with severity refinement, otherwise the hospital would systematically overestimate the severity of

[4]Makris and Siciliani (2013) analyze optimal incentive schemes for altruistic providers, in the presence of adverse selection, limited liability, and altruistic providers. They also show that the optimal regulation contract depends on whether the level of altruism is low, moderate, or high. However, contrary to our paper, they do not allow for moral hazard and the adverse-selection variable (the hospital's efficiency) is a discrete variable that can take two possible values whereas a continuum of types is assumed in our paper.

illness.

Finally, under moderate altruism, we show that the refinement based on CCs is optimal. However, the refinement based on severity is not always optimal. Intuitively, the optimal contract under moderate altruism can be seen as a mix of the two "polar"contacts (i.e. under low and high altruism). Thus, if the adverse selection effect is higher than the moral-hazard effect, then the payment with CCs will be lower than without CCs, and the quality provided is higher than the efficient level. If the reverse is true, then the payment with CCs will be higher than without CCs, so that the quality is distorted below its efficient level. Again, it follows that the regulator may find it optimal not to refine the payments in terms of severity.

The paper is organized as follows. The model is presented in section 2. Benchmark cases are analyzed in section 3. In section 4, we determine the optimal contract under moral hazard, adverse selection, and limited liability. Some conclusions are drawn in section 5.

2 The model

We consider the hospital's payment problem as a regulation problem. There are three actors in the system: the patients (assumed to be passive), a hospital, and a regulator.

2.1 The background

We consider a population of patients of mass 1. We let β denote the severity of illness. The frequency of $\beta \in B = [\underline{\beta}, \overline{\beta}]$ among the population is $f(\beta)$. Let $F(\beta) = \int_{\underline{\beta}}^{\beta} f(u)du$ be the cumulative distribution.

We consider that the probability of occurrence of CCs depends on the level of quality q chosen by the hospital. More precisely, this probability is a decreasing function of q. So, without loss of generality, we denote the probability of occurrence of CCs by $(1 - q)$, where $q \in [0, 1]$. Choosing a quality q involves the hospital incurring a non monetary disutility $\psi(q)$, such that: no quality implies no disutility ($\psi(0) = 0$), quality increases the disutility at an increasing rate ($\psi'(q) > 0, \psi''(q) > 0$), the marginal disutility is convex ($\psi'''(q) > 0$), and Inada's conditions are verified ($\lim_{q \to 0} \psi'(q) = 0$, and $\lim_{q \to 1} \psi'(q) = +\infty$).[5]

[5]The last two assumptions ensure a well behaved problem and avoid corner solutions.

When treating a patient β, the hospital has a cost function $c_H(\beta)$ if CCs occur (with probability $(1-q)$) and $c_L(\beta)$ if not (with probability q). We assume $c_L(\beta) < c_H(\beta)$, $0 < c'_L(\beta) < c'_H(\beta)$, and $c''_L(\beta) < c''_H(\beta)$. This means that: (1) costs are increasing in β at an increasing rate; (2) the effect of β on costs is always higher when CCs occur than when not.

Let $S(\beta)$ denote the benefit that the regulator attaches to having a patient β treated, with $S'(\beta) > 0$. Thus, the regulator values more highly the treatment of patients with more severe illnesses. This assumption seems to be realistic insofar as the most severely ill patients very likely receive more benefit from treatment than less severely ill patients.

Besides, the hospital is assumed to be altruistic. More exactly, let $\alpha \in [0,1]$ denote the degree to which the hospital takes the patient's benefit into account. We assume that α is common knowledge.[6]

If CCs occur, we assume that the hospital receives a payment, t_H, from the regulator and t_L if not. We also consider λ as the shadow cost of public funds, which implies that payments have to be multiplied by $(1+\lambda)$.

2.2 The payoffs

The hospital is risk-neutral. For a given β, q, t_L, and t_H, it has a utility

$$\begin{aligned} U &= q\big(t_L - c_L(\beta)\big) + (1-q)\big(t_H - c_H(\beta)\big) - \psi(q) + \alpha S(\beta) \\ &= t_H - c_H(\beta) + q\big[\big(t_L - t_H\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(q) + \alpha S(\beta). \end{aligned} \tag{1}$$

The regulator is utilitarian and benevolent. For a quadruplet $\{\beta, q, t_L, t_H\}$, the social welfare is

$$W = S(\beta) - \big(1+\lambda\big)\big(qt_L + (1-q)t_H\big) + U. \tag{2}$$

Notice that we do not include altruistic preferences of the hospital in social welfare in order to avoid undesirable double counting.[7]

[6]See Jack (2005) and Choné and Ma (2011) for models where altruism is unknown.

[7]See Hammond (1987) for a justification of excluding altruistic preferences from social welfare.

2.3 Information

The severity β is privately observed by the hospital. However, it is common knowledge that f is common knowledge and continuous on B. We assume the standard monotone hazard rate property $\left(\frac{F(\beta)}{f(\beta)}\right)' > 0$.[8]

The occurrence of CCs is observable by the regulator and verifiable by a court of law. Since the regulator does not observe β, she only knows that the cost belongs to $[c_H(\underline{\beta}), c_H(\overline{\beta})]$ if CCs occurs, and to $[c_L(\underline{\beta}), c_L(\overline{\beta})]$ if not. By contrast, the quality chosen by the hospital is not observable.

The combination of adverse selection and moral hazard leads to a mixed regulation problem.

2.4 The problem

The contract. From Myerson (1982), we appeal to the revelation principle to focus on direct revelation mechanisms without loss of generality. Thus, the regulator designs a compensation scheme $\langle t_L(\tilde{\beta}), t_H(\tilde{\beta})\rangle$ specifying the payments for any hospital's report $\tilde{\beta}$.

The constraints. There are three kinds of constraints.

- *Incentive compatibility constraints*: The hospital has higher utility when it reports the true level of severity β of any patient and provides the recommended level of quality. Let $Q(\beta)$ be the regulator's recommendation on quality if the patient is β. Using (1), we get $\forall \beta, \tilde{\beta} \in B, \forall Q(\beta), \tilde{q} \in [0,1]$,

$$\begin{aligned} U(\beta) &= t_H(\beta) - c_H(\beta) + Q(\beta)\big[\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(Q(\beta)) + \alpha S(\beta) \\ &\geq t_H(\tilde{\beta}) - c_H(\beta) + \tilde{q}\big[\big(t_L(\tilde{\beta}) - t_H(\tilde{\beta})\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(\tilde{q}) + \alpha S(\beta). \quad (3) \end{aligned}$$

- *No dumping constraints*: The hospital has no incentive to shun unprofitable patients if $\forall \beta \in B$:

$$U(\beta) \geq 0, \quad (4)$$

where 0 is its reservation utility.

[8] This assumption avoids pooling contracts in the standard adverse-selection setting.

- *Overall limited liability constraints*: The hospital cannot end up with a negative payoff either in the worst case where all the population is subject to CCs or in the most favorable case where no patients are subject to CCs. This leads to:

$$\int_B \big\{t_L(\beta) - c_L(\beta)\big\} f(\beta) d\beta \geq 0; \tag{5}$$

$$\int_B \big\{t_H(\beta) - c_H(\beta)\big\} f(\beta) d\beta \geq 0. \tag{6}$$

The objective function. From (1), the expected payment is

$$qt_L + (1-q)t_H = c_H(\beta) + q\big(c_L(\beta) - c_H(\beta)\big) + \psi(q) - \alpha S(\beta) + U. \tag{7}$$

Combining (2) and (7), at the recommended level of quality, the social welfare is

$$S(\beta) - (1+\lambda)\big[c_H(\beta) + Q(\beta)\big(c_L(\beta) - c_H(\beta)\big) + \psi(Q(\beta)) - \alpha S(\beta)\big] - \lambda U(\beta), \tag{8}$$

and the expected social welfare

$$E(W) = \int_B \big\{S(\beta) - (1+\lambda)\big[c_H(\beta) + Q(\beta)\big(c_L(\beta) - c_H(\beta)\big) + \psi(Q(\beta)) - \alpha S(\beta)\big] - \lambda U(\beta)\big\} f(\beta) d\beta. \tag{9}$$

At this stage, it is important to notice that the third term in the integrand is the cost of the hospital's utility. When the hospital gets a rent, i.e. a positive utility, it is socially costly. This observation will be of great importance in the following analysis.

The health regulation problem consists in maximizing (9) wrt $Q(\beta)$ and $U(\beta)$, subject to (3)-(6).

3 Benchmarks

In this section, let us first consider the first-best solution. Then, we determine the optimal regulation under moral hazard either without or with limited liability.

3.1 First-best

Assume that quality and severity are observable by the regulator and liability constraints are ignored. Then, the first-best level of quality $Q^{FB}(\beta)$ follows from (8) and is such that,

$\forall \beta \in B$

$$c_H(\beta) - c_L(\beta) - \psi'(Q^{FB}(\beta)) = 0. \tag{10}$$

The efficient quality is such that the marginal surplus is null. That is, the marginal benefit, the cost saving, $c_H - c_L$, equals the marginal disutility ψ'.

3.2 Moral hazard

Assume now that quality is no longer observable whereas severity is. Let us first analyze the incentive constraints and then the optimal contracts.

The moral-hazard incentive constraints. Since severity is observable, the incentive constraints (3) reduce to the constraints, $\forall \beta \in B, \forall Q(\beta), \tilde{q} \in [0,1]$

$$\begin{aligned} Q(\beta)\big[\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(Q(\beta)) \\ \geq \tilde{q}\big[\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(\tilde{q}). \end{aligned} \tag{11}$$

Thus, faced with an incentive contract $\langle t_L(\beta), t_H(\beta)\rangle$, the hospital chooses the level of quality according to the following lemma.

Lemma 1. *The moral-hazard incentive constraints are equivalent to, $\forall \beta \in B$*

$$\begin{cases} \big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big) - \psi'(Q(\beta)) = 0, \\ \textit{with } Q(\beta) \textit{ implicitly defined by } Q(\beta) = q(t_L(\beta) - t_H(\beta), \beta). \end{cases} \tag{12}$$

Proof. (12) is the necessary condition applied to (11). According to the assumptions made on ψ, the condition (12) is also sufficient and $Q(\beta)$ is an interior solution. □

Two comments can be made. First, the moral-hazard incentive constraints (12) can be interpreted in the following manner. Since $c_H(\beta) - c_L(\beta) > 0$, the hospital is naturally incentivized to exert quality to save cost. It follows that the regulator can use the spread of payments $\big(t_L(\beta) - t_H(\beta)\big)$ to modulate (encourage or moderate) these incentives. In other words, $\big(t_L(\beta) - t_H(\beta)\big)$ represents the power of incentives.

Second, notice that $t_L(\beta) - t_H(\beta) < 0$ is compatible with the incentives to provide quality as long as

$$\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big) > 0. \tag{13}$$

By contrast, if it is not the case, the hospital provides no quality and CCs arise with certainty. In the following analysis, we will consider that (13) is always satisfied. It follows from (13) and the assumptions made on ψ that $\forall\big(t_L(\beta) - t_H(\beta)\big)$,

$$Q(\beta)\big[\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(Q(\beta)) > 0. \tag{14}$$

Now, let $Q_i(\beta)$ be the partial derivative of $q(t_L(\beta) - t_H(\beta), \beta)$ with respect to the i^{th} argument. Then, the following lemma exhibits the properties of the quality provided by the hospital.

Lemma 2. *The quality properties are*

$$\begin{aligned}
Q_1(\beta) &= \frac{1}{\psi''(Q(\beta))} > 0, \\
Q_2(\beta) &= -\frac{\big(c_L(\beta) - c_H(\beta)\big)'}{\psi''(Q(\beta))} > 0 \\
Q_{11}(\beta) &= -\frac{\psi'''(Q(\beta))}{\psi''(Q(\beta))^3} < 0, \\
Q_{12}(\beta) &= \frac{\psi'''(Q(\beta))}{\psi''(Q(\beta))^3}\big(c_L(\beta) - c_H(\beta)\big)' < 0.
\end{aligned}$$

Proof. Straightforward by applying the implicit function theorem to (12). □

Thus, quality increases with the power of incentives, at a decreasing rate. It also increases with severity. The severity decreases the marginal productivity of the power of incentives.

Equipped with the incentives to provide quality, let us now examine the moral-hazard contracts.

No overall limited liability. If we ignore the overall limited liability constraints, the regulator's problem is to maximize the objective function (9) subject to the no shun constraints (4), given the moral-hazard incentive constraints in Lemma 1. Then, the optimal regulation contract is given in the following lemma.

Lemma 3. *The moral-hazard regulation contract with no overall limited liability entails,* $\forall\beta \in B$

$$U(\beta) = 0, \tag{15}$$

$$c_H(\beta) - c_L(\beta) - \psi'(Q(\beta)) = 0. \tag{16}$$

Proof. Straightforward. □

To analyze this contract, recall that hospital rents are costly. Thus, whenever possible, the regulator leaves no rent. This is precisely what (15) states. From (16), we see that the optimal regulation entails an efficient level of quality. In that case, the marginal benefit, $\big(c_H - c_L\big)$, equals the marginal disutility ψ'.

From (12) and (16), it follows that the power of incentives is necessarily null. This implies, $\forall \beta \in B$

$$t_L(\beta) = t_H(\beta). \tag{17}$$

So, in a context of moral hazard with no overall limited liability, the features of the optimal regulation are:

- refinement with or without CCs is not optimal,
- refinement based on severity is optimal.

The optimal regulation can be implemented by a fixed payment $t(\beta) = t_L(\beta) = t_H(\beta)$, such that $U = 0$. This payment can be written as

$$t(\beta) = c_H(\beta) + Q(\beta)\big(c_L(\beta) - c_H(\beta)\big) + \psi(Q(\beta)) - \alpha S(\beta).$$

Overall limited liability. Let us now analyze the optimal regulation under moral hazard with overall limited liability. Let us introduce a notation and a lemma. We define the function $LR(\beta)$ as

$$LR(\beta) = Q(\beta)\big[\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(Q(\beta)) + \alpha S(\beta). \tag{18}$$

Lemma 4. *The overall limited liability constraints (5) and (6) are equivalent to*

$$\int_B U(\beta) f(\beta) d\beta \geq \int_B LR(\beta) f(\beta) d\beta. \tag{19}$$

Proof. First, from (12), we get $t_H(\beta) - c_H(\beta) = t_L(\beta) - c_L(\beta) - \psi'(Q(\beta))$. So, the constraint (6) becomes $\int_B \big\{t_L(\beta) - c_L(\beta)\big\} f(\beta) d\beta \geq \int_B \psi'(Q(\beta)) f(\beta) d\beta$. Since $\psi'(Q(\beta)) > 0 \ \forall \beta$, we have $\int_B \big\{t_L(\beta) - c_L(\beta)\big\} f(\beta) d\beta > 0$. Therefore, if (6) is satisfied, (5) is automatically too. Second, using (1), we have $t_H(\beta) - c_H(\beta) = U(\beta) - \big[Q(\beta)\big[\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(Q(\beta)) + \alpha S(\beta)\big]$. Thus, (6) and (18) lead to (19). □

The overall limited liability constraint (19) can be interpreted. Recall that U is the hospital's rent. By (14), the term LR is strictly positive, and thus higher than the reservation utility. So, this represents the minimal rent that the regulator must leave to the hospital. This is the so-called limited liability rent due to the fact that the hospital cannot end up with a negative payoff. Thus, the LHS of (19) corresponds to the overall rent whereas the RHS corresponds to the overall limited liability rent. The limited liability constraints come down to the fact that the former cannot be lower than the latter.

Given the moral-hazard incentive constraints (12), the regulator's problem is to maximize the objective function (9) subject to the no shun constraints (4) and the overall limited liability constraint (19). Then, the following lemma presents the optimal regulation contract.[9]

Lemma 5. *The moral-hazard regulation contract with overall limited liability entails,* $\forall \beta \in B$

$$U(\beta) > 0, \tag{20}$$

$$c_H(\beta) - c_L(\beta) - \psi'(Q(\beta)) = \frac{\lambda}{1+\lambda} Q(\beta)\psi''(Q(\beta)). \tag{21}$$

Let us interpret this lemma. Equation (20) tells us that the hospital gets a strictly positive rent. Indeed, U cannot be set to 0 as previously, otherwise the overall limited liability constraint (19) would be violated. Therefore, U must be increased such that the overall rent, $\int U f d\beta$, is just equal to the overall limited liability rent $\int LR f d\beta$. It follows that the constraint (19) becomes even less costly for the regulator as the overall limited liability rent is reduced. As it happens, the limited liability rent increases with the power of incentives $\left(t_L - t_H\right)$.[10] Thus the cost of the overall limited liability rent can only be reduced through a decrease in the power of incentives. It follows from Lemma 2 that the level of quality is lower than the first-best level. Indeed, we see, from (21), that the level of Q is now set such that the marginal surplus equals the marginal cost of the limited liability rent (weighted by $\frac{\lambda}{1+\lambda}$).

Combining (12) and (21), the power of incentives now becomes

$$t_L(\beta) - t_H(\beta) = -\frac{\lambda}{1+\lambda} Q(\beta)\psi''(Q(\beta)).$$

[9] See appendix 6.1 for a proof.

[10] This result is straightforward using the definition of $LR(\beta)$ and the envelop theorem.

Obviously, the power of incentives is negative. So, it is decreased compared to the case without overall limited liability.

So, in a context of moral hazard with overall limited liability, the features of the optimal regulation are:

- refinement with or without CCs becomes optimal,
- refinement based on the severity remains optimal.

Besides, we can note that the payment in the event of CCs is higher than without CCs. The optimal regulation can be implemented by an infinity of payments. However, a very simple implementation is $t_H(\beta) = c_H(\beta)$.

4 Adverse selection, moral hazard, and liability

Let us now assume that the severity of illness β is privately observed by the hospital. Thus, we analyze the optimal regulation under adverse selection, moral hazard, and limited liability. We first reformulate the incentives and no shun constraints and then we analyze the optimal regulation contracts.

4.1 Reformulation

Let us make the following assumption.

Assumption 1. $Q(\beta)c'_L(\beta) + \big(1 - Q(\beta)\big)c'_H(\beta) > \alpha S'(\beta)$.

Assumption 1 means that the expected cost increases faster than the benefit.[11]

Regarding incentive constraints, the following lemma can be stated.[12]

Lemma 6. *The incentive constraints (3) are equivalent to,* $\forall \beta \in B$

$$U'(\beta) = -Q(\beta)\big(c_L(\beta) - c_H(\beta)\big)' - c'_H(\beta) + \alpha S'(\beta) < 0, \tag{22}$$

$$\big(t_L(\beta) - t_H(\beta)\big)' \geq 0. \tag{23}$$

[11]The same kind of assumption is used by Chalkley and Malcomson (2002), insofar as they consider that costs plus non monetary costs rise in β faster than benefit.

[12]See appendix 6.2 for a proof.

The first condition (22) indicates that the slope of the information rent is $-Q(\beta)\big(c_L(\beta)-c_H(\beta)\big)'-c'_H(\beta)+\alpha S'(\beta)$. Under Assumption 1, this is negative. This reflects the idea that the hospital's natural incentive is to overestimate the severity of illness. So, the slope indicates how the rent must change with β to compensate for this incentive. Then, the slope of the information rent is negative which means that a higher rent must be left as severity declines.

The second condition (23) indicates that the power of incentives must increase with severity.

Observe also that the slope is reduced (i.e. becomes less negative) when Q is increased, thus when the power of incentives $\big(t_L - t_H\big)$ increases from Lemma 2.

Let us now examine the no shun constraints.

Lemma 7. *The no shun constraints (4) are equivalent to*

$$U(\overline{\beta}) \geq 0. \tag{24}$$

Proof. Since $U(\beta)$ is strictly decreasing from (22), $U(\overline{\beta}) \geq 0$ ensures that the no shun constraints are satisfied for severity $\beta < \overline{\beta}$. □

Given the moral-hazard incentive constraint (12), the regulator's problem is to maximize the objective function (9) subject to the overall limited liability constraints (19), the incentive constraints (22) and (23), and the no shun constraint (24).

4.2 Optimal contracts

Our analysis will show that the optimal contract to be offered to the hospital depends on its level of altruism. More precisely, let us introduce two (endogenously determined) threshold values $\underline{\alpha}$ and $\overline{\alpha}$, with $\underline{\alpha} < \overline{\alpha}$. Like Makris and Siciliani (2013), given these threshold values, we will refer to the level of altruism as low ($\alpha < \underline{\alpha}$), moderate ($\underline{\alpha} < \alpha < \overline{\alpha}$), or high ($\alpha > \overline{\alpha}$).

Then, let us first study the optimal contract under successively low and high values of altruism. Second, we analyze the case of moderate values of altruism.

The low-altruism case, i.e. $\alpha < \underline{\alpha}$. When the hospital exhibits a low level of altruism, the following proposition can be stated.[13]

[13] See appendix 6.3 for a proof.

Proposition 1. *Let $\alpha < \underline{\alpha}$. The optimal regulation contract under moral hazard, adverse selection, and overall limited liability entails,* $\forall \beta \in B$

$$\underline{U}^*(\beta) \geq 0, \text{ with equality holding at } \overline{\beta}, \tag{25}$$

$$c_H(\beta) - c_L(\beta) - \psi'(\underline{Q}^*(\beta)) = \frac{\lambda}{1+\lambda}\frac{F(\beta)}{f(\beta)}\big(c_L(\beta) - c_H(\beta)\big)', \tag{26}$$

with $\underline{\alpha}$ such that (19) is satisfied at equality at $\langle \underline{t}_L^*(\beta), \underline{t}_H^*(\beta)\rangle$.

This proposition calls for some comments. Equation (25) states that the regulator must leave a rent to the hospital (except for the patient with the highest severity). This rent is an information rent which comes from Lemmas 6 and 7, and is equal to

$$\underline{IR}^*(\beta) = \int_{\beta}^{\overline{\beta}} \big\{\underline{Q}^*(u)\big(c_L(u) - c_H(u)\big)' + c_H'(u) - \alpha S'(u)\big\}du + \underline{U}^*(\overline{\beta}),$$

with $\underline{U}^*(\overline{\beta}) = 0$.

It is paid to elicit truthful information from the hospital, i.e. to cancel its natural incentives to overestimate severity.

As we already know, this rent is costly. To reduce this agency cost, the regulator introduces distortions with respect to the first-best, which impact the quality provided by the hospital. More precisely, from (26), it is easy to observe upward distortions, except for $\beta = \underline{\beta}$. In other words, quality is increased in comparison with the first-best level defined in (10) since it reduces the slope, and thus the level of the information rent. For $\beta = \underline{\beta}$, the RHS of (26) vanishes and quality equals the first-best level. At the optimum, Q is increased until the marginal surplus equals the (negative) marginal cost of the information rent (weighted by $\frac{\lambda}{1+\lambda}$). More precisely, F measures the proportion of severity that the hospital could overestimate until β if it had no information rent.

In a nutshell, the trade-offs at work in the low-altruism case are those of the standard adverse-selection model. Indeed, when the level of altruism is low, the overall limited liability is "easily"satisfied. In other words, the information rent left to the hospital is sufficient to ensure that the overall rent $\int U f d\beta$ covers the overall limited liability rent $\int R f d\beta$ and so that the overall limited liability constraint is free. Therefore, the dominant purpose in the overall limited liability constraint (19) is to reduce the rent U, as in a model with adverse selection alone.

In order to increase the level of quality provided, the regulator increases the power of incentives (relative to the first-best situation). More precisely, combining (12) and (26) the optimal power of incentives in the low-altruism case is

$$\underline{t}_L^*(\beta) - \underline{t}_H^*(\beta) = -\frac{\lambda}{1+\lambda}\frac{F(\beta)}{f(\beta)}\big(c_L(\beta) - c_H(\beta)\big)' \geq 0.$$

Therefore, the payment when CCs arise is lower than when not $\forall \beta \neq \underline{\beta}$ and both payments are equal when $\beta = \underline{\beta}$.

To summarize, under the low-altruism case, the features of the optimal regulation are:

- refinement based on the severity is optimal,
- refinement with or without CCs is also optimal.

These properties are also those of the moral-hazard contract. However, adding adverse selection to moral hazard implies a major difference: the payment with CCs is now lower than without CCs which implies that the quality provided is higher (instead of lower) than the first-best.

The high-altruism case, i.e. $\alpha > \overline{\alpha}$. When the hospital exhibits a high level of altruism, the following proposition can be stated.[14]

Proposition 2. *Let $\alpha > \overline{\alpha}$. The optimal moral-hazard adverse-selection regulation contract with overall limited liability entails $\forall \beta \in B$*

$$\overline{U}^*(\beta) > 0, \tag{27}$$

$$c_H(\beta) - c_L(\beta) - \psi'(\overline{Q}^*(\beta)) = \frac{\lambda}{1+\lambda}\int_B \overline{Q}^*(\beta)\psi''(\overline{Q}^*(\beta))f(\beta)d\beta. \tag{28}$$

with $\overline{\alpha}$ such that (19) is satisfied at equality at $\langle \overline{t}_L^*(\beta), \overline{t}_H^*(\beta)\rangle$ and $\overline{U}^*(\overline{\beta}) = 0$.

This proposition can be interpreted. Except for the integral in the RHS of (28), the optimal contract in the high-altruism case is the same as those of moral hazard alone with overall limited liability. Indeed, whatever the level of severity, the contract entails

[14] See appendix 6.3 for a proof.

- a rent left to the hospital from (27),
- a downward distortion of quality from (28).

Why? When the hospital's altruism is high, the overall limited liability is "hardly"satisfied. In other words, the overall rent at the preceding solution, i.e. when $U = \underline{U}^*$, is no longer sufficient to cover the overall limited liability rent and this constraint must be binding. So, in the overall limited liability constraint (19), the dominant purpose of the regulator is to reduce the overall limited liability rent, and thus the limited liability rent. Therefore, the regulator faces, a priori, the same trade-offs as with moral hazard alone. Her ideal solution would be to propose the same contract. However, this is impossible since the moral-hazard power of incentives is not implementable, insofar as it violates the monotonicity condition which states that the power of incentives must be non-decreasing.

In this case, the regulator must seek the implementable contract which is as close to the moral-hazard contract as possible. She does that by pooling the moral-hazard solution. Indeed, combining (12) and (28), the power of incentives is

$$\overline{t}_L^* - \overline{t}_H^* = -\frac{\lambda}{1+\lambda} \int_B \overline{Q}^*(\beta)\psi''(\overline{Q}^*(\beta))f(\beta)d\beta,$$

which no longer depends on the level of severity. Note also that the payment in case of CCs is higher than without CCs.

To be complete, (27) states that the rent left to the hospital is a limited liability rent and (28) that Q is decreased because this reduces this rent. At the optimum, Q is determined such that the marginal surplus equals the overall marginal cost of the limited liability rent and not the pointwise one as in moral hazard alone (weighted by $\frac{\lambda}{1+\lambda}$).

To summarize, under the high-altruism case, the optimal regulation contract has the following features:

- refinement with or without CCs is optimal,
- refinement based on severity is not.

Thus, adding adverse selection to moral hazard implies a major change with respect to moral hazard alone: it becomes optimal not to take severity into account in the design of the optimal contract. This implies that the payment $t_H = c_H$ no longer matters insofar as this is not incentive compatible. Since U decreases with β, lesser severities imply a higher rent than the limited liability rent: greater severities need the reverse.

The moderate-altruism case, i.e. $\underline{\alpha} < \alpha < \overline{\alpha}$. When the hospital exhibits a moderate level of altruism, the following proposition can be stated.[15]

Proposition 3. *Let $\underline{\alpha} < \alpha < \overline{\alpha}$ and μ be the multiplier of (19).*

The moral-hazard adverse-selection contract with overall limited liability entails

- $\forall \beta \in B$

$$\lambda > \mu^* > 0, \tag{29}$$

$$U^*(\beta) \geq 0, \ \textit{with equality holding at } \overline{\beta}, \tag{30}$$

$$\begin{aligned} c_H(\beta) - c_L(\beta) - \psi'(Q^*(\beta)) = & \frac{\lambda - \mu^*}{1+\lambda} \frac{F(\beta)}{f(\beta)} \big(c_L(\beta) - c_H(\beta)\big)' \\ & + \frac{\mu^*}{1+\lambda} Q^*(\beta) \psi''(Q^*(\beta)), \end{aligned} \tag{31}$$

  whenever (31) leads to $(t_L^*(\beta) - t_H^*(\beta))' \geq 0$;

- *if there is an interval $[\beta_0, \beta_1] \subseteq B$ where (31) leads to $(t_L^*(\beta) - t_H^*(\beta))' < 0$, we get over an interval $[\beta^*, \beta^{**}] \supseteq [\beta_0, \beta_1]$*

$$\begin{aligned} c_H(\beta) - c_L(\beta) - \psi'(Q^*(\beta)) = \int_B \Bigg\{ & \frac{\lambda - \mu^*}{1+\lambda} \frac{F(\beta)}{f(\beta)} \big(c_L(\beta) - c_H(\beta)\big)' \\ & + \frac{\mu^*}{1+\lambda} Q^*(\beta) \psi''(Q^*(\beta)) \Bigg\} f(\beta) d\beta, \end{aligned}$$

  where $t_L^*(\beta^*) - t_H^*(\beta^*) = t_L^*(\beta^{**}) - t_H^*(\beta^{**})$ are given by (31).

This proposition shows that the optimal contract in the moderate-altruism case is a simple mix of the two polar contracts.

Let us first comment on the first point of Proposition 3. In this first point, the solution comes from the fact that the overall limited liability constraint is binding, i.e. $\mu^* > 0$ (see (29)), as in the high-altruism case, while being compatible with no rent at the highest

[15] See appendix 6.3 for a proof.

severity, i.e $U(\overline{\beta}) = 0$ (see (30)), as in the low-altruism case. Therefore, the marginal cost of the rent becomes the weighted average of the marginal cost of the information rent (weight $\frac{\lambda-\mu^*}{1+\lambda}$) and the marginal cost of the limited liability rent (weight $\frac{\mu^*}{1+\lambda}$). This is (31).

Besides, it should be noted that the RHS of (31) can be either positive or negative. More precisely, when $\beta = \underline{\beta}$, the first term of the RHS of (31) vanishes and therefore the RHS of (31) is positive, which corresponds to a downward distortion of the quality provided. Moreover, the RHS of (31) is obviously decreasing in β since $(t_L - t_H)$ is assumed to be increasing in β. Therefore, when β increases (and thus becomes higher than $\underline{\beta}$), we may have two cases:

- although the RHS of (31) decreases in β, it remains positive even for $\beta = \overline{\beta}$. In this case, we observe a downward distortion of the quality provided for all β,
- if the RHS of (31) is negative for $\beta = \overline{\beta}$, this implies that a threshold value, β^0, exists such that the RHS of (31) is positive for $\beta < \beta^0$, vanishes for $\beta = \beta^0$, and is negative for $\beta > \beta^0$. Therefore, the contract entails a downward distortion of the quality provided for $\beta < \beta^0$ and an upward distortion for $\beta > \beta^0$. When $\beta = \beta^0$, the hospital provides the first-best level of quality.

Moreover, combining (12) and (31), the power of incentives is

$$t_L^*(\beta) - t_H^*(\beta) = -\frac{\mu^*}{1+\lambda} Q^*(\beta)\psi''(Q^*(\beta)) - \frac{\lambda - \mu^*}{1+\lambda} \frac{F(\beta)}{f(\beta)} \big(c_L(\beta) - c_H(\beta)\big)'. \tag{32}$$

Following the same reasoning as for the quality provided, we have $t_L^*(\beta) < t_H^*(\beta)$ for $\beta = \underline{\beta}$. If the RHS of (32) is negative for $\beta = \overline{\beta}$, then $t_L^*(\beta) < t_H^*(\beta)$ for all β. If the RHS of (32) is positive for $\beta = \overline{\beta}$, then we have:

- $t_L^*(\beta) < t_H^*(\beta)$ for $\beta < \beta^0$,
- $t_L^*(\beta) = t_H^*(\beta)$ for $\beta = \beta^0$,
- $t_L^*(\beta) > t_H^*(\beta)$ for $\beta > \beta^0$.

Let us now comment on the second point of Proposition 3. We know from Proposition 2 that the marginal cost of the limited liability rent leads to a non implementable power of incentives. In this event, there must be pooling. The second point of Proposition 3 states that if this effect is sufficiently high over the interval $[\beta_0, \beta_1]$ so that the power of incentives strictly decreases, then pooling occurs on the interval $[\beta^*, \beta^{**}]$.

To summarize, when the hospital exhibits a moderate level of altruism, the optimal regulation contract has the following features:

- refinement with or without CCs is optimal (except for $\beta = \beta^0$),
- refinement based on severity is not always optimal.

5 Conclusion

In this paper, we have determined the optimal regulation contract to be offered to an altruistic hospital. Our analysis has several policy implications in terms of determination of DRG payments. First, it allows us to analyze whether some refinements observed in many countries (based on the severity of illness and on the occurrence of CCs) are optimal. Second, for each refinement, we determine the optimal level of the hospital's payment.

In a context of adverse selection, moral hazard, and limited liability, our analysis shows that the refinement based on the occurrence of CCs is optimal. This refinement corresponds to many DRG payment policies in practice, e.g. in France, Switzerland, and the United States. However, somewhat counterintuitively, when the hospital exhibits a low level of altruism, we show that the optimal payment in the occurrence of CCs has to be lower than without CCs. On the contrary, when the hospital's altruism is high, the hospital should receive a higher payment in the event of CCs. The moderate-altruism case seems to be much more difficult to implement since the comparison of both payments depends on several parameters such as cost functions, the shadow cost of public funds, and the level of severity.

Concerning the refinement based on the severity of illness, our analysis shows that it has to be introduced when the hospital's altruism is low. This refinement is not always optimal under moderate altruism and should not be used when the hospital exhibits a high level of altruism.

Our normative approach assumes that the optimal payments to be given to the hospital depend on its known level of altruism. However, in practice, the level of altruism may be difficult to assess. While empirical evidence seems to support theories of hospital altruism,[16] some studies have highlighted a huge heterogeneity in physicians' altruistic preferences.[17]

Moreover, the ownership of the hospital cannot be considered as the key criterion that determines the level of altruism of hospitals. Indeed, Duggan (2000) shows that decision-makers in private not-for-profit hospitals are no more altruistic than their counterparts in profit-maximizing facilities. Therefore, further research needs to be done to understand hospitals' intrinsic motivations and their responses to incentives in order to define more precisely the optimal regulatory policy.

6 Appendix

6.1 Proof of Lemma 5

To facilitate the resolution, we introduce the following variable. Let

$$L(\beta) = \int_{\underline{\beta}}^{\beta} \{U(\varepsilon) - LR(\varepsilon)\} f(\varepsilon) d\varepsilon.$$

Thus (19) leads to

$$L(\overline{\beta}) \geq 0. \tag{33}$$

Moreover, we get

$$L(\underline{\beta}) = 0, \tag{34}$$

$$L'(\beta) = \big\{U(\beta) - LR(\beta)\big\} f(\beta). \tag{35}$$

Therefore, the problem is an optimal control problem with $\big(t_L(\beta) - t_H(\beta)\big)$ and $U(\beta)$ the controls, $L(\beta)$ the state variable, (33)-(34) the initial and terminal conditions, and (35) the state equation. We associate the costate variable $\mu(\beta)$ with the state $L(\beta)$ and the multiplier $\eta(\beta)$ with the constraint (4).

[16]Cf. e.g. Gaskin (1997).

[17]See the survey on "provider altruism in health economics"by Galizzi et al. (2015).

Using (18), the Hamiltonian is

$$\begin{aligned}\mathcal{H}(\beta) =& \big\{S(\beta) - (1+\lambda)\big[c_H(\beta) + Q(\beta)\big(c_L(\beta) - c_H(\beta)\big) + \psi(Q(\beta)) - \alpha S(\beta)\big] - \lambda U(\beta)\big\} f(\beta) \\ &+ \mu(\beta)\big\{U(\beta) - \big[Q(\beta)\big[\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(Q(\beta)) + \alpha S(\beta)\big]\big\} f(\beta).\end{aligned}$$

The Lagrangian is

$$\mathcal{L} = H(\beta) + \eta(\beta) U(\beta).$$

Following Seierstad and Sydsaeter (1987) and ignoring arguments for simplicity, necessary conditions are, given (12),

$$\frac{\partial \mathcal{L}}{\partial (t_L - t_H)} = -(1+\lambda)\big(Q_1(c_L - c_H) + \psi' Q_1\big) f - \mu Q f = 0 \tag{36}$$

$$\frac{\partial \mathcal{L}}{\partial U} = -\lambda f + \mu f + \eta = 0 \tag{37}$$

$$\mu' = \frac{\partial \mathcal{L}}{\partial L} = 0; \tag{38}$$

complementarity slackness conditions are

$$\eta \geq 0, \eta U = 0; \tag{39}$$

and transversality conditions are

$$\mu(\underline{\beta}) \text{ no condition}; \mu(\overline{\beta}) \geq 0, \mu(\overline{\beta}) L(\overline{\beta}) = 0. \tag{40}$$

First, let $L(\overline{\beta}) > 0$.

Using (40), we get $\mu(\overline{\beta}) = 0$. Since μ is constant from (38), we get $\mu = 0$. Notice that we must have $\eta = \lambda f > 0$ from (37) (otherwise, $\lambda f = 0$, a contraction). It follows from (39) that $U = 0$. Using Lemma 1 and (36), we get $Q_1\big(t_L - t_H\big) = 0 \Rightarrow t_L = t_H$.

Inserting $U = 0$ and $t_L - t_H = 0$ into $L(\overline{\beta})$ leads to $-\int_B \big\{Q\big[c_H - c_L\big] - \psi(Q) + \alpha S\big\} f d\beta < 0$, that violates the initial condition (14).

Second, let $L(\overline{\beta}) = 0$.

From (40), we get $\mu(\overline{\beta}) \geq 0$. Let $\mu < \lambda$. Since μ and λ are constant, we have $\eta = (\lambda - \mu) f > 0$ by (37), which implies $U = 0$ by (39). Thus, using (14), $L(\overline{\beta})$ reduces to $-\int_B \big\{Q\big[\big(t_L - t_H\big) - \big(c_L - c_H\big)\big] - \psi(Q) + \alpha S\big\} f d\beta < 0$.

So, we must have $\eta = 0$ and $U > 0$ by (39). This leads to (20). It follows that $\mu = \lambda$ by (37). Inserting this into (36) leads to $\big(c_L - c_H\big) - \psi' = -\frac{\lambda}{1+\lambda}\frac{Q}{Q_1} > 0$. Then, using Lemma 2 gives (21).

Since the Hamiltonian does not depend on L and is linear in U, sufficient conditions require the Hamiltonian to be concave in $(t_L - t_H)$. This requires $-(1+\lambda)\big(Q_{11}(c_L - c_H) + \psi' Q_{11} + \psi'' Q_1\big) - \mu Q_1 < 0$. Using Lemma 2 and $\mu = \lambda > 0$, this occurs if $-(1+\lambda)\big(Q_{11}(c_L - c_H) + \psi'' Q_1\big) - \mu Q_1 < (1+\lambda)\psi' Q_{11} < 0$.

6.2 Proof of Lemma 6

Instead of insisting on the generalized incentive constraint (3), we adopt the usual process consisting in viewing the quality choice as being completely delegated to the hospital and incorporated into the adverse-selection problem. Following (12) in the moral-hazard section, the hospital selects a quality such that $\forall \beta, \tilde{\beta} \in B$

$$\big(t_L(\tilde{\beta}) - t_H(\tilde{\beta})\big) - \big(c_L(\beta) - c_H(\beta)\big) - \psi'(q(t_L(\tilde{\beta}) - t_H(\tilde{\beta}), \beta)) = 0. \tag{41}$$

The adverse-selection incentive constraints become $\forall \beta, \tilde{\beta} \in B$

$$\begin{aligned} U(\beta) =& u(\beta,\beta) \geq u(\tilde{\beta},\beta) = t_H(\tilde{\beta}) - c_H(\beta) \\ & \qquad + q(t_L(\tilde{\beta}) - t_H(\tilde{\beta}), \beta)\big[\big(t_L(\tilde{\beta}) - t_H(\tilde{\beta})\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] \\ & \qquad - \psi(q(t_L(\tilde{\beta}) - t_H(\tilde{\beta}), \beta)) + \alpha S(\beta). \end{aligned}$$

Incentive compatibility requires $\forall \beta \in B$

$$u_1(\beta,\beta) = 0, \tag{42}$$

$$u_{11}(\beta,\beta) \leq 0. \tag{43}$$

Using (41) to apply the envelop theorem, (42) is equivalent to

$$t_H'(\beta) + q(t_L(\beta) - t_H(\beta), \beta)\big(t_L(\beta) - t_H(\beta)\big)' = 0. \tag{44}$$

Using (42), we have $u_{11}(\beta,\beta) + u_{12}(\beta,\beta) = 0$. Thus (43) is equivalent to $u_{12}(\beta,\beta) \geq 0$. From (44), we get $u_{12}(\beta,\beta) = Q_2(t_L(\beta) - t_H(\beta), \beta)\big(t_L(\beta) - t_H(\beta)\big)'$. Using Lemma 2, we get (23).

Moreover, differentiating $U(\beta)$ and combining with (42), we get $U'(\beta) = u_2(\beta, \beta)$, which leads to (22) (using again the envelop theorem and (41)).

Finally, we can see that $\frac{\partial}{\partial \beta}\left(\frac{\partial u / \partial (t_L - t_H)}{\partial u / \partial t_H}\right) = Q_2(t_L(\beta) - t_H(\beta), \beta) > 0$, from Lemma 2. The Spence-Mirrless condition is satisfied and (22) and (23) are sufficient to elicit truthful revelation.

6.3 Proof of Propositions 1-3

To simplify the analysis, we ignore in a first step the constraint (23). We again use the variable $L(\beta)$. The problem is an optimal control problem with $\big(t_L(\beta) - t_H(\beta)\big)$ the control, $L(\beta)$ and $U(\beta)$ the state variables, and (33), (34), and (24) the initial and terminal conditions. Let $\mu(\beta)$ be the costate variable associated with the state $L(\beta)$ and $\omega(\beta)$ the costate variable associated with the state $U(\beta)$. The Hamiltonian is

$$\begin{aligned}\mathcal{H}(\beta) =& \big\{S(\beta) - (1+\lambda)\big[c_H(\beta) + Q(\beta)\big(c_L(\beta) - c_H(\beta)\big) + \psi(Q(\beta)) - \alpha S(\beta)\big] - \lambda U(\beta)\big\} f(\beta) \\ &+ \mu(\beta)\big\{U(\beta) - \big[Q(\beta)\big[\big(t_L(\beta) - t_H(\beta)\big) - \big(c_L(\beta) - c_H(\beta)\big)\big] - \psi(Q(\beta)) + \alpha S(\beta)\big]\big\} f(\beta) \\ &- \omega(\beta)\big\{c'_H(\beta) + Q(\beta)\big(c_L(\beta) - c_H(\beta)\big)' - \alpha S'(\beta)\big\}.\end{aligned}$$

Following Seierstad and Sydsaeter (1987) and ignoring arguments for simplicity, necessary conditions are, given (12),

$$\frac{\partial \mathcal{H}}{\partial (t_L - t_H)} = -(1+\lambda)\big(Q_1(c_L - c_H) + \psi' Q_1\big) f - \mu Q f - \omega Q_1 \big(c_L - c_H\big)' = 0, \tag{45}$$

$$\mu' = \frac{\partial \mathcal{H}}{\partial L} = 0, \tag{46}$$

$$\omega' = -\frac{\partial \mathcal{H}}{\partial U} = \lambda f - \mu f; \tag{47}$$

and transversality conditions are

$$\mu(\underline{\beta}) \text{ no condition}; \mu(\overline{\beta}) \geq 0, \mu(\overline{\beta}) L(\overline{\beta}) = 0, \tag{48}$$

$$\omega(\underline{\beta}) = 0; \omega(\overline{\beta}) \geq 0, \omega(\overline{\beta}) U(\overline{\beta}) = 0. \tag{49}$$

Proposition 1. Let $L(\overline{\beta}) > 0$.

From (48), we get $\mu(\overline{\beta}) = 0$. Since μ is constant from (47), we get $\mu = 0$. Thus $\omega' = \lambda f > 0$ from (46), which implies $\omega = \lambda F$, $\omega(\overline{\beta}) = \lambda > 0$, and $U(\overline{\beta}) = 0$ by (49). This is (25). Inserting this into (45) and rearranging, we get (26).

Moreover, using (12) and (45), we get $-(1+\lambda)Q_1\big(t_L - t_H\big)f - \lambda F Q_1\big(c_L - c_H\big)' = 0$,

$$\Rightarrow t_L - t_H = -\frac{\lambda}{1+\lambda}\frac{F}{f}\big(c_L - c_H\big)' > 0.$$

Differentiating, we get $(t_L - t_H)' = -\frac{\lambda}{1+\lambda}\left(\left(\frac{F}{f}\right)'\big(c_L - c_H\big)' + \left(\frac{F}{f}\right)\big(c_L - c_H\big)''\right) > 0$.

Finally, integrating (22), we get $\underline{U}^* = \int_{\underline{\beta}}^{\overline{\beta}}\big\{c_H' + \underline{Q}^*\big(c_L - c_H\big)' - \alpha S'\big\}d\varepsilon$. So, $\int_B \underline{U}^* f d\beta = \int_B \big\{c_H' + \underline{Q}^*\big(c_L - c_H\big)' - \alpha S'\big\}F d\beta$ after integration by parts. Plugging this function into $L(\underline{\beta}) > 0$, we get

$$\int_B \big\{\big[c_H' + \underline{Q}^*\big(c_L - c_H\big)' - \alpha S'\big]\frac{F}{f} - \big[\underline{Q}^*\big[\big(\underline{t}_L^* - \underline{t}_H^*\big) - \big(c_L - c_H\big)\big] - \psi(\underline{Q}^*) + \alpha S\big]\big\} f d\beta > 0$$
$$\Leftrightarrow \int_B \big\{\big[c_H' + \underline{Q}^*\big(c_L - c_H\big)'\big]\frac{F}{f} - \big[\underline{Q}^*\big[\big(\underline{t}_L^* - \underline{t}_H^*\big) - \big(c_L - c_H\big)\big] - \psi(\underline{Q}^*)\big]\big\} f d\beta > \alpha \int_B \big\{S'F + Sf\big\}d\beta$$
$$\Leftrightarrow \alpha < \frac{1}{S(\overline{\beta})}\int_B \big\{\big[c_H' + \underline{Q}^*\big(c_L - c_H\big)'\big]\frac{F}{f} - \big[\underline{Q}^*\big[\big(\underline{t}_L^* - \underline{t}_H^*\big) - \big(c_L - c_H\big)\big] - \psi(\underline{Q}^*)\big]\big\} f d\beta.$$

Let us define $\underline{\alpha}$ as in Proposition 1. This completes the proof of Proposition 1.

Propositions 2 and 3. Let $L(\overline{\beta}) = 0$.

From (46) and (48), we get μ constant and $\mu \geq 0$.

Let $\mu > \lambda$.

Since μ and λ are constant, we have $\omega' = (\lambda - \mu)f < 0$ by (47). By (49), this implies $\omega(\overline{\beta}) < 0$, a contradiction.

Let $\mu = \lambda$.

It follows $\omega' = 0$ by (47). By (49), this implies $\omega = 0$ and thus $U(\overline{\beta}) > 0$. This proves (27). Inserting this into (45), we get, using (12) and after simplifications

$$-(1+\lambda)\big(Q_1\big(t_L - t_H\big)\big) - \lambda Q = 0.$$

Totally differentiating, we get, using Lemma 2 and $\big(t_L - t_H\big) < 0$ by Lemma 5,

$$\big(t_L - t_H\big)' = -\frac{-(1+\lambda)\big(Q_{12}\big(t_L - t_H\big) + Q_1\big) - \lambda Q_2}{-(1+\lambda)\big(Q_{11}\big(t_L - t_H\big) + Q_1\big) - \lambda Q_1} < 0.$$

So, this solution does not satisfy the monotonicity constraint $\left(t_L - t_H\right)' \geq 0$. Thus, the optimal solution is given by the average solution $t_L - t_H = \frac{\lambda}{1+\lambda}\int_B \frac{Q}{Q_1} f d\beta$. Using (12) and Lemma 2 completes the proof.

Following analogous calculus as in the preceding paragraph, we get

- $\overline{U}^* = \overline{U}^*(\overline{\beta}) + \int_{\beta}^{\overline{\beta}} \left\{c_H' + \overline{Q}^*\left(c_L - c_H\right)' - \alpha S'\right\} d\varepsilon$,
- $\int_B \overline{U}^* f d\beta = \int_B \left\{c_H' + \overline{Q}^*\left(c_L - c_H\right)' - \alpha S'\right\} F d\beta + \overline{U}^*(\overline{\beta})$,
- $\alpha = \frac{1}{S(\overline{\beta})}\left(\int_B \left\{\left[c_H' + \overline{Q}^*\left(c_L - c_H\right)'\right]\frac{F}{f} - \left[\underline{Q}^*\left[\left(\overline{t}_L^* - \overline{t}_H^*\right) - \left(c_L - c_H\right)\right] - \psi(\overline{Q}^*)\right]\right\} f d\beta + \overline{U}^*(\overline{\beta})\right)$.

Let us define $\overline{\alpha}$ as in Proposition 2. This completes the proof of Proposition 2.

Let $0 < \mu < \lambda$.

Since μ and λ are constant, we have $\omega' = (\lambda - \mu) f > 0$ by (47). By (49), this implies $\omega = (\lambda - \mu) F$ and thus $\omega(\overline{\beta}) = (\lambda - \mu) > 0 \Rightarrow U(\overline{\beta}) = 0$. This is (30).

Moreover, we get:

$$-(1+\lambda) Q_1\left(t_L - t_H\right) f - \mu Q f - (\lambda - \mu) F Q_1 \left(c_L - c_H\right)' = 0$$

and

$$t_L - t_H = -\frac{F}{f}\left(c_L - c_H\right)' \frac{\lambda - \mu}{1+\lambda} - \frac{Q}{Q_1}\frac{\mu}{1+\lambda}. \tag{50}$$

Combining (50) and (12) yields (31).

When such power of incentives is not implementable, standard techniques, e.g. Guesnerie and Laffont (1984), lead to the second part of Proposition 3.

Since the Hamiltonian does not depend on L and is linear in U, sufficient conditions require the Hamiltonian to be concave in $(t_L - t_H)$. This requires $-(1+\lambda)\big(Q_{11}(c_L - c_H) + \psi' Q_{11} + \psi'' Q_1\big) f - \mu Q_1 f - \omega Q_{11}\left(c_L - c_H\right)' < 0$. Using Lemma 2, $\mu \geq 0$, and $\omega \geq 0$, this occurs if $-(1+\lambda)\big(Q_{11}(c_L - c_H) + \psi'' Q_1\big) f - \mu Q_1 f - \omega Q_{11}\left(c_L - c_H\right)' < (1+\lambda)\psi' Q_{11} f < 0$.

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