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http://dx.doi.org/10.14195/2183-203X_39_1

Doctor-Nurse Teams, Incentives and Behavior

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resumo

abstract / résumé

Ao longo dos últimos anos, os enfermeiros têm registado ganhos de conhecimentos e é habitual que enfermeiros e médicos trabalhem juntos em equipa. Usando um modelo baseado na teoria dos contratos, o objetivo deste artigo é analisar os efeitos de uma melhoria da produtividade dos enfermeiros nos incentivos pagos e no comportamento dos médicos e enfermeiros, em particular, quando o orçamento é limitado. Os resultados mostram que depois de uma melhoria da produtividade dos enfermeiros, estes passam a receber um incentivo de menor valor mas o orçamento global dos incentivos é mais elevado. Quando o orçamento dos cuidados de saúde é limitado, os resultados mostram que o tratamento dos doentes fica ao cargo dos enfermeiros, e não dos médicos, refletindo uma atitude de *free-riding* por estes. O contributo deste trabalho é particularmente relevante para os *policy makers* dos recursos humanos das unidades de cuidados primários.

JEL Classification: I19, D82.

Nurses have been gaining expertise over time and it is common that they work together in a team with doctors to treat patients. Using a model based on contract theory, the aim of this article is to analyze the effects of an improvement in nurses' productivity on the incentives paid and on the behavior of doctors and nurses, in particular when the budgets are limited. The results show that following an improvement in nurse productivity, nurses' incentives are lower but the overall budget of incentives is higher. Under a restricted health care budget, results show that the treatment of patients is mainly carried out by nurses, and not doctors, reflecting free-riding by doctors. The contribution of this work is particularly relevant for human resources policy makers in primary health-care units.

Au cours des dernières années, les infirmières ont enregistré des gains en matière de connaissances et il est habituel pour les infirmières et les médecins travaillent ensemble comme une équipe. Basé sur un modèle de la théorie des contrats, le but de cet article est analyser les effets de l'amélioration de la productivité des infirmières sur les incitations payées et les comportements des médecins et des infirmières, en particulier, lorsque le budget est limité. Les résultats montrent que, après une amélioration de la productivité des infirmières, ils doivent recevoir un motivation de valeur inférieur, mais le budget global d'incitations est plus élevé. Lorsque le budget des soins de santé est limité, les résultats montrent que le traitement des patients est de la responsabilité des infirmières, et pas des médecins, ce qui reflète une attitude de *free-riding* par eux. La contribution de ce travail est particulièrement pertinent pour les décideurs politiques de ressources humaines des établissements de soins primaires.





1. Introduction

It is natural that doctors and nurses work in teams. The list of references to this type of team outside of Economics is long. These teams may be explicit (Firth-Cozens, 2001) or not (Anderson and Halley, 2008; Radcliffe, 2000), and may or may not be part of a hierarchy of authority.

The main feature of a doctor-nurse team is that it aims to improve a patient's health condition, but it is not possible to clearly identify the contribution of each individual to that goal. This idea of a team coincides with the definition of teams proposed by Alchian and Demsetz (1972)¹.

Doctor-nurse team work was initially described by Stein (1967). In this team, the doctor is more relevant than the nurse, in the sense that the nurse has a lower level of education, status and payment. The nurse is seen as the doctor's third arm with the nurse's productivity comparably lower.

More than twenty years later, Stein and two of his colleagues revisited doctor-nurse team work and conclude that nurses now have a different role (Stein et al., 1990). Nurses have become more autonomous health professionals, with well defined areas of expertise, and nursing has increasingly become an associated science to medicine.

The improvement in the level of expertise and productivity of nurses has been documented by Brown (1988). He concludes that physicians' offices would be more profitable if nurses substituted assistant physicians. Some research shows that nurses have increased their expertise so much that they can substitute doctors². A review of this topic has been carried out by Richardson and Maynard (1995).

Our aims are: i) to model the doctor-nurse team game, where agents are heterogeneous in their productivities, ii) to analyze the effects of an improvement in nurse productivity on the incentives offered and how the choice of agents on their efforts impacts patients, in particular, under limited health budgets. It is not our purpose to study the relationship between doctors and nurses.

The proposed model is based on contract theory employing a comparative statics analysis for two different points in time. It considers a team of a doctor and a nurse, who exert effort to treat or improve the health status of patients. The improvement in the nurse's expertise is captured in the team production function. The principal is the contractor who pays the incentives to the team but he cannot observe their efforts; he only observes the outcome of the efforts.

The results show that with nurses having improved their expertise, the bud-get needed to provide incentives to both agents is higher than before. This happens because the increase in the nurse's productivity creates a free-riding possibility for the doctor. As a consequence, the doctor needs higher incentives to be diligent. If budgets are sticky and limited then it becomes impossible to provide high incentives for both agents. The contractor can adopt one of two possible attitudes: either the incentives are kept constant, or one agent is chosen to whom the necessary incentives will be provided to exert effort. In both situations, the effort to treat the patient is provided by the nurse, and not the doctor, because the nurse is highly productive and can substitute for the doctor's effort.

The scenario described here is more likely in non-surgical areas of health care, such as primary care and family health care units as well as rehabilitation units. The model described in this work does not apply to a hospital ward, where a set of patients are to be found, but it applies to primary health care units where the medical attention is fully given to each patient at a time. There is no trade-off between agents' effort and number of patients receiving attention. All patients looking for medical primary care, receive it. This care is provided either with high, or low, professional commitment to improve the patient condition.

¹ According to Alchian and Demsetz's definition, health care team work is such that it is not possible to separate it into two different production functions, respectively dependent on the labor of doctor and nurse.

² For instance, in some countries and under some conditions, nurses prescribe drugs (Lewis-Evans and Jester, 2004; While and Biggs, 2004).



This work provides new insights for policy makers and managers of health care units. Firstly, it provides some of the theoretical underpinnings for the possible and potential substitutability between doctors and nurses. Secondly, it describes how doctors and nurses choose their efforts when there are team performance incentives. These incentives may be monetary or non-monetary. An example of monetary team incentives can be found in Portuguese primary care (Fialho et al, 2011) or in the accountable care organizations in the USA (Frandsen and Rebitzer, 2014). Thirdly, the increasing concerns with efficiency and internal organization raise several challenges. The results in this paper show that the most common form of organization in health care ought to be handled carefully. This organization, based on teams, may raise several problems related to payments, professional conflicts and distrust, along with doubts about medical hierarchies and responsibilities, whenever nurses tend to take on more tasks to guarantee that patients get treatment or health improvement. Some of these issues relating to doctor-nurse relationships have been discussed by different researchers (e.g. Kenaszchuk et al., 2010 and Tang et al., 2013).

This paper is organized as follows. In the following section we describe the model. In Sections 3 and 4, we analyze the old and new team production technology. Then, in Section 5, we briefly extend the model. Finally, in the last section we present the conclusion. The proofs are presented in the appendix.

2. The model

2.1. The players

We assume a simplified and reduced hierarchy of two tiers: the top tier is the principal or the part contracting health professionals (it can be the Ministry of Health, a primary health care unit, an insurance company or a manager –here it is referred to as the contractor) and the bottom tier is the health care team, composed of one doctor and one nurse.

2.1.1. The health care team

The team in health care is composed of a doctor (d) and a nurse (n) and it is not possible to separate the contribution of each one of them to treat patients. Patients treatment in primary care require triage, examination, prescription, medicines dispensation, patients advise as well as emotional and physical support and so on. Although it may be possible to identify tasks and who does them, it is not possible to quantify and analyse the importance of each in the success of treating a patient.

The agents are risk neutral and limited liability constrained.

We assume that both agents exert an effort for treating the patient: the doctor exerts effort a and nurse exerts effort e . These efforts, for simplicity, are of a high or low level: $a, e \in \{H, L\}$. We represent the probability that agents choose a high level of effort by p_i , $i = d, n$. We also represent the agent effort choices by the set (a, e) , where $a, e \in \{H, L\}$. So the set of possible alternatives is (HH) , (HL) , (LH) and (LL) .

The agents have a von-Neumann Morgenstern utility function which is additively separable in money (w) and in cost of effort (v): $U_i = w_i - v_i(j)$, $i = d, n$ and $j = a, e$. This component of the cost of effort captures any re-scaling of the cost of effort that one may wish to consider, such as that arising from on-the-job training or job features.

Assumption 1

The disutility of the agent's efforts is positive, if the effort is high. But if the effort is low, there is no cost of effort. Formally, we have $v_i(H) = v_i > 0$ and $v_i(L) = 0$, $i = d, n$.



For the sake of simplicity, we take it that $v_d = qv_n$, and $q > 1$.

We assume that doctors have a larger cost of effort ($q > 1$) due to the features of their training, continuing study and job characteristics.

For very similar costs of effort, it suffices to perform a local analysis such that q tends to 1 ($q \rightarrow 1$). If it is believed that the cost of efforts is very different because of the nature of the tasks performed by doctors and nurses, then q takes large values. So the parameter q allows capturing both any similarity and difference between the agents' costs of effort.

We assume for now that the reservation utility (\bar{U}_i , $i=d, n$) of both agents is sufficiently small, non negative, and it may differ between doctor and nurse.³

We assume for the sake of simplicity that the reservation utility does not change over time. Changing the reservation utility over time would just re-size results without changing the conclusions. On the other hand, we can assume that the outside option for agents in health care is either working in a least preferred position in the health care sector or working in the non-health care sector or even being unemployed, which would always be the least preferred option for these agents.

2.1.2. The contractor

We consider the contractor to be a perfect agent of a Ministry of Health or of shareholders such that limited budgets are available to pay incentives and pressure exists for cost constraint, either from the parliament or from the share-holders. We also consider the contractor to be a perfect agent for patients, looking for the best possible outcome for them.

The contractor aims to maximize the patient's benefit net of incentives paid to doctors and nurses, in expected terms. We assume that the expected benefit of patients is sufficiently large so that the most preferable situation is the one where both agents exert high effort that is (HH). All the other possible situations yield a lower patient benefit. These situations may occur where agents exert less than the high level of effort, such as in (HL), (LH) and (LL). We also assume that such patient benefit may be ranked in decreasing order as (HH), (HL), (LH) and (LL). The patient's benefit is represented by G_{ij} , $i, j = H; L$, and so the highest is G_{HH} and the lowest G_{LL} .

When no budget limitation exists and there is a sufficient budget to pay the incentives to doctors and nurses to have them exerting a high level of effort, then the most preferred agent choice of effort (HH) is implemented and patients get the highest possible benefit.

In the case where the budget is sticky and limited, such that there is not enough budget to pay the incentives that motivate the highest level of effort from doctors and nurses, then the contractor may be of two types: myopic or selective. If the contractor is myopic and so he just keeps paying the incentives offered previously under the full budget. If the contractor is selective, he is able to choose which equilibrium will be implemented. The equilibrium is chosen that yields the highest expected net benefit, that is, the patient's benefit G_{ij} less the incentives paid to the agents.

2.2. The contracts

The contracts cannot be based on the individual efforts, which are not observable, but are based on the team output (Y), which can be observed. We assume that this signal is either success, or failure, in the patient treatment or improvement of well-being, that is, $Y \in \{S, F\}$.

The incentives are offered according to the observed signal of health output $w_i \in \{h_i, l_i\}$, $i = d, n$. In particular, the high payment (h_i) is given if $Y = S$ and the low payment (l_i) is given if $Y = F$.

Agents are liability constrained, so that they cannot be paid less than a certain non-negative amount of money ($l_i \geq 0$), which raises a moral hazard problem.

³ In the extensions section, we show that this assumption for the reservation utility is not crucial for the results.



The most common methods for paying health care professionals are a salary, fee-for-service and capitation (Robinson, 2001; Maynard, 2005). However, recently there has been some discussion, with associated examples, of pay-per-performance and team based incentives (Burgess and Propper, 2000; Hehenkamp and Kaarboe, 2011; Frandsen and Rebitzer, 2014). Therefore, the payments we suggest for the contracts are incentives that depend on the observed performance. The incentives we consider in this work may be monetary (as the pay-per-performance incentive) or may be non-monetary, meaning incentives that implicitly reflect the trust of patients, providers and society in general, which are provided after the output has been observed, as suggested by Maynard (2005).

2.3. Health production technology before and after

The health production technology is given by the probability of obtaining success in the patient treatment given the efforts of doctor and nurse, which is p_{ae} , as shown in Table 1. A successful treatment is obtained when health care is provided to improve a patient situation and the patient experience that improvement. Otherwise, when there is no improvement, then there is a treatment failure.

(a, e)	probability of success
HH	p_{HH}
HL	p_{HL}
LH	p_{LH}
LL	p_{LL}

Assumption 2

We assume that $p_{HH} > p_{HL} > p_{LH} > p_{LL}$.

This assumption justifies three major aspects. The first aspect is that this production function allows factors to be complements and substitutes. On the one hand, doctor and nurse efforts are complements, because with the doctor and nurse simultaneously exerting a high level of effort, the probability of success increases, that is, $p_{HH} > p_{HL}$ and $p_{HH} > p_{LH}$. On the other hand, the efforts may be substitutes when only one agent supplies effort and success is obtained more often than when no agent supplies effort, that is why $p_{HL} > p_{LL}$ and $p_{LH} > p_{LL}$. This becomes clearer when p_{LH} is very close to p_{HL} , that is $p_{LH} \rightarrow p_{HL}$, because the same outcome can be achieved with different inputs.

The second aspect is that differences in doctor and nurse productivities are taken into account by considering $p_{HL} > p_{LH}$. That is, doctors are more productive than nurses when producing successful outputs using one unit of effort. But this difference can be minimized by having $p_{LH} \rightarrow p_{HL}$.

Finally, the third aspect is that health professionals are always considered to make a positive contribution, and so $p_{HL} > p_{LL}$ and $p_{LH} > p_{LL}$.

The marginal productivity of agents can be measured as a difference in probabilities of success (that is, the increase in the probability of success after the increase of one unit of effort). For the doctor, given nurse effort, the marginal productivity is measured by $MP_d^e = (p_{He} - p_{Le})_{e=L,H}$. And for the nurse, marginal productivity is given by $MP_n^a = (p_{aH} - p_{aL})_{a=L,H}$.



It should be noted that the marginal productivities depend on what the other member of team is doing.

To capture the effect of the improvement in nurse expertise, the model is analysed⁴ before and after that improvement. We represent these two periods by a superscript $t = \{0, 1\}$, where $t = 0$ is before, and $t = 1$ is after improvement.

The improvement of the nurse expertise is captured by:

- 1) an increase in the probability of success, when the nurse is the only member of the team exerting a high effort (p_{LH}), and
- 2) an increase in the probability of success, when both doctor and nurse are exerting a high effort ($\uparrow p_{HH}$). We assume this increase because there is a natural spillover effect on the team work due to the improvement in the nurse's expertise.

Assumption 3

The probabilities of success p_{HH} and p_{LH} before and after are such that $p^1_{HH} = p^0_{HH} + \varepsilon$ and $p^1_{LH} = p^0_{LH} + \mu$, $\varepsilon > 0$, $0 < \mu < 1$, $\varepsilon < \mu$.

After the change in nurse productivity, the ranking of probabilities is maintained:

$$p^t_{HH} > p_{HL} > p^t_{LH} > p_{LL}, \quad t = 0, 1.$$

We assume that $\varepsilon < \mu$ because some skills and tasks performed by doctors and nurses overlap when both are exerting a high level of effort and because an increase in the productivity of nurses is such that the ranking of probabilities is kept.

Other possibilities that could capture the increase in the nurse's marginal productivity would involve a decrease in p_{HL} and/or p_{LL} which is neither consistent with our context of change in the team production, nor does it reflect the continuous improvement of health care technology.

2.4. Timing of the game

The timing of the game is as follows:

- 1st stage: the contractor offers the contract to the doctor and the nurse.
- 2nd stage: the team accepts or rejects (if one of the agents or both reject, the game ends),
- 3rd stage: each team member simultaneously exerts effort,
- 4th stage: output is observed and payments are made.

The game is solved by backward induction.

3. The old team production technology

3.1. The incentives

The incentives offered to the agents are such that they minimize the expected expenses that implement the most preferred efforts, that is (HH): So formally we have the following optimization problem:

⁴ We do not consider any improvement in the doctor productivity for the sake of simplicity. In this way we avoid cumbersome modelling which would not provide value added to the findings. We are not defending the idea that doctors have not improved their productivity over time.



$$\text{Min}_{h_d, l_d} [p_{HH}(h_d + h_n) + (1 - p_{HH})(l_d + l_n)]$$

subject to the participation constraints, the incentive compatible constraints and the limited liability constraints of agents (as presented in the appendix).

Solving this optimization problem gives us the following payments and corresponding budgets.

Let the difference between high and low payments be given by

$$\Delta w_i^t = h_i^t - l_i^t, i = d, n.$$

Lemma 1 - optimal incentives

The set of incentives that minimizes the expected budget and implements (HH) as a Nash equilibrium, when both agents decide their efforts simultaneously, is given by the following $(l_d^t, l_n^t, h_d^t, h_n^t)$:

$$\begin{cases} l_d^t = l_n^t = 0, \text{ if } Y = F, \forall t \\ h_d^t = \Delta w_d^t = \frac{v_d}{p_{HH}^t - p_{LH}^1} = \frac{v_d}{MP_d^{e=1}}, \forall t, \text{ if } Y = S, \\ h_n^t = \Delta w_n^t = \frac{v_n}{p_{HH}^t - p_{HL}^1} = \frac{v_n}{MP_n^{a=1}}, \forall t, \text{ if } Y = S \end{cases}$$

The corresponding success and failure budgets are given by

$$B_S^t = h_d^t + h_n^t > 0 \text{ and } B_F^t = l_d^t + l_n^t = 0.$$

3.2. The Nash equilibrium

The defined incentives, for sure, implement the Nash equilibrium (HH). It may be possible to find other equilibria, given the offered incentives. Hence, a guarantee has to be made such that the agents do not have an incentive to deviate from the equilibrium (HH). Indeed the following two results can be shown.

Result 1

The equilibrium (HH) Pareto dominates any other possible equilibria.⁵

Result 2

No profitable coalition between doctor and nurse can be formed that would induce another outcome different from the (HH) Nash equilibrium.

Therefore, given the optimal incentives, the equilibrium chosen by the agents in the team is the Nash equilibrium (HH) and there is no incentive for agents to deviate from this equilibrium.

⁵ Dominance is strict except for the equilibrium (LH).



3.3. Strategic relationship between efforts

It is worth knowing how the agents' efforts behave strategically, given the choice of effort by the other agent.

The concept of strategic complements and strategic substitutes used here is close to that presented by Bulow et al (1985): the increase in the probability of exerting high effort by one agent results in the variation of the expected utility of the other agent (in the team), considering that agents are not exerting high effort initially. If agents have efforts which are strategic complements then the increase in the probability of exerting high effort by one agent implies the increase of that probability by the other agent. The increase in the probabilities of exerting a high effort by both agents, increases the probability of a successful outcome and so it increases the expected utility of agents.

For the case of efforts which are strategic substitutes, an increase in the probability of exerting high effort by one agent results in the decrease of the probability of exerting a high effort by the other agent which, at the end, reduces the expected utility of both agents.

To find the strategic relationship between efforts, after deriving the best response correspondence for each agent, we check how each agent responds to an increase in the probability of the other agent exerting a high level of effort. We find three possible results, which are the three possible cases of strategic relationship between doctor and nurse efforts. The cases represent strategic complements, substitutes or independence. However, the case of independence is not of interest for this work (Result 3 is derived in the appendix).

Result 3 - The strategic relationship between efforts⁶ (listed in three possible cases):

Case 1) Efforts are strategic complements when $MP_n^{a=H} > MP_n^{t,a=L}$ or $MP_d^{t,e=H} > MP_d^{e=L}$.

Case 2) Efforts are strategic substitutes when $MP_n^{a=H} < MP_n^{t,a=L}$ or $MP_d^{t,e=H} < MP_d^{e=L}$.

Case 3) Efforts are independent when $MP_n^{a=H} = MP_n^{t,a=L}$ or $MP_d^{t,e=H} = MP_d^{e=L}$,

where MP means marginal productivity.

These strategic relationships are relevant later for describing the equilibrium that emerges under a restricted budget.

4. The team technology

4.1. The implications of the improvement in nurse expertise

4.1.1. In the members of the team

The improvement in nurse expertise, as described before, is captured by an increase in p_{LH} larger than the increase in p_{HH} . This results in two changes:

- i) in doctor marginal productivities: $MP_d^{e=H}$ decreases and $MP_d^{e=L}$ remains unaltered,
- ii) in nurse marginal productivities: both $MP_n^{a=H}$ and $MP_n^{a=L}$ increase.

Taking into account *Lemma 1*, which gives the optimal payments, these changes imply that the doctor requires a larger incentive to exert a high level of effort⁷. On the contrary, a relatively lower incentive is

⁶ The strategic relationship between efforts (strategic complements or substitutes) is different from the production relationship of efforts (complements or substitutes), even though they may be related.

⁷ Note that $\Delta w_d^t > \Delta w_d^0 \Leftrightarrow \frac{V_d^t}{p_{HH}^t - p_{LH}^t} > \frac{V_d^0}{p_{HH}^0 - p_{LH}^0}$, where $\Delta w_d^t = h_d^t - l_d^t$, $t = 0, 1$.



needed for the nurse to exert a high level of effort⁸. In absolute value, the larger change of incentives is observed for the doctor and so the larger impact on the budget of incentives is originated by this change.

Firstly, the increase in the nurse productivity decreases the value of her incentive, because her marginal productivity increases, independent of the effort decision of the doctor, and so the likelihood of the team achieving successful outcomes is higher. Secondly, one would expect some compensation in the expenditures of the incentives in the budget resulting from the opposing increase and decrease in incentives paid to doctors and nurses, respectively.

However, this is not the case, as we show in what follows.

4.1.2. The budget of incentives

In comparing the success budgets before and after, we find that an increase has occurred. Since the patients' benefit is sufficiently high and the concerns for the public health exist, it is worth keep paying to doctors and nurses, even though the health public expenses are higher.

Recall that $q = \frac{V_d}{V_n}$ and let \bar{q} be a threshold value such that

$$\bar{q} = \frac{\varepsilon}{\mu - \varepsilon} \frac{MP_d^{1,e=H}}{MP_n^{1,a=H}} \frac{MP_d^{0,e=H}}{MP_n^{0,a=H}}.$$

Comparing the budgets before and after the improvement of the productivity of the nurse it is found that the threshold value for the difference in budgets is given by \bar{q} . This result is presented in *Proposition 1* (the proof is in the appendix).

Proposition 1 - the success budget before and after

The success budget that implements the equilibrium (*HH*) in $t = 1$ is larger than that in $t = 0$, that is, $B_S^1 > B_S^0, \forall q > \bar{q}$.

When the budget of success becomes lower after the increase in nurse productivity (that is, when $q < \bar{q}$), then, economically speaking, there would not be much to say as resources would not be limited. Moreover, it seems unrealistic that health care budgets are decreasing.⁹ For this reason, we will concentrate on the case where the success budget needed to pay the incentives increases.

The increase in the budget arises due to the asymmetric change in the marginal productivities of the agents: doctor productivity decreases while nurse productivity increases. This asymmetric change yields a higher budget of incentives necessary to implement (*HH*) as a Nash equilibrium since the incentives offered to doctors are higher while those for nurses are lower.

The increase in the budget may be justified because it is on the patients' best interest that doctors and nurses exert a high level of effort and provide full attention to patients. Otherwise, there would not be enough improvements on the patients' health conditions.

If the contractor adjusts the budget for the new situation then the equilibrium (*HH*) continues to emerge, as expected. However, it may be difficult to adjust the budget, for bureaucratic reasons (either the public health budgets are limited, or these budgets are sluggish to adjust for political or strategic reasons). Thus, if the available budget is the same as the old incentive budget, at $t=0$, then Nash equilibrium (*HH*) cannot be implemented at $t=1$.

⁸ Note that $\Delta w_n^1 < \Delta w_n^0 \Leftrightarrow \frac{v_n}{P_{HH}^1 - P_{LH}^1} < \frac{v_n}{P_{HH}^0 - P_{LH}^0}$, where $\Delta w_n^t = h_n^t - l_n^t, t = 0, 1$.

⁹ It is not our purpose to discuss this here. We do not present any evidence of increasing health care budgets but rather refer to anecdotal evidence from newspapers or statistical databases such as those provided by Eurostat or the OECD.



4.2. Sticky budgets

If the budget associated with success is sticky in its adjustment to new productivities, then the contractor is bound by the old incentives budget for use under the new team productivities.

We consider that the contractor can be either myopic or selective. A myopic contractor offers the same incentives at $t=0$ and $t=1$.

A selective contractor changes the incentives offered at $t=1$ and chooses the equilibrium to be implemented, given the restricted budget of incentives.

4.2.1. The myopic contractor

We shall consider that contractor does not change the optimal incentives and keeps those in place at $t=0$, that is, $(I_d = I_n = 0; h_d \text{ and } h_n > 0)_{t=0}$.

Under these incentives we find that the emerging Nash equilibrium is (LH) at $t=1$. This equilibrium arises when the doctor's marginal contribution to success is not very high and the productivity of the nurse is sufficiently high, so that the nurse finds it worthwhile to compensate and substitute for the lack of the doctor's effort. This is the case of free-riding in teams, which may happen because efforts may happen to be strategic substitutes at $t=1$. This was not the case at $t=0$, where the efforts of the team where strategic complements.

This is a relevant result since it makes it clear that the change in nurses' expertise allows for free riding by the most productive agent, the doctor. The result is presented in *Proposition 2* (the proof is in the appendix).

Proposition 2 - conditions for the equilibrium (LH)

At $t = 1$ there is a Nash equilibrium (LH) when the old incentives of $t = 0$ are offered.

Moreover, there are additional conditions that hold the Nash equilibrium (LH) : on top of the old incentives, when i) at $t=0$ the efforts are strategic complements and ii) at $t=1$ the efforts are either strategic substitutes or strategic complements.

So, according to *Proposition 2*, there are conditions that hold the Nash equilibrium (LH) . There are also conditions under which this equilibrium holds when doctors and nurses efforts were strategic complements before and may even be strategic substitutes afterwards. These results, that show the possible emergency of the equilibrium (LH) , provide a possible perspective on the historical relationship between doctors and nurses: from a "joint work perspective" to a "free-riding work perspective".

Given the incentives offered in $t=0$ and considering other compatible conditions (as shown in the appendix), it is possible to find other Nash equilibria.¹⁰ It is worth noticing that there are no conditions that sustain the Nash equilibrium (HL) .

4.2.2. The contractor is selective

If the contractor is selective then he chooses which equilibrium is to be implemented, given the success budget from $t=0$.

The choice is determined by selecting that which provides the higher social benefit, net of incentives. Moreover, since in the emerging equilibrium only one of the agents is paid to exert a high level of effort, then we have the following lemma (proof can be found in the appendix):

¹⁰ All the other possible equilibria are not relevant for the purpose of this work and therefore are not referred to here.



Lemma 2 - optimal incentives that implement equilibria (LH) and (HL)

i) to implement (LH), the offer made is $\Delta w'_d = 0$ and $\Delta w'_n = \frac{v_n}{p'_{LH} - p_{LL}}$;

ii) to implement (HL), the offer made is $\Delta w'_d = \frac{v_d}{p_{HL} - p_{LL}}$ and $\Delta w'_n = 0$.

Recall that $q = \frac{v_d}{v_n}$ and let q_1 be a threshold value such that

$$q_1 = \frac{p'_{LH}}{p_{HL}} \frac{MP_d^{e=L}}{MP_n^{1,e=L}} + MP_d^{e=L} \left[\frac{G_{HL}}{v_n} - \frac{p'_{LH}}{p_{HL}} \frac{G_{LH}}{v_n} \right]$$

where G_{HL} and G_{LH} are the patient's benefits associated with each possible outcome. Comparing the expected net benefits of (LH) and (HL), it can be seen that the threshold point is given by q_1 . This result is presented in *Proposition 3* (proof can be found in the appendix).

Proposition 3 - condition for the choice of (LH)

When $q > q_1$, the equilibrium (LH) is preferred to equilibrium (HL).

From the condition obtained in *Proposition 3*, even when the increase in the productivity of the nurse is very high, so that p'_{LH} gets very close to p_{HL} , then the threshold value tends to 1, and so (LH) is preferred. This condition, $q > 1$, is always true, in accordance with *Assumption 1*. Therefore, (LH) is chosen by the contractor because it provides higher net expected benefits.

5. Extensions

5.1. When the reservation utility is large

We have assumed that the reservation utility of both agents was sufficiently small. The formal translation of this assumption is to say that

$$\bar{U}_d < v_d \frac{p'_{LH}}{p'_{HH} - p'_{LH}} \quad \text{and} \quad \bar{U}_n < v_n \frac{p_{HL}}{p'_{HH} - p_{HL}}$$

The question may then be raised as to what would happen if the utilities were larger than those values.

5.1.1. The incentives

When the reservation utility is large, we have the following incentives for the doctor.

Lemma 3 - optimal incentives for the doctor

When $\bar{U}_d > v_d \frac{p'_{LH}}{p'_{HH} - p'_{LH}}$, the doctor's incentives are given by

$$h_d = \bar{U}_d + v_d \frac{(1 - p'_{LH})}{p'_{HH} - p'_{LH}} \quad \text{and} \quad l_d = \bar{U}_d - v_d \frac{p'_{LH}}{p'_{HH} - p'_{LH}}.$$



These incentives yield the same payment spread as that in *Lemma 1*, that is, for the doctor $\Delta w_d^i = h_d^i - l_d = \frac{v_d}{p_{HH}^i - p_{LH}^i}$. For the nurse, the process of deduction is similar.

5.1.2. The budget

This budget for success increases with p_{LH}^i , meaning that the change of nurse expertise implies an increase in the budget to implement the equilibrium where both agents exert a high effort. Therefore, the analysis as developed in the previous sections continues to be applicable.

5.2. Different changes in probabilities

5.2.1. The increase in p_{LH} changes the ranking of probabilities

In an extreme case, it could be the true that the improvement in the nurse's expertise was such that the likelihood of success in the patient treatment, when the nurse exerts a high level of effort, would be higher than that of the doctor's, that is, $p_{LH}^1 > p_{HL}$.

Suppose the ranking of probabilities is $p_{HH} > p_{LH}^1 > p_{HL} > p_{LL}$. We need to separate the case where the agents' cost of effort is similar (q tends to 1) from that where it is different.

i) When the costs of effort are similar, then

$$\Delta w_d^1 = h_d^1 = \frac{v_d}{p_{HH}^1 - p_{LH}^1} \quad \text{and} \quad \Delta w_n^1 = h_n^1 = \frac{v_n}{p_{HH}^1 - p_{HL}}$$

and so the doctor's payment is higher than the nurses'. It is clear that the preferred equilibrium (LH), not only is cheaper, but it also yields success more often.

ii) When the costs of effort are different (q is large), we take *Proposition 3* and conclude that it still holds. For a sufficiently large patient benefit G_{LH} , the equilibrium (LH) is always preferred to (HL).

If that benefit is not so large then it may still be possible that (LH) is preferred to (HL) for some cases such that $q > q_1$.

Therefore, if there is a change in the probability ranking such that $p_{LH}^1 > p_{HL}$, it becomes even more evident that the contractor will pay nurses a lower incentive and choose the equilibrium (LH), which yields higher probability of successful outcome.

5.2.2. The increase ε is larger than the increase μ

It is shown in *Proposition 2* that the Nash equilibrium (HH) arises when $\varepsilon > \mu$. Therefore, if the change in nurse expertise results in increasing returns of scale, meaning a larger increase in p_{HH} than the increase in p_{LH} , then the incentive budget would be enough to pay for a high effort level of both agents.

5.3. Risk averse agents

We have assumed risk neutral agents with a limited liability constraint in order to induce the problem of moral hazard. The results of the model do not change if we instead assume risk averse agents.

Suppose the utility of the agents is given by $U_i = u(w_i) - v_i$, $i = d, n$, where $u'(w_i) > 0$ and $u''(w_i) \leq 0$, then *Lemma 4* follows.



Lemma 4 - optimal incentives

The optimal incentives that implement the Nash equilibrium (HH) are such that

$$\Delta u_d^t = \frac{v_d}{p_{HH}^t - p_{LH}^1} \quad \text{and} \quad \Delta u_n^t = \frac{v_n}{p_{HH}^t - p_{HL}}$$

The optimal incentives are given by

$$h_d = u^{-1}\left(\bar{U}_d + v_d \frac{1 - p_{LH}^1}{p_{HH}^t - p_{LH}}\right); l_d = u^{-1}\left(\bar{U}_d - v_d \frac{p_{LH}^1}{p_{HH}^t - p_{LH}}\right);$$

$$h_n = u^{-1}\left(\bar{U}_n + v_n \frac{1 - p_{HL}}{p_{HH}^t - p_{HL}}\right); l_n = u^{-1}\left(\bar{U}_n - v_n \frac{p_{HL}}{p_{HH}^t - p_{HL}}\right).$$

Therefore, with such payments the analysis previously presented for the case of risk neutral and limited liability agents continues to hold.

5.4. Larger Teams

Multiple nurse teams

If we consider the common health care team with one doctor and several nurses (no matter how many), the model can be extended easily.

We know that the optimal incentive of the doctor is an inverse function of his productivity measured when all the nurses are working:

$$\Delta w_d = \frac{v_d}{p_{HH(H)}^t - p_{LH(H)}^1},$$

where $p_{aH(H)}$ means the probability of success when all the nurses are exerting a high level of effort, for a given doctor's effort.

So if we consider an increase in the probability of success when all¹¹ the nurses are exerting a high level of effort but not the doctor (that is, $\uparrow p_{LH(H)}$) as a result of the change in the team production structure, it obviously implies an increase in the doctor's incentive due to an improvement in the productivity of nurses. Then again, the doctor is motivated to free-ride on the nurses' high level of effort and, since the budget is limited, nurses end up exerting a high level of effort with a lower incentive.

Multiple teams

If we assume that the health care unit is composed of N identical teams, then the budget of incentives when success is observed is

$$NB_S^t = N \frac{v_d}{p_{HH}^t - p_{LH}^1} + N \frac{v_n}{p_{HH}^t - p_{HL}}$$

11 This is an oversimplification view of the way teams work and nurses decide to exert high effort. In reality it may happen that only some of the nurses choose to exert high effort which could result in a different outcome.



As previously, under the new scenario, the old budget of incentives is insufficient to make agents choose to exert a high level of effort. In the most extreme options available, the contractor either pays the optimal incentives to some teams and gives no incentives to the other teams, or one of the agents is paid, and where the conditions of *Proposition 3* hold, then nurses are paid a lower incentive.

6. Conclusion

Nursing has been changing over time and this work analyses some effects of the improvement in nurses' education and skills to treat patients. Considering the natural team between a doctor and a nurse, a model based on contracts is proposed to analyze the effects of such improvement on the incentives offered and on the agents' choice of effort to treat patients. The particular scenario of limited and sticky health budgets is carefully considered.

We show that after the improvement in nurses' expertise, the incentives for nurses are lower than before, but the overall incentives budget is higher. Doctors receive a higher incentive and they can now free-ride on nurses' effort because nurses are more productive. Moreover, when the budgets are rigid and cannot adjust to the new production conditions, the treatment of patients is mainly provided by nurses and not doctors. Because a nurse's effort substitutes a doctor's effort, doctors' free ride on nurses' effort, and the final outcome is similar.

The results of this work are of major importance for human resources policy makers in non-surgical health care units. Not only it is shown how substitutability between doctors and nurses in a team may emerge and be explored, but grounding is also provided for discussions at different levels relating to payments, conflicts and distrust, the correct implementation of medical hierarchies and responsibilities within the health care organization.

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Appendix:

Proof - Lemma 1

$$\text{Min}_{h_i, l_i} [p_{HH}^t(h_d + h_n) + (1 - p_{HH})(l_d + l_n)]$$

$$\Leftrightarrow \text{Max}_{h_i, l_i} [-p_{HH}^t(h_d + h_n) - (1 - p_{HH}^t)(l_d + l_n)], \quad i = d, n$$

s.t.

$$PC_d : EU_d(H, H) \geq \bar{U}_d \Leftrightarrow p_{HH}^t h_d - p_{HH}^t l_d + l_d - v_d \geq \bar{U}_d$$

$$PC_n : EU_n(H, H) \geq \bar{U}_n \Leftrightarrow p_{HH}^t h_n - p_{HH}^t l_n + l_n - v_n \geq \bar{U}_n$$

$$ICC_d : EU_d(H, H) \geq EU_d(L, H) \Leftrightarrow p_{HH}^t h_d - p_{HH}^t l_d + l_d - v_d \geq p_{LH}^t h_d - p_{LH}^t l_d + l_d$$

$$ICC_n : EU_n(H, H) \geq EU_n(H, L) \Leftrightarrow p_{HH}^t h_n - p_{HH}^t l_n + l_n - v_n \geq p_{HL} h_n - p_{HL} l_n + l_n$$

$$LL_d : l_d \geq 0$$

$$LL_n : l_n \geq 0$$

(PC_i - participation constraint; ICC_i - incentive compatibility constraint;

LL_i - limited liability constraint)

Taking LL_i constraints binding, because it is the minimum that can be paid, then $l_d = 0$ and $l_n = 0$ and so

$$PC_d : p_{HH}^t h_d - v_d \geq \bar{U}_d$$

$$PC_n : p_{HH}^t h_n - v_n \geq \bar{U}_n$$

$$ICC_d : p_{HH}^t h_d - v_d \geq p_{LH} h_d$$

$$ICC_n : p_{HH}^t h_n - v_n \geq p_{HL} h_n$$

i) It is not possible to have a PC binding and a ICC not binding because agents need incentives to exert high effort. Thus, this case is excluded.



ii) Taking the ICC binding but not the PC, one gets the following:

$$(p_{HH}^t - p_{LH})h_d - v_d = 0 \Leftrightarrow h_d = \frac{v_d}{p_{HH}^t - p_{LH}} \text{ and } \Delta w_d^t = h_d - l_d = \frac{v_d}{p_{HH}^t - p_{LH}}, \text{ and}$$

$$(p_{HH}^t - p_{HL}^t)h_n - v_n = 0 \Leftrightarrow h_n = \frac{v_n}{p_{HH}^t - p_{HL}^t} \text{ and } \Delta w_n^t = h_n - l_n = \frac{v_n}{p_{HH}^t - p_{HL}^t}.$$

Moreover,

$$\text{from } PC_d : p_{HH}^t h_d - v_d \geq \bar{U}_d \Leftrightarrow \bar{U}_d \leq p_{HH}^t h_d - v_d \Leftrightarrow \bar{U}_d \leq v_d \frac{p_{LH}^t}{p_{HH}^t - p_{LH}},$$

and

$$\text{from } PC_n : \bar{U}_n \leq v_n \frac{p_{HL}}{p_{HH}^t - p_{HL}}.$$

Proof - Results 1 and 2

Given the incentives offered by the contractor to doctors and nurses, such that, $\Delta w_d^t = h_d - l_d = \frac{v_d}{p_{HH}^t - p_{LH}^t}$ and $\Delta w_n^t = h_n - l_n = \frac{v_n}{p_{HH}^t - p_{HL}^t}$ and also $l_d = 0$ and $l_n = 0$, it can be shown that agents do not have incentives to deviate from the Nash Equilibrium (HH) nor to make a coalition to deviate from that equilibrium. These are shown in *result 1* and *2*.

Result 1

Equilibrium HH dominates any of the other possible equilibria

Given the payment $\Delta w_d^t = \frac{v_d}{p_{HH}^t - p_{LH}^t}$,

For the doctor:



$EU_d(HH) > EU_d(LL) \Leftrightarrow p_{HH}^t \Delta w_d^t - v_d > p_{LL} \Delta w_d^t \Leftrightarrow p_{HH}^t - p_{LL} > p_{HH}^t - p_{LH}^t$, is always found to be true.

$EU_d(HH) \geq EU_d(LH) \Leftrightarrow p_{HH}^t \Delta w_d^t - v_d \geq p_{LH}^t \Delta w_d^t$, is always found to be true.

$EU_d(HH) > EU_d(HL) \Leftrightarrow p_{HH}^t \Delta w_d^t - v_d > p_{HL} \Delta w_d^t - v_d$, is always found to be true.

Identical results can be shown for the nurse.

Result 2

No profitable coalition exists.

The proof comes directly from the Pareto dominance of the equilibrium (HH).

Thus, it is not possible to find a condition such that

$$\sum_i EU_i(HH) < \sum_i EU_i(HL),$$

$$\sum_i EU_i(HH) < \sum_i EU_i(LH) \text{ and}$$

$$\sum_i EU_i(HH) < \sum_i EU_i(LL), i = d, n.$$

Proof - Result 3: Cases of strategic relationship between efforts

Each agent is maximizing his/her expected utility which is given by

$$\text{Max}_{p_i} \{EU_i(w_i, p_i) = h_i \Pr(Y = S) + l_i \Pr(Y = F) - p_i v_i\}, i = d, n, \text{ where}$$

$$\Pr(Y = S) = p_d \cdot p_n \cdot p_{HH}^t + p_d \cdot (1 - p_n) \cdot p_{HL} + (1 - p_d) \cdot p_n \cdot p_{LH}^t + (1 - p_d)(1 - p_n) \cdot p_{LL},$$

$$\Pr(Y = F) = 1 - \Pr(Y = S).$$

By computing the first order condition relative to p_i , we derive the best response correspondence (BRC) of both agents.



We denote $h_i - l_i$ as Δw_i , $i = d, n$.

$$\text{Nurse BRC: } p_n = \begin{cases} 0, & \text{if } \Delta w_n [p_d(p_{HH}^t - p_{HL}) + (1 - p_d)(p_{LH}^t - p_{LL})] - v_n < 0. \\]0, 1[, & \text{if } \Delta w_n [p_d(p_{HH}^t - p_{HL}) + (1 - p_d)(p_{LH}^t - p_{LL})] - v_n = 0. \\ 1, & \text{if } \Delta w_n [p_d(p_{HH}^t - p_{HL}) + (1 - p_d)(p_{LH}^t - p_{LL})] - v_n > 0. \end{cases}$$

$$\text{Doctor BRC: } p_d = \begin{cases} 0, & \text{if } \Delta w_d [p_n(p_{HH}^t - p_{LH}^t) + (1 - p_n)(p_{HL} - p_{LL})] - v_d < 0. \\]0, 1[, & \text{if } \Delta w_d [p_n(p_{HH}^t - p_{LH}^t) + (1 - p_n)(p_{HL} - p_{LL})] - v_d = 0. \\ 1, & \text{if } \Delta w_d [p_n(p_{HH}^t - p_{LH}^t) + (1 - p_n)(p_{HL} - p_{LL})] - v_d > 0. \end{cases}$$

After differentiating the defining condition of the BRC, we get the following

strategic relationship between efforts:

$$\text{For the nurse: } \frac{\partial(\Delta w_n [p_d(p_{HH}^t - p_{HL}) + (1 - p_d)(p_{LH}^t - p_{LL})])}{\partial p_d} =$$

$$= \Delta w_n [(p_{HH}^t - p_{HL}) - (p_{LH}^t - p_{LL})].$$

$$\text{For the doctor: } \frac{\partial(w_d [p_n(p_{HH}^t - p_{LH}^t) + (1 - p_n)(p_{HL} - p_{LL})])}{\partial p_n} =$$

$$= \Delta w_d [(p_{HH}^t - p_{LH}^t) - (p_{HL} - p_{LL})].$$

Efforts are strategic complements for the nurse:

take the derivative obtained for the nurse $\frac{\partial(\cdot)}{\partial p_d}$ and suppose that $\frac{\partial(\cdot)}{\partial p_d} > 0$,

that is,

$$p_{HH}^t - p_{HL} > p_{LH}^t - p_{LL} \Leftrightarrow MP_n^{t,a=H} > MP_n^{t,a=L}.$$

If $\frac{\partial(\cdot)}{\partial p_d} > 0$ then an increase of p_d causes an increase in the condition

$$\Delta w_n [p_d(p_{HH}^t - p_{HL}) + (1 - p_d)(p_{LH}^t - p_{LL})] - v_n.$$

i) Suppose that initially the condition

$$\Delta w_n [p_d(p_{HH}^t - p_{HL}) + (1 - p_d)(p_{LH}^t - p_{LL})] - v_n \leq 0 \Leftrightarrow$$

$$\Leftrightarrow \Delta w_n [p_d MP_n^{t,a=H} + (1 - p_d) MP_n^{t,a=L}] - v_n \leq 0$$



then after an increase in p_d , this condition becomes larger than 0 and so the nurse increases her probability of exerting high effort to 1. Thus, an increase in p_d , increases the likelihood that nurses choose a higher level of effort.

ii) Suppose that initially the condition

$$\Delta w_n [p_d(p_{HH}^t - p_{HL}) + (1 - p_d)(p_{LH}^t - p_{LL})] - v_n > 0,$$

then there is no effect on the nurse's effort because it is already at the highest level.

The other cases are deduced in a similar way. Thus, we have

Case 1) Efforts are strategic complements when $MP_n^{t,a=H} > MP_n^{t,a=L}$ or $MP_d^{t,e=H} > MP_d^{t,e=L}$.

Case 2) Efforts are strategic substitutes when $MP_n^{t,a=H} < MP_n^{t,a=L}$ or $MP_d^{t,e=H} < MP_d^{t,e=L}$.

Proof - Proposition 1

Comparing the success budgets for $t = 0$ and $t = 1$.

$$B_0^S = \frac{v_d}{p_{HH}^0 - p_{LH}^0} + \frac{v_n}{p_{HH}^0 - p_{HL}}$$

$$B_1^S = \frac{v_d}{p_{HH}^1 - p_{LH}^1} + \frac{v_n}{p_{HH}^1 - p_{HL}}$$

where by assumption $v_d = qv_n$.

$$B_1^S > B_0^S \Rightarrow$$

$$\Rightarrow \frac{qv_n}{p_{HH}^1 - p_{LH}^1} + \frac{v_n}{p_{HH}^1 - p_{HL}} > \frac{qv_n}{p_{HH}^0 - p_{LH}^0} + \frac{v_n}{p_{HH}^0 - p_{HL}} \Leftrightarrow q > \bar{q},$$

$$\text{where } \bar{q} = \frac{\varepsilon (p_{HH}^1 - p_{01}^1)(p_{HH}^0 - p_{LH}^0)}{(\mu - \varepsilon)(p_{HH}^0 - p_{HL})(p_{HH}^1 - p_{HL})}.$$



In case $q = 1$ then $B_1^S > B_0^S \Rightarrow$

$$\Rightarrow v_n > \left[\frac{1}{p_{HH}^1 - p_{LH}^1} + \frac{1}{p_{HH}^1 - p_{HL}^1} - \frac{1}{p_{HH}^0 - p_{LH}^0} - \frac{1}{p_{HH}^0 - p_{HL}^0} \right]^{-1}, \text{ which}$$

is a positive number, as expected for v_n .

Proof - Proposition 2

Given the payments $\Delta w_d^0 = \frac{v_d}{p_{HH}^0 - p_{LH}^0}$ and $\Delta w_n^0 = \frac{v_n}{p_{HH}^0 - p_{HL}^0}$ and the BRC of result 3, we have the following Nash strategies and Nash equilibria.

There are 4 possible Nash equilibria as shown in the next table:

	$p_n=1$	$p_n=0$
$p_d=1$	HH	HL
$p_d=0$	LH	LL

We now proceed by checking the possible existence of each Nash equilibrium and corresponding conditions.

1) *The pair of strategies (LL)*

i) Given $p_n = 0$,

from the doctor's BRC we obtain

$$\frac{v_d}{p_{HH}^0 - p_{LH}^0} (p_{HL} - p_{LL}) - v_d < 0$$

because $p_{HL} - p_{LL} < p_{HH}^0 - p_{LH}^0$.

Then $p_d = 0$.

ii) Given $p_d = 0$,

from the nurse's BRC we obtain



$$\frac{v_n}{p_{HH}^0 - p_{HL}}(p_{LH}^1 - p_{LL}) - v_n \geq 0.$$

a) If the condition $p_{LH}^1 - p_{LL} > p_{HH}^0 - p_{HL}$ holds,

then $p_n = 1$, and so (LL) cannot be a Nash Equilibrium.

b) If the condition $p_{LH}^1 - p_{LL} > p_{HH}^0 - p_{HL}$ does not hold,

then $p_n = 0$.

Thus, (LL) is a Nash Equilibrium.

2) The pair of strategies (HH)

i) Given $p_d = 1$, then

from the nurse's BRC we obtain

$$\frac{v_n}{p_{HH}^0 - p_{HL}}(p_{HH}^1 - p_{HL}) - v_n > 0$$

because $p_{HH}^1 > p_{HH}^0$ by assumption.

Then $p_n = 1$.

ii) Given $p_n = 1$, then

from the doctor's BRC we obtain

$$\frac{v_d}{p_{HH}^0 - p_{LH}^0}(p_{HH}^1 - p_{LH}^1) - v_d < 0$$

because $p_{HH}^1 - p_{LH}^1 < p_{HH}^0 - p_{LH}^0 \Leftrightarrow \varepsilon - \mu < 0$,

which is a true condition by assumption.

Then $p_d = 0$.

Thus, the pair (HH) cannot be a Nash equilibrium.



3) The pair of strategies (LH)

i) Given $p_d = 0$,

from the nurse's BRC we obtain

$$\frac{v_n}{p_{HH}^0 - p_{HL}}(p_{LH}^1 - p_{LL}) - v_n \geq 0.$$

If the condition $p_{LH}^1 - p_{LL} > p_{HH}^0 - p_{HL}$ holds [*Condition A*],

then $p_n = 1$.

ii) Given $p_n = 1$, then

from the doctor's BRC we obtain

$$\frac{v_d}{p_{HH}^0 - p_{LH}^0}(p_{HH}^1 - p_{LH}^1) - v_d < 0$$

because $p_{HH}^1 - p_{LH}^1 < p_{HH}^0 - p_{LH}^0 \Leftrightarrow \varepsilon - \mu < 0$,

which is a true condition by assumption.

Then $p_d = 0$.

Thus, (LH) is a Nash Equilibrium.

Next, in order to obtain more information, Condition A, deduced above, is re-written as follows:

a.1) Re-writing *condition A* with reference to $t = 0$ and we get

$$p_{LH}^0 + \mu - p_{LL} > p_{HH}^0 - p_{HL} > 0 \Leftrightarrow \mu > p_{HH}^0 - p_{HL} - (p_{LH}^0 - p_{LL}) > 0 \Leftrightarrow$$

$$\Leftrightarrow \mu > MP_n^{0,a=L} - MP_n^{0,a=L} > 0 \text{ or } \mu > p_{HH}^0 - p_{LH}^0 - (p_{HL} - p_{LL}) >$$

$$0 \Leftrightarrow \mu > MP_d^{0,e=H} - MP_d^{e=L} > 0$$

meaning that efforts are strategic complements at $t = 0$, as shown in

result 3.



a.2) Re-writing *condition A* with reference to $t = 1$ and we get

$$p_{LH}^1 - p_{LL} > p_{HH}^1 - \varepsilon - p_{HL} > 0 \Leftrightarrow p_{HL} - p_{LL} > p_{HH}^1 - p_{LH}^1 - \varepsilon > 0 \Leftrightarrow \\ \Leftrightarrow \frac{p_{HL} - p_{LL}}{p_{HH}^1 - p_{LH}^1} > 1 - \frac{\varepsilon}{p_{HH}^1 - p_{LH}^1} .$$

Consider this condition true so it follows.

The right hand side of the condition is always $1 - \frac{\varepsilon}{p_{HH}^1 - p_{LH}^1} < 1$ because $0 < \frac{\varepsilon}{p_{HH}^1 - p_{LH}^1} \geq 1$.

The left hand side of the condition may be either i) $\frac{p_{HL} - p_{LL}}{p_{HH}^1 - p_{LH}^1} > 1$, when $\frac{\varepsilon}{p_{HH}^1 - p_{LH}^1} < 1$

or ii) $\left[1 - \frac{\varepsilon}{p_{HH}^1 - p_{LH}^1} \right] < \frac{p_{HL} - p_{LL}}{p_{HH}^1 - p_{LH}^1} < 1$, when $\frac{\varepsilon}{p_{HH}^1 - p_{LH}^1} > 1$.

Re-writing these expressions one gets either i) $\frac{MP_d^{e=L}}{MP_d^{1,e=H}} > 1$

or ii) $\left[1 - \frac{\varepsilon}{p_{HH}^1 - p_{LH}^1} \right] < \frac{MP_d^{e=L}}{MP_d^{1,e=H}} < 1$,

that is, in first expression i) the efforts are strategic substitutes, while in the second expression ii) the efforts are strategic complements at $t = 1$, as shown in *result 3*.

4) The pair of strategies (HL)

Given $p_d = 1$, then

from the nurse's BRC we obtain

$$\frac{v_n}{p_{HH}^0 - p_{HL}} (p_{HH}^1 - p_{HL}) - v_n > 0$$

because $p_{HH}^1 > p_{HH}^0$ by assumption.

Then $p_n = 1$ and so (HL) cannot be a Nash Equilibrium.



Proof - Lemma 2

$$\underset{h_i, l_i}{Min}(p_{HH}^t(h_d+h_n)+(1-p_{HH}^t)(l_d+l_n)) \Leftrightarrow \underset{h_i, l_i}{Max}[-p_{HH}^t(h_d+h_n)-(1-p_{HH}^t)(l_d+l_n)]$$

s.t.

$$PC_d : EU_d(LH) \geq 0 \Leftrightarrow p_{LH}^t h_d - p_{LH}^t l_d + l_d \geq 0$$

$$PC_n : EU_n(LH) \geq 0 \Leftrightarrow p_{LH}^t h_n - p_{LH}^t l_n + l_n - v_n \geq 0$$

$$ICC_n : EU_n(LH) \geq EU_n(LL) \Leftrightarrow p_{LH}^t h_n - p_{LH}^t l_n + l_n - v_n \geq p_{LL} h_n - p_{LL} l_n + l_n$$

$$LL_d : l_d \geq \bar{w}_d \geq 0$$

$$LL_n : l_n \geq \bar{w}_n \geq 0$$

Since we are looking for the minimum bonus, we take the low incentive $\bar{w}_d = \bar{w}_n = 0$.

There is no need to satisfy the doctor's *ICC* because he is exerting a low level of effort. By looking at the *PC_d*, we deduce that doctor's incentive is null:

$$EU_d(LH) \geq 0 \Leftrightarrow p_{LH}^t h_d - p_{LH}^t l_d + l_d \geq 0 \Leftrightarrow p_{LH}^t h_d \geq 0.$$

Then we just need to look for the optimal bonus of the nurse:

$$\underset{h_n}{Max}[-p_{HH}^t h_n] \text{ st } PC_n, ICC_n \text{ and } LL_n.$$

The *PC* not binding and the *ICC* binding and so:

$$\begin{cases} p_{LH}^t h_n - v_n \geq 0 \Leftrightarrow p_{LH}^t \cdot \frac{v_n}{p_{LH}^t - p_{LL}} - v_n \geq 0 \\ p_{LH}^t h_n - v_n - p_{LL} h_n = 0 \Leftrightarrow h_n = \frac{v_n}{p_{LH}^t - p_{LL}} \end{cases},$$

$$\text{thus, } \Delta w'_n = \frac{v_n}{p_{LH}^t - p_{LL}}.$$

**Proof - Proposition 3**

Under the new team production structure $LH \succ HL$ means that the expected net benefit of LH is larger than the expected net benefit of HL :

$$\begin{aligned} p_{LH}^1(G_{LH} - \frac{v_n}{p_{LH}^1 - p_{LL}}) &> p_{HL}(G_{HL} - \frac{v_d}{p_{HL} - p_{LL}}) \Leftrightarrow \\ \Leftrightarrow p_{LH}^1 G_{LH} - p_{LH}^1 \frac{v_n}{p_{LH}^1 - p_{LL}} &- p_{HL} G_{HL} + p_{HL} \frac{v_n}{p_{HL} - p_{LL}} > 0 \Leftrightarrow \\ \Leftrightarrow q > \frac{p_{LH}^1 p_{HL} - p_{LL}}{p_{HL} p_{LH}^1 - p_{LL}} + \left[\frac{G_{HL}}{v_n} - \frac{p_{LH}^1 G_{LH}}{p_{HL} v_n} \right] &(p_{HL} - p_{LL}) \Leftrightarrow \\ \Leftrightarrow q > q_1. \end{aligned}$$

$$\text{When } p_{LH}^1 \rightarrow p_{HL} \text{ then } q > \lim_{p_{LH}^1 \rightarrow p_{HL}} \{q_1\} = 1 + [G_{HL} - G_{LH}] \frac{(p_{HL} - p_{LL})}{v_n}.$$

If $(G_{HL} - G_{LH}) \rightarrow 0$ then $q > 1$.

Proof - Lemma 3

See proof of Lemma 1-3rd case: PC and ICC are binding

Proof - Lemma 4

The optimization problem is

$$\text{Min}_{h_i, l_i} [p_{HH}^t(h_d + h_n) + (1 - p_{HH}^t)(l_d + l_n)] \Leftrightarrow \text{Max}_{h_i, l_i} [-p_{HH}^t(h_d + h_n) - (1 - p_{HH}^t)(l_d + l_n)]$$

s.t.

$$PC_d : EU_d(H, H) \geq \bar{U}_d \Leftrightarrow p_{HH}^t u(h_d) + (1 - p_{HH}^t) u(l_d) - v_d \geq \bar{U}_d$$

$$PC_n : EU_n(H, H) \geq \bar{U}_n \Leftrightarrow p_{HH}^t u(h_n) + (1 - p_{HH}^t) u(l_n) - v_n \geq \bar{U}_n$$

$$ICC_d : EU_d(H, H) \geq EU_d(L, H)$$

$$\Leftrightarrow p_{HH}^t u(h_d) + (1 - p_{HH}^t) u(l_d) - v_d \geq p_{LH}^t u(h_d) + -(1 - p_{LH}^t) u(l_d)$$

$$ICC_n : EU_n(H, H) \geq EU_n(H, L)$$

$$\Leftrightarrow p_{HH}^t u(h_n) + (1 - p_{HH}^t) u(l_n) - v_n \geq p_{HL} u(h_n) + (1 - p_{HL}) u(l_n)$$

(PC_i - participation constraint and ICC_i - incentive compatibility constraint)



Assumption: $u'(\cdot) > 0$ and $u''(\cdot) < 0$.

We need to implement the following change of variables:

$$u(h_i) = \bar{u}_i, \Rightarrow h_i = \vartheta_i(\bar{u}_i), \quad i = d, n$$

$$u(l_i) = \underline{u}_i, \Rightarrow l_i = \vartheta_i(\underline{u}_i), \quad i = d, n$$

By solving the optimization problem and taking the PC and ICC to be binding, we find the optimal payments and the optimal utility spread:

$$u(h_d) = \bar{u}_d = \bar{U}_d + \frac{1 - p_{LH}}{p_{HH}^t - p_{LH}} v_d \Rightarrow h_d = u^{-1}\left(\bar{U}_d + \frac{1 - p_{LH}}{p_{HH}^t - p_{LH}} v_d\right)$$

$$u(l_d) = \underline{u}_d = \bar{U}_d - \frac{p_{LH}}{p_{HH}^t - p_{LH}} v_d \Rightarrow l_d = u^{-1}\left(\bar{U}_d - \frac{p_{LH}}{p_{HH}^t - p_{LH}} v_d\right)$$

So we get

$$\Delta u_d = u(h_d) - u(l_d) = \frac{v_d}{p_{HH}^t - p_{LH}}.$$

The analogous calculus can be resolved for the nurse which results in

$$\Delta u_n = u(h_n) - u(l_n) = \frac{v_n}{p_{HH}^t - p_{HL}}.$$