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Innovation Procurement Auctions and Administration Costs

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Abstract: We analyze the innovation problem currently facing a particular sector of the pharmaceutical industry and propose the use of procurement auctions to encourage innovation. We investigate the impact of operating costs on procurement auctions for innovation that potentially use both prizes, in the form of direct monetary transfers, and contracts as incentives. We find that, when faced with per-agent costs to conduct the procurement auction, extending the mechanism to two periods by performing an initial entry auction can result in higher welfare if agents have prior knowledge of their capabilities. Furthermore, we find that only the principal and innovator are likely to benefit from the entry auction, whereas the manufacturers will be worse off.

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1.0 Introduction

Throughout the history of our species, humans have been innovating, finding solutions to solve countless problems. It is because of those innovations that we enjoy our current quality of life and expected lifespan. In particular, medical innovations have had a profound impact on these two aspects. Antimicrobials have been used to prevent and cure debilitating, often life-threatening diseases. However, we are now observing widespread antibiotic resistance where antibiotics that were previously used to treat a specific infection is no longer effective. Unfortunately, antibiotic innovation has been stagnant, and combined with growing antibiotic resistance, has lead to the emergence of bacteria strains that are even resistant to treatments of last resort. The two obvious solutions would entail addressing either the causes of growing antimicrobial resistance, such as overuse of antibiotics in humans and livestock, or the lack innovation within this particular sector of the pharmaceutical industry.

In this paper, we explore how both monetary prizes and production contracts can be used as incentives to procure new innovations. In particular, we model how the addition of administration costs related to the innovation procurement auction adversely affects the principal, agents, and quality of the innovation. The rationale behind studying how administration costs can affect the outcome of procurement auctions relates to the characteristics of pharmaceutical R&D. Verifying the value of a new drug involves lengthy and expensive clinical trials. In our model, we assume that the principal is responsible for conducting at least some of the clinical trial process, such as one of the later stages, to verify the value of an innovation. The principal is also assumed to verify that the quality of the product being manufactured by the winner of the contract is of sufficient quality, which is also likely to be costly. These verification costs, which can be significant, are included in the administration costs related to procurement.

We then propose a simple solution to mitigate the impact of the administration or verification costs. We find that the implementation of an entry auction largely reverses the negative effects of the administration costs. Furthermore, depending on the entry-auction bids, the principal may even have higher utility than before the effects of costly verification were accounted for. When looking at ex-ante utility, we find that the principal is always better off extracting as much rents as possible from the entry auction.

1.1 Background

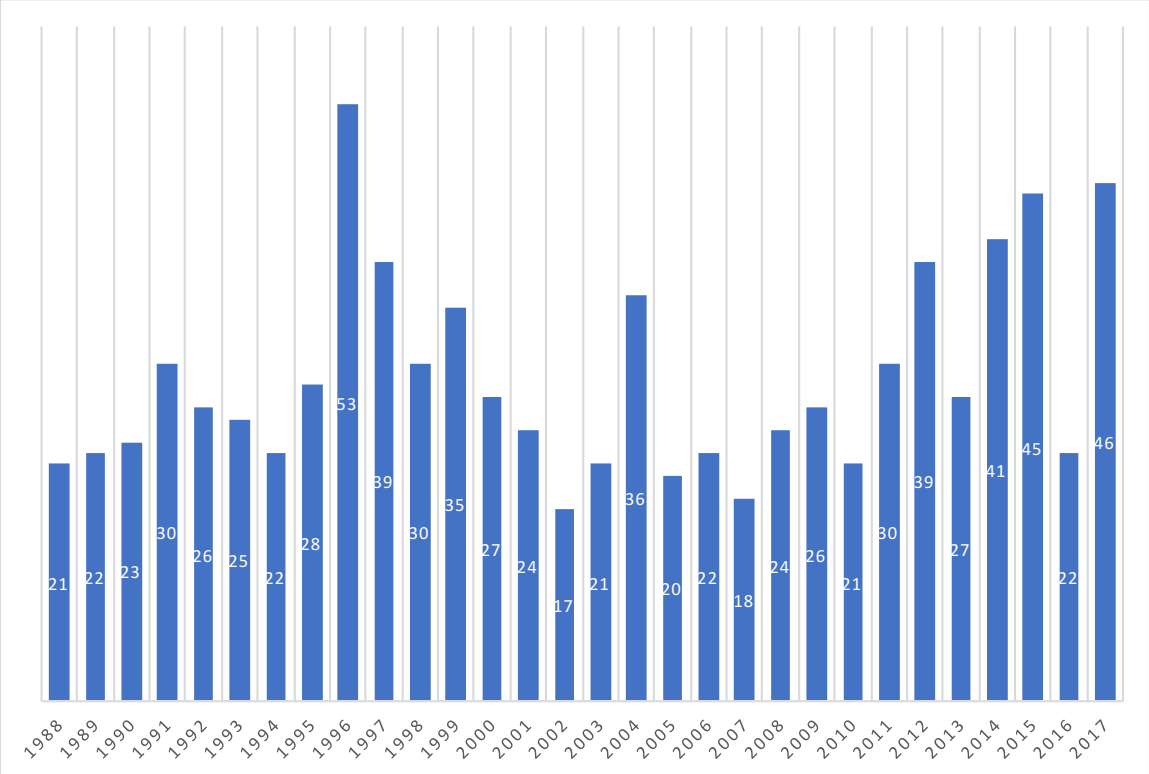
Innovation and methods to encourage innovation, primarily through the protection of intellectual property rights, has been frequently debated. However, sometimes patents alone don't provide sufficient incentive to encourage innovation in some sectors. To see an example of this, let's consider the defense industry. The types of innovations that nations procure for defense varies quite a bit, from technology that has a multitude of uses outside of defense, such as radars, satellites, and navigation, to rather specialized technology, such as missile defense systems and combat aircraft. When we consider the market for more specialized technology, it may simply be that the market is too small for competing firms to invest enough such that the quality of innovation is up to par. Another possibility that is particularly relevant to defense innovations is the government regulations over who you're allowed to sell to. So even if there was enough demand to justify the investments in R&D, regulations may significantly reduce the size of the effective market. Because of the lack of innovation, various governments worldwide have implemented programs to procure innovations that address their specific needs.

Another industry that often suffers to a greater degree from a lack of innovation is the pharmaceutical industry. Let's consider the pharmaceutical market in the United States, which is by far the largest market in the world and accounts for approximately 40% of worldwide revenue (Dubois et al., 2015). As you can see in Figure 1, in 1996, the number of novel drugs approved, consisting of New Molecular Entities (NMEs) and New Biologic Entities (NBEs), was a record high of 58. Since then, even though investments in R&D have only increased, the number of NME and NBE approvals have yet to return to such high levels. However, the number of novel drug approvals isn't necessarily representative of how much innovation is being generated because not all innovations are equal.

There are several different ways to categorize how innovative a new drug is, and the Food and Drug Administration (FDA) has a special designation for those that are the most innovative — first-in-class. These first-in-class drugs, which have a new and unique mechanism of action for treating a medical condition, are arguably the most innovative. That doesn't mean that new drugs without this designation aren't important

because follow-on drugs often provide useful improvements over the more ground-breaking drugs. However, given the high level of uncertainty that goes into developing

Figure 1: NME and NBE Approvals 1988–2017



Source: U.S. Food and Drug Administration (2018)

pharmaceuticals, and even more for pharmaceuticals with a mechanism of action that hasn't been exhibited in a previously approved drug, it follows that first-in-class drugs are the riskiest endeavors, in part due to the lower clinical trial success rates compared to follow-on counterparts.

Looking at this from the firm's perspective, a problem with developing first-in-class pharmaceuticals is that knowledge spillovers occur. Once a company develops a new drug with a novel mechanism of action, competing firms can design analogs, which are molecules that are similar in structure and have a similar effect, once the innovating firm has proven the mechanism of action to be effective. This allows the firms that act as followers to benefit from other firms' more cutting-edge research while simultaneously taking fewer risks, thus reducing the incentive to be more innovative.

To illustrate the innovation problem in the pharmaceutical industry, we need look no further than the antibiotic sector. Antibiotics are used to treat bacterial infections, many of which can be life threatening. However, bacteria have a tendency to develop resistance to the antibiotics that we use. Even drugs of last resort, which are usually reserved for treatment after other options have been exhausted to limit antimicrobial resistance, are also becoming ineffective against the more resilient strains. When a strain of bacteria becomes resistant to a particular antibiotic, that resistance often applies to other drugs within the same class that share a similar mechanism of action. For this reason, continued innovative drug development is particularly important; it can even be argued that continued drug development is more important for antimicrobials as opposed to other therapeutic areas because we cannot rely on our previous supply of drugs to remain effective for treating the same conditions in the future.

To make matters worse, antibiotic innovation has been relatively stagnant. This is particularly evident when looking at the number of first-in-class antibiotics that have been approved by the FDA in the United States. Since the turn of the 21st century, only 5 new classes of antibiotics have been approved, some of which have a narrow spectrum of activity, and that number compares unfavorably to the 20 classes of antibiotics that were developed and approved between 1940–1962. Not only are fewer innovative antibiotics being released into the market, but fewer firms are conducting R&D in this area. In the 1990's, there were 18 major pharmaceutical firms actively researching antibiotics; there are now only 5 major firms doing such research (Ventola, 2015). Of course, some of these firms have undergone mergers and, for others, research is increasingly being outsourced in the form of larger firms acquiring startup biotech companies once their innovations start to show promise. However, innovation in many areas, particularly with antibiotics, still hasn't improved.

One possible explanation as to why innovation in antibiotic development seems to have stalled is that intellectual property protections are insufficient in terms of length and breadth. Intellectual property rights for inventions are guaranteed by patents, which prevent competitors from releasing products that use your invention for the duration of validity — generally 20 years from the initial filing date. This policy may be effective for other industries where inventions aren't required to go through the lengthy clinical trial and approval process mandated by the FDA. Firms often file patents for

pharmaceuticals early in the development timeline when it shows promise. Because drugs are patented sometime during the lengthy clinical trial process, the average effective patent length for NCEs that receive market approval is less than 10 years (Eisman & Wardell, 1981).

A potentially more pressing problem with the patent system as it related to pharmaceuticals is that patents confer imperfect protection for knowledge gained through R&D activities. In patent applications for chemicals, the chemical structures are permitted to be a somewhat generic skeletal depiction of the molecule, which is known as a Markush structure. Markush groups, which are often depicted as R groups, can be used to represent a group of chemical elements, or functional groups, with a similar structure or property. It is the Markush claims that allow a patent application to potentially cover a multitude of similar chemicals based on their expected similarity to the chemical you have been researching. However, more recent rules issued by the United States Patent and Trademark Office (USPTO) restricts the breadth of Markush claims, limiting a patent in regard to the number of analogs that can be covered.

To illustrate how this can potentially limit the protection of intellectual property, let's consider a scenario where a NME can either be innovative, which we can categorize as a first-in-class drug, or not innovative, which we can call a follow-on drug. When the creator of the first-in-class drug files for a patent, included in the application is the chemical structure of the molecule. Now, because of the USPTO restrictions, only a limited number of functional groups can be claimed in the application. Now, let's say that another firm decides to make a follow-on drug that is structurally similar to the first-in-class drug, but different enough so that the original patent isn't violated. In other words, the first firm undertook the most risk in creating a new drug with a novel mechanism of action and the second firm, after seeing that the first drug was effective, developed a chemical analog that involved less financial risk because the mechanism of action was already proven. Because of the similar structure and mechanism of action of the analog, it is possible that it will be a perfect substitute to the original chemical. Because the original innovator cannot patent all possible analogs of a base structure, the product of their R&D, including the potential discovery of a new and effective mechanism of action, isn't fully protected.

To get inspiration, we can take a look at two prominent procurement programs. Procurement of innovation is quite common in the national defense sector where innovations often don't have much value on the open market, either due to a lack of applicable transferability or trade restrictions. However, at least in the US, defense innovation contracts tend to be guaranteed before a product is ready. In the case where the US directly funds the R&D as a part of the procurement contract, there can be many inefficiencies. It isn't uncommon for budgets to spiral out of control and end up costing the government far more than it expected to spend. For example, the multi-national procurement of Lockheed Martin's F-35 aircraft. The contracts for the development and procurement of different elements tend to be any combination of fixed price incentives, cost plus incentive fees, and firm fixed priced contract line item numbers. Additionally, because the contracts for some parts of development, including the engine, don't have any actual contracted ceiling price, development and procurement costs have often risen above the initial target price. Furthermore, even with a price ceiling, there is no guarantee that the delivered result will see the expectations given the price paid for procurement. It could, however, be the case that there wouldn't be enough innovation in the defense industry if it weren't for the direct funding of R&D by outside parties.

The most notable examples of public procurement in health-related sectors are the Forward Commitment Procurement (FCP) and pre-commercial procurement (PCP) activities that are used by the UK's National Health Service (NHS) National Innovation Centre (NIC). FCP is the advanced purchase of an innovative solution within a relatively short timeframe — usually up to a year. IF there is a need in the market that cannot be met by current technology, the NIC will engage in FCP if they believe the need can be easily met once the industry is aware of it. PCP is the procurement of R&D to get an innovative solution over a relatively longer time horizon. The NHS uses PCP when there is no technology available to address the problem and there isn't any indication that there will soon be a solution developed in the market without intervention. When procuring an innovation via PCP, the NHS will employ a competitive staged approach involved design, developing/prototyping, and demonstrating the innovations. However, the NHS hasn't procured any pharmaceutical R&D, likely due to the rather long development timelines when compared to medical devices, the types of innovations typically procured (Yeow & Edler, 2012).

Now we have established that there is an innovation problem in the pharmaceutical industry that is most evident in the antibiotic sector. Whatever the reason for the lack of innovation — whether due to imperfect intellectual property protection, insufficient effective patent length, or some other potential reason not covered — something needs to be done to address it. Given the massive hurdles associated with patent reform, we instead look toward demand-side incentives for innovation, such as public procurement. We can also take into account the pitfalls of currently implemented procurement programs and hopefully find ways to improve.

To model how we can encourage innovation in the absence of effective patent rights, we remove intellectual property rights entirely, meaning that any firm can produce any other firm's innovation. We will then analyze the situation where cash prizes and contracts are available as incentives to innovate and extend the analysis to situations where the principal faces additional costs of operating or administering the auction. In practice, these administration costs may be related to organizing and conducting the auction itself, verification of the value of the innovation, or verification of an agent's ability to manufacture the innovation with sufficient quality. While the model and mechanism that will be analyzed is not specific to pharmaceutical innovation, the potentially high verification costs, which could be significant enough to have a notable impact on the principal and agents, are representative of pharmaceutical innovations because verification may entail lengthy and expensive clinical trials.

2.0 Literature Review

2.1 The Foundations of Auction Theory

Much of auction and mechanism design has developed because of the inability of some market forces to provide efficient allocations of resources. The general goal of auction theory is to address such inefficiencies by designing mechanisms that result in optimal allocations. Although Vickrey's 1961 paper, which found that truthfully bidding one's value was incentive compatible in a second-price sealed-bid auction, was ground breaking at the time and managed to influence decades of research into auction theory, it did have its limitations in the range of environments that the method would be applicable. Clarke (1971) and Groves (1973) went on to generalize the results of the Vickrey auction to apply to multiple items into what we commonly refer to today as the Vickrey-Clarke-Groves (VCG) auction, which is what virtually all auctions are compared to.

2.2 Procurement Auctions

Procurement auctions are a specific type of auction where a buyer is receiving multiple offers from various sellers, where he hopes to drive the price down. The application of procurement auctions has gained significant interest over the past few decade due to the increasing awareness of various market failures to encourage innovation, particularly for highly specialized goods that have little value on the open market. When modeling sequential procurement auctions, Cisternas and Figueroa (2015) show that giving the first-period winner an advantage results in over-investment by the winner to a level above the social optimum. Depending on your goals, this can be viewed good, because then the buyer might receive the second-period item at a lower cost, or bad, because the over investment results in an aggregate deadweight loss. Our paper differs from the previously mentioned work in that we give the innovator an advantage, and, when faced with costly entry auctions, is the only agent that can end up better off than before. Other authors, such as Ji and Li (2008) have found that, by using secret reserve prices, the equilibrium bids decline over successive stages in multi-round procurement auctions, thus showing that repeated competition can improve outcomes for the seller.

Che et al. (2017) models procurement auctions with the potential for prizes and contracts to incentivize innovation. They find that the only time additional cash prizes are optimal is when the value of the innovation would be high enough such that the contract alone would be insufficient motivation to innovate. Our paper uses an adjusted model from the aforementioned paper where the principal now incurs a per-person cost from administering the procurement auction and we extend our analysis to a multi-period auction to reduce the impact of such costs.

2.3 Auctions with Costly Entry

Often times when conducting auctions, there may be costs involved to participate such as completing due diligence by gathering information about the principal or other agents prior to entry. Giebe (2014) modeled the effects of entry auctions on innovation contests and found that, through competition during the initial stage, sellers bid down the profit differences between fixed-prize and first-score auctions. In our work, we implement the sealed-bid uniform-price entry auction that Giebe (2014) analyzed. Lu and Ye (2017) extend the analysis of previously discussed sequential procurement auctions to include costly information acquisition for agents and justify the prevalence of non-binding bids. Our paper differs in that rather than the bidders incurring information acquisition costs, we burden the principal with those costs. Similar to our paper, Samuelson (1985) shows that limiting bidder entry when competing incurs costs can increase overall welfare in the presence of entry costs that cannot be recovered. However, our model also involves the procurement of an innovation through R&D activities where the value of the innovation that will be produced is determined endogenously. When investigating the effects of entry investment on procurement auctions, Kjerstad and Vagstad (2000) find that the optimal mechanism suffers from distortions when learning private information prior to entry while standard auctions with uninformed participants don't suffer such distortions of effort. Kaplan and Sela (2006) find that asymmetric second-price auctions with private information regarding individual cost of entry can use reservation prices to increase profits compared to when uniform entry fees are used. This related to our paper in that we find that the principal is better off when increasing the bids from the entry auction, extracting as much rents as possible.

3.0 The Model

We consider a mechanism through which a principal, potentially representing a government agency or large non-profit organization, wants to procure an innovation that cannot be met with currently available products and meets his particular needs. The principal can decide the specific requirements that the innovation must satisfy. Going back to the pharmaceutical industry problem discussed earlier, we can, for example, think of such a requirement that a new drug, such as an antibiotic, needs to treat a specific disease using a novel mechanism of action. We disregard the potential outside commercial value of the innovation as that doesn't change our analysis. Furthermore, we will assume that intellectual property rights are insufficient for encouraging innovation in this industry and thus ignore them. To accomplish this, we use a modified version of the model from Che et al. (2017) to account for the principal incurring cost p_i for administering the procurement auction. To see a brief explanation for various symbols, see Appendix A.

To model both endogenous innovation effort and the implementation auction, we can formulate the procurement as two separate stages. In the first stage, after the announcement of the procurement competition, an innovating firm, or agent, $i = 1$ exerts effort $e_i \geq 0$ to develop an innovation through R&D to address the principal's needs. Effort is costly, so we have $c(e_i) \geq 0$. The costs that are encompassed by effort relates to R&D, such as hiring and funding motivated researchers. We assume $c(e_i)$ is convex increasing in e_i with $c''(e_i) > 0$ and $c'(0) = 0$. and Because the results of R&D is inherently uncertain, the value of the innovation v is drawn from $V := [\underline{v}, \bar{v}]$ according to the cumulative distribution function $F(\cdot \mid e)$ with density $f(\cdot \mid e)$. Even with uncertainty, an increase in effort will increase the expected value of the innovation by shifting the distribution according to the monotony likelihood ratio property. Further, while we assume that effort e is unobservable, we allow the value of the project to be publicly observable. Such might be the case when you can verify the efficacy of the innovation through double-blind clinical trials.

Assuming that the quality or characteristics of the innovation meets the principals needs, the next stage can proceed. Now, all of the firms compete to manufacture the innovation. Because we have removed the protections for intellectual property, all firms now need to compete against one another in an auction to manufacture the innovation for the principal. We further assume that each firm $i \in N := \{1, \ldots, n\}$ faces a cost of production $\theta_i \in \Theta := [\underline{\theta}, \bar{\theta}]$ distributed according to c.d.f. $G_i(\cdot)$ with density $g_i(\cdot)$. We assume that the distributions of θ_i and v are overlapping such that $\underline{\theta} < \bar{v}$, implying that an allocation is feasible, and $\dfrac{G_i(\theta_i)}{g_i(\theta_i)}$ is non decreasing in θ for all firms. If no firm gets chosen to manufacture the innovation, no transfers are made. If a project is implemented, the principal's welfare its the difference between the price paid, t, and the value of the innovation, v.

The treatment here largely follows that of Che et al. (2017).
Applying the revelation principle that is standard in market and mechanism design, we can restate the objective of the principal as choosing an incentive compatible direct revelation mechanism that specifies the probability $x_i(v, \theta)$ of being chosen to manufacture the innovation and the expected transfer $t_i(v, \theta)$.

Principal's objective is to solve

$$\max_{x,t,e} \; E_{v,\theta}[w(v, \theta) \mid e] \qquad \text{[P]}$$

where his ex post surplus is

$$w(v, \theta) = \sum_{i \in N} [v x_i(v, \theta) - t_i(v, \theta) - p_i]$$

with p_i referring to additional cost to the principal when firm i participates. We also have the following individual rationality and incentive compatibility constrains:

$$U_i(v, \theta) \geq 0 \quad \forall i \in N, \forall v \in V, \forall \theta_i \in \Theta \qquad \text{[IR]}$$

$$U_i(v, \theta_i) \geq u_i(v, \theta_i' \mid \theta_i), \quad \forall i \in N, \forall v \in V^n, \forall (\theta_i, \theta_i') \in \Theta^2 \qquad \text{[IC]}$$

Here, because we cannot force agents to participate, individual rationality requires that the expected utility for an agent participating in the procurement is non-negative and incentive compatibility requires that the utility for an agent is at least as high when truthfully bidding at cost as it is when the agent bids some other cost θ_i'.

Furthermore, firm i's interim expected profits from lying is

$u_i(v, \theta_i' \mid \theta_i) = \mathbb{E}_{\theta_{-i}}[t_i(v, \theta_i', \theta_{-i}) - \theta_i x_i(v, \theta_i', \theta_{-i})]$

and from reporting the truth is

$U_i(v, \theta_i) = u_i(v, \theta_i \mid \theta_i)$

The buyer's limited liability [LL] and moral hazard [MH] constraints are

$$\mathbb{E}_\theta[w(v, \theta) \mid e] \geq 0, \quad \forall v \in V \qquad \text{[LL]}$$

$$e \in arg \max_{\tilde{e}} \{\mathbb{E}_{v,\theta}[U_i(v, \theta_i) \mid \tilde{e}] - c(\tilde{e})\}. \quad \forall i \in N \qquad \text{[MH]}$$

Proposition 1: There exists an optimal mechanism, consisting of an allocation, transfer rules, and optimal effort, that solves the principal's problem when it is costly for the principal to administer the procurement. Furthermore, the effects of an identical administration cost for each firm $i \in N$ on the optimal allocation, transfer, and effort can be characterized as follows:

A. The optimal allocation rule selects firm i to produce the innovation with probability

$$x_i^*(v, \theta) = \begin{cases} 1 & \text{if } K_i^*(v, \theta_i) \leq min\ \{v, min_{j \neq i} K_j^*(v, \theta_j)\} \\ 0 & \text{otherwise} \end{cases}$$

where $K_i^*(v, \theta_i) := \begin{cases} J_i(\theta_i) - min\{\beta^*(v), 1\} \frac{G_i(\theta_i)}{g_i(\theta_i)} & if\ i = 1 \\ J_i(\theta_i) & if\ i \neq 1 \end{cases}$

where $i = 1$ refers to the innovating firm and $\beta^*(v) := \lambda^* \frac{f_e(v \mid e^*)}{f(v \mid e^*)}$ is the incentive benefit for increasing payment to the innovator.

The difference between the two alternatives for K_i, when comparing the innovating and non-innovating agents, is the benefit of shifting the contract toward the innovator as a way to encourage innovation.

B. The corresponding transfer rule gives firm i an expected transfer

$$T_i^*(v,\theta_i) := \rho_1^*(v) + \int_{\theta_i}^{\bar{\theta}} X_i^*(v,s)ds + \theta_i X_i^*(v,\theta_i)$$

where the first term corresponds the the additional cash prize awarded to the innovating firm ($i = 1$), the second term corresponds to the information rent from assigning the contract, and the third term corresponds to the expected cost of the manufacturing contract.

where $\rho_1^*(v) := \begin{cases} \sum_{i\in N}[[v - J_i(\theta_i)]x_i^*(v,\theta) - p_i] & if\ \beta^*(v) > 0 \\ 0 & if\ \beta^*(v) < 0 \end{cases}$

and the effect of the administration cost results in a decrease in the expected transfer to firms.

C. The optimal effort level e^* satisfies

$$c'(e^*) = \int_v \int_\theta \left[\rho_1^*(v) + \frac{G_1(\theta_i)}{g_1(\theta_1)} x_1^*(v,\theta)\right] dG(\theta) f_e(v \mid e^*)dv$$

and because the administration costs decrease $\rho_1^*(v)$, the optimal level of effort also decreases. Our previously mentioned assumptions about the cost of effort function allow us to draw this conclusion.

Proof: To prove all parts of Proposition 1, we will solve the problem to find the optimal mechanism.

To solve the principal's problem [P], we first reformulate [IC] in terms of allocation and transfer rules.
Let

$$X_i(v,\theta_i) := \int_{\theta_{-i}} x_i(v,\theta) dG_{-i}(\theta_{-i}) \qquad \forall i \in N,\ \forall v \in V,\ \forall \theta_i \in \Theta$$

$$T_i(v,\theta_i) := \int_{\theta_{-i}} t_i(v,\theta) dG_{-i}(\theta_{-i}) \qquad \forall i \in N,\ \forall v \in V,\ \forall \theta_i \in \Theta$$

denote the interim allocation and transfer, respectively, for firm i, and let

$$U_i(v,\theta_i) := T_i(v,\theta_i) - \theta_i X_i(v,\theta_i) \qquad [1]$$

denote firm i's interim expected profit. We can then rewrite the incentive compatibility constraint as

$$T_i(v,\theta_i) - \theta_i X_i(v,\theta_i) \geq T_i(v,\theta_i') - \theta_i X_i(v,\theta_i') \qquad \forall v \in V,\ \forall (\theta_i,\theta_i') \in \Theta$$

The envelope condition gives us

$$U_i(v,\theta_i) = \rho_i(v) + \int_{\theta_i}^{\bar{\theta}} X_i(v,\theta) d\theta \qquad [2]$$

where

$$\rho_i(v) := U_i(v,\bar{\theta})$$

is agent i's rent when his costs are the highest.

We can now rewrite the firm i's expected rent as

$$\int_{\theta_i} U_i(v,\theta_i) dG_i(\theta_i) = \int_{\theta_i} \left[\rho_i(v) + \int_{\theta_i}^{\bar{\theta}} X_i(v,s) ds \right] dG_i(\theta_i)$$

$$= \rho_i(v) + \int_{\theta_i} X_i(v,\theta_i) \frac{G_i(\theta_i)}{g_i(\theta_i)} dG_i(\theta_i) \qquad [3]$$

As you can see, when $i \neq 1$, or in other words when the firm in question is not the innovator, it is optimal to set $\rho_i(v) = 0$ as it only serves to reduce the principal's surplus.

By employing [1] and [3], we express the total expected transfer to agents as

$$\int_{\theta} \sum_{i \in N} t_i(v,\theta) dG(\theta) = \sum_{i \in N} \int_{\theta_i} T_i(v,\theta_i) dG_i(\theta_i)$$

$$= \rho_1(v) + \int_\theta \sum_{i \in N} x_i(v, \theta_i) J_i(\theta_i) dG(\theta) \qquad [4]$$

where $J_i(\theta_i) := \theta_i + \dfrac{G_i(\theta_i)}{g_i(\theta_i)}$ denotes firm i's virtual costs, which is strictly increasing

We can substitute [4] into [P], rewriting [LL] as

$$\int_\theta \sum_{i \in N} [[v - J_i(\theta_i)] x_i(v, \theta) - p_i] dG(\theta) \geq \rho_1(v) \quad \forall v \in V \qquad [\widehat{LL}]$$

Then [IR] becomes

$$\rho_i(v) \geq 0, \quad \forall v \in V \qquad [\widehat{IR}]$$

Turning our attention to the effort constraint, from before we have the [MH] condition

$$e \in arg\ \max_{\tilde{e}} \{\mathbb{E}_{v,\theta}[U_i(v, \theta_i) \mid \tilde{e}] - c(\tilde{e})\}$$

combined with [3]

$$\int_{\theta_i} U_i(v, \theta_i) dG_i(\theta_i) = \rho_i(v) + \int_{\theta_i} X_i(v, \theta_i) \frac{G_i(\theta_i)}{g_i(\theta_i)} dG_i(\theta_i)$$

the effort constraint can now be rewritten as

$$e \in arg\ max \left\{ \mathbb{E} \left[\rho_i(v) + \int_{\theta_i} X_i(v, \theta_i) \frac{G_i(\theta_i)}{g_i(\theta_i)} dG_i(\theta_i) \right] \right\}$$

Taking the F.O.C., we get

$$\int_v \int_\theta \left[\rho_i(v) + \frac{G_1(\theta_1)}{g_1(\theta_1)} x_1(v, \theta) \right] dG(\theta) f_e(v \mid e) dv \geq c'(e) \qquad [\widehat{MH}]$$

Now, we can rewrite [P] as [$\widehat{P}$]:

$$\max_{e,x(v,\theta),\rho_1(v)} \int_v \left\{ \int_\theta \left[\sum_{i\in N} [v - J_i(\theta_i)]x_i(v,\theta) - p_i \right] dG(\theta) - \rho_1(v) \right\} f(v \mid e)dv$$

s.t. [$\widehat{LL}$],[$\widehat{IR}$], and [$\widehat{MH}$]

It follows that the integrand of the Lagrangian is

$$L(v,\theta,e) := [1+\mu(v)]\left\{ \left[v - \theta_1 - p_1 - \left(1 - \frac{\beta(v)}{1+\mu(v)}\right)\frac{G_1(\theta_1)}{g_1(\theta_1)} \right] x_1(v,\theta) + \sum_{j\in N, j\neq 1} [[v - J_j(\theta_j)]x_j(v,\theta) - p_j] \right\}$$

$$-\rho_1(v)[1 + \mu(v) - \nu(v) - \beta(v)] - \lambda c'(e)$$

where $\mu(v) \geq 0$, $\nu(v) \geq 0$, and $\lambda \geq 0$ are the Lagrange multipliers associated with the limited liability, individual rationality, and moral hazard constraints, respectively, and

$$\beta(v) := \lambda \frac{f_e(v \mid e)}{f(v \mid e)}$$

Because $L(v,\theta,e)$ is linear in $\rho_1(v)$, its coefficient is zero. Therefore,

$$1 + \mu^*(v) - \beta^*(v) - \nu^*(v) = 0 \qquad [5]$$

$L(v,\theta,e)$ is also linear in x, therefore the following holds in an optimal solution:

$$x_i{}^*(v,\theta) = \begin{cases} 1 & if\ \tilde{K}_i(v,\theta_i) \leq min\{v, min_{j\neq i}\tilde{K}_j(v,\theta_j)\} \\ 0 & otherwise \end{cases} \qquad [6]$$

where

$$\tilde{K}_i(v,\theta_i) := \begin{cases} J_i(\theta_i) - \frac{\beta^*(v)}{1+\mu^*(v)}\frac{G_i(\theta_i)}{g_i(\theta_i)} & if\ i = 1 \\ J_i(\theta_i) & otherwise \end{cases}$$

Optimal level of effort e^* needs to satisfy

$$\frac{\partial}{\partial e}\int_v\int_\theta L(v,\theta,e^*)f(v \mid e^*)dG(\theta)dv = 0 \qquad [7]$$

Complementary slackness implies the following conditions:

$$\nu^*(v)\rho_1^*(v) = 0 \qquad [CS1]$$

$$\mu^*(v)\left\{\int_\theta \sum_{i\in N}[[v - J_i(\theta_i)]x_i^*(v,\theta) - p_i]dG(\theta) - \rho_1^*(v)\right\} = 0 \qquad [CS2]$$

$$\lambda^*\left[\int_v\int_\theta\left[\rho_1^*(v) + \frac{G_1(\theta_i)}{g_1(\theta_i)}x_1^*(v,\theta)\right]dG(\theta)f_e(v \mid e^*)dv - c'(e^*)\right] = 0 \qquad [CS3]$$

Now, to characterize the optimal solution, we first consider two cases, when $v < \underline{\theta}$ and when $v > \underline{\theta}$. From [5] we see that when $v < \underline{\theta}$, we have that $\tilde{K}_i(v,\theta_i) \geq \theta_i$. Therefore, $\tilde{K}_i(v,\theta_i)$ and $K_i^*(v,\theta_i)$ results in an optimal transfer allocation $x_i^*(v,\theta) = 0$. Then, combining the [LL] and [IR] constraints implies

$$\rho_1^*(v) = \int_\theta \sum_{i\in N}[[v - J_i(\theta_i)]x_i^*(v,\theta) - p_i]dG(\theta) = 0$$

This means that when the value of the innovation is less than the lowest possible bid, the principal would be better off not accepting any bids. Therefore, no contract would be awarded and no transfer would be made.

Next, we consider the case where the value of the innovation is greater than the minimum cost of production, or $v > \underline{\theta}$. If the value is lower than the threshold value for offering a prize, i.e. when $v < \hat{v}$, then $\beta^*(v) < 1$. Therefore, $1 + \mu^*(v) - \beta^*(v) > \mu^*(v) \geq 0$. Together with [5}, this implies $\nu^*(v) > 0$. Because complementary slackness must hold, we have that $\rho_1^*(v) = 0$. When $i = 1$, we can then rewrite

$$\tilde{K}_i(v,\theta_i) = \left[J_i(\theta_i) - \frac{\beta^*(v)}{1+\mu^*(v)} \frac{G_i(\theta_i)}{g_i(\theta_i)} \right],$$

expressing $\tilde{K}_i(v,\theta)$ as

$$\theta_i + \left[1 - \frac{\beta^*(v)}{1-\mu^*(v)} \right] \frac{G_i(\theta_i)}{g_i(\theta_i)}$$

Combining this with [5] and $\nu_i^*(v) > 0$, we get that

$$\left[1 - \frac{\beta^*(v)}{1-\mu^*(v)} \right] > 0$$

It follows that $\tilde{K}_i(v,\theta_i) > \theta_i$, which is increasing in θ_i .

Then, keeping in mind that $\rho_1^*(v) = 0$, and turning our attention to the CS constraint associated with $\mu^*(v)$, we have

$$\mathbb{E}_\theta \left[\sum_{i \in N} [v - J_i(\theta)] x_i(v,\theta) - p_i \right] = \int_{\underline{\theta}}^{\bar{\theta}} [v - J_i(\theta_i) - p_i] dG(\theta) \qquad [8]$$

$$= v - \theta - np$$

$$> 0$$

when $v - \theta \neq np$ and ignoring the possibility that it is negative because the principal wouldn't voluntarily start an auction that, in expectation, he ends up worse off, implying that $\mu^*(v) = 0$.

Next, we look at the case where $v > \hat{v}$ and $\beta^*(v) > 1$. Referring back to [5], we now see that $1 - \beta^*(v) - \nu^*(v) < 0$, implying $\mu^*(v) > 0$. Now, using [CS2], we have

$$\rho_1^*(v) = \int_\theta \sum_{i \in N} [[v - J_i(\theta_i)] x_i^*(v,\theta) - p_i] dG(\theta) \qquad [9]$$

This is the optimal monetary prize that is awarded to the firm that innovates.

Next, we consider two scenarios, when $\nu^*(v) > 0$ and when $\nu^*(v) = 0$. The former scenario would imply that $\rho_1^*(v) > 0$, which is a contradiction to [CS1].

Therefore, the latter scenario where $\nu^*(v) = 0$ must be true, meaning $1 + \mu^*(v) = \beta^*(v)$. Substituting this result into $\tilde{K}_i(v, \theta_i)$, we get $\tilde{K}_1^*(v, \theta_1) = \theta_1$.

To find the expected transfer $T_i^*(v, \theta)$, we use the interim allocation and payment [1] for firm i and the incentive compatibility constraint [2]. We have already defined the cash prize incentive $\rho_1^*(v)$ in [9] above, and we have that $\rho_i^*(v) = 0$ when $i \neq 1$. Then we the expected transfer $T_i^*(v, \theta_i) = \rho_1^*(v) + \int_{\theta_i}^{\bar{\theta}} X_i^*(v, s)ds + \theta_i X_i^*(v, \theta_i)$,

keeping in mind that the administration costs decrease $\rho_1^*(v)$, decreasing the expected transfer to the agents, thus proving part B of Proposition 1.

It follows that $K_i^*(v, \theta_i) = J_i(\theta_i)$ when $i \neq 1$ and $K_i^*(v, \theta_i) = J_i(\theta_i) - min\{1,\ \beta(v)\}\frac{G_i(\theta_i)}{g_i(\theta_i)}$ when $i = 1$. This, combined with [6] gets us the complete allocation rule, proving part A of Proposition 1.

Next, we show that the optimal $\lambda^* > 0$ exists. If $\lambda^* = 0$, $\beta^*(v) = 0$, implying $\mu^*(v) = 0$, $\rho_1^*(v) = 0$, and $\nu^*(v) > 0$. We then have the Lagrangian

$L(v, \theta, e^*) = max\{0, v - min_i J_i(\theta_i)\}$

Then, we have

$$\frac{\partial}{\partial e}\int_v\int_\theta L(v, \theta, e)dG(\theta)f(v \mid e)dv|_{e=e^*} = \int_v\int_\theta max\{0, v - min_i J_i(\theta_i)\}dG(\theta)f_e(v \mid e^*)dv > 0$$

contradicting [7].

Taking into consideration that $\lambda^* > 0$, [CS3] implies

$$\int_v \int_\theta \left[\rho_1^*(v) + \frac{G_1(\theta_i)}{g_1(\theta_1)} x_1^*(v, \theta) \right] dG(\theta) f_e(v \mid e^*) dv = c'(e^*)$$

Because the left hand side is positive and our assumption that $c'(0) = 0$, we have that the optimal level of effort $e^* > 0$. Furthermore, because the addition of the administration costs causes $\rho_1^*(v)$ to decrease, $c'(e^*)$ must also decrease, implying that the inclusion of p_i decreases the optimal level of effort. This proves part C of Proposition 1.

That concludes proof of Proposition 1 and the characterization of the optimal mechanism in the face of uniform per-agent administration costs.

As we have previously shown, we see that the introduction of verification costs results in a decrease in expected transfers to the agents and a decrease in the optimal level of effort, and by extension, the expected value of the innovation. This situation does seem rather unfortunate for the principal. However, there may be a way to alleviate, to some degree, the negative impact on his utility.

Next, we endogenize entry and relax the assumption of no private information about costs prior to entering the procurement contest. Suppose that each firm $i \in N$ privately knows their own firm's manufacturing capabilities, but they don't know their competitor's abilities. What is known to each firm is where their own firm ranks in ability out of the total group of firms, with 1 being the best and n being the worst. To clarify, by ability we simply mean that the c.d.f. $G(\cdot \mid 1)$ is shifted more to the left the than $G(\cdot \mid 2)$, meaning that the expected cost drawn from the distribution is lower for firms with better ability. The principal can now decide how many firms he lets into the procurement auction and ideally improve his expected outcome. To eliminate the worst participants, the principal simply needs to conduct a uniform price auction. We assume that there are no costs associated with the uniform price auction as there need not be any verification involved. However, it would be reasonable to assume that any costs that are associated with the uniform price auction are going to be lower than those

associated with the procurement auction. Therefore, even if there are costs involved, our following results do not change.

To analyze how entry auctions affect the outcomes of the procurement mechanism, we will use the sealed-bid uniform-price auction as a benchmark for comparison. But first, we characterize the result of the entry auction.

Let b_i represent the lowest qualifying bid, which is the price that every winning agent pays, during the initial sealed-bid uniform price entry auction. It follows that the principal's per-person cost is reduced to $p_i - b_i$. However, this isn't the total cost reduction to the principal as there is also a reduction in the number of participants. We will let $\hat{n} \in N$ represent the number of remaining agents that will participate in the procurement auction after the entry auction.

Proposition 2: When a principal conducting a procurement auction faces an identical cost to administer the auction for each agent, provided agents know their type, the principal can increase his welfare and the innovator's welfare at the cost of the non-innovating agents' welfare by implementing a simple sealed-bid uniform-price auction.

We will skip the full proof as it is nearly identical to that of Theorem 1 except n is reduced to $\hat{n}$ and there is now a transfer of b_i from each agent that participates in the second auction to the principal. What follows is a characterization of the relevant effects of the initial entry auction.

Because the agents will now each need to transfer b_i to the principal, the agents' costs, denoted by $J_i(\theta_i)$, increases. This results in a decrease in the probability for any agent i to be chosen to manufacture the innovation. Although all agents pay the same bid so their chances of winning relative to one another does not change, holding the value of the innovation constant, there is a decreased probability that any principal's minimum cost will be less than or equal to v.

The transfer of b_i also gives us the following expected prize to the innovating firm if $\beta^*(v)$, the incentive benefit for the innovator to increase effort, is sufficiently high:

$$\rho_1^*(v) = \sum_{i=1}^{\hat{n}} [[v - J_i(\theta_i)]x_i^*(v,\theta) - p_i + b_i]$$

Thus the increase in an individual agents' costs are offset by an even larger increase in the prize for a valuable innovation. However, the decrease in the number of agents results in an increase in this transfer $\rho(v)$ even when the principal's per-agent cost is higher than the winning entry auction bid.

The increase in the prize is particularly important when considering that the level of effort affects the value of the innovation. We have that

$$c'(e^*) = \int_v \int_\theta \left[\rho_1^*(v) + \frac{G_1(\theta_i)}{g_1(\theta_1)} x_1^*(v,\theta)\right] dG(\theta) f_e(v \mid e^*) dv$$

where the slope of the cost function, given the optimal level of effort, is increased after the entry auction. Because we assume that the cost function is convex and zero effort costs nothing, an increase in the slope of the cost function at e^* implies a higher optimal level of effort. This increase in effort corresponds to an increase in the expected value of the innovation.

Now, we refer back to the principal's objective function

$$\max_{x,t,e} E_{v,\theta}[w(v,\theta) \mid e]$$

where

$$w(v,\theta) = \sum_{i=1}^{\hat{n}} [v x_i(v,\theta) - t_i(v,\theta) - p_i + b_i]$$

Recall that the implementation of the entry auction results in an increase in the expected value of the innovation and an increase in the expected transfer to agents when the value of the innovation is high. In this case, the increased value of the innovation is largely negated by the increase in transfer to the innovator. Though, when $\beta^*(v) > 1$, an increase in the transfer to the innovator results in a disproportionately

large increase in the value of the innovation. That result, combined with the decrease in the net per-agent costs, allows the principal to offer more money to the innovator, leading to an increase in the principal's utility when compared to the single period procurement auction with administration costs. From these results, it would follow that the principal, at least in expectation, is best off when extracting the maximum amount of rents from the entry auction.

Contingent upon the relative difference between variables, the implementation of the entry auction when faced with administration costs may result in an increase in the principal's utility compared to the single auction optimal mechanism results even when the principal doesn't face the administration costs in the latter. The explanation is fairly simple. If b_i is sufficiently high such that $b_i - p_i > 0$, then the revenue from the entry auction reverses the negative effect on innovation incentive of the decrease in prize money from the costs faced by the principal. The end result is an increase in the total prize money available by extracting rents from all participating agents and transferring it to the innovator. Furthermore, depending on the distribution of bids, it could even be in the principal's best interest to not eliminate any agent.

However, when $\beta^*(v) < 1$, it is not optimal to encourage further innovation through the additional incentive of a cash prize to the innovator. In this case, the double auction mechanism does not have any effect on the value of the innovation, nor does it have any effect on the transfers to the agents. Nonetheless, it does serve to increase the principal's surplus when faced with administration costs simply through offsetting the costs associated with administering the procurement auction.

Finally, the implementation of an entry auction allows the principal to reduce the number of agents, offsetting the costs of procurement, and potentially increasing the optimal level of effort for the innovator, resulting in an increase in the value of the innovation provided. While the entry auction isn't always beneficial for the agents, it is always beneficial to the principal.

4.0 Discussion

We analyzed a case where an optimal mechanism for procuring an innovation through the use of prizes and contracts was rendered sub-optimal when the principal faces identical costs based on the number of firms it is overseeing. These costs that the principal faces may arise from conducting the procurement auction itself or verification of the value of the innovation or the manufacturer's ability to adequately manufacture it. In Proposition 1, we demonstrated the effects of the optimal mechanism on the optimal allocations, transfers, utilities, and effort. We then proposed that the implementation of an entry auction would allow the principal to reduce the number of agents, offsetting the costs of procurement, and potentially increasing the optimal level of effort for the innovator, resulting in an increase in the value of the innovation provided. That effect, as shown in Proposition 2, increases the principal's utility, potentially to a level higher than the situation without any administration costs associated with procurement. This contributes to the overall body of knowledge by showing how the operation or administration costs for running innovation procurement auctions can distort outcomes and how switching to a different auction format, even as simple as an entry auction, can improve the principal's utility and the innovator's incentive to exert more effort, resulting in a higher level of innovation.

Ideally, this research will help lead to the development of better, more robust mechanisms to encourage innovation. Though this model doesn't take into account the dimension of time and the lengths of contracts, we can still apply intuition to consider how a guaranteed contract may potentially continue longer than the patent's lifespan, addresses the problem of insufficient patent length. With a longer exclusivity period, the firm doesn't have as much need to promote overuse of the antibiotic early in the product's effective lifespan to maximize profits since the time horizon is longer. Referring back to our motivation, antibiotic effectiveness and lack of resistance can be seen as a non-renewable resource. Optimal extraction of non-renewable resources, if given a longer time to extract benefits, says that we will extract less in each period, meaning that we will smooth consumption over time. It follows that an extended contract may be beneficial not just to encourage innovation, but also to slow the decline of antibiotic effectiveness.

While the mechanism specifies that a buyer is looking to procure a new innovation, if the buyer represents a governmental or intergovernmental organization, a winner of the competition might not even be needed for a new suitable innovation to surface. Simply spurring investment may be enough. Take for example the recent ebola outbreaks of West Africa that garnered international media attention in 2014. Though the threat of a global epidemic is no longer imminent, there is a promising vaccine going through clinical trials currently because of the initial hysteria surrounding the disease outbreak. However, if the principal is indeed concerned with the overall rate of innovation, the utility function would need to be changed to account for that. On the one hand, the dual auction as modeled makes the procurement more efficient. On the other hand, if we were to extend the model by allowing for multiple innovators, a reduction in the number of agents would correspond to a reduction in the overall rate of innovation induced by the procurement auction.

Additionally, the offering of contracts, as opposed to simply extending patent length can offer additional benefits that may not have been directly addressed previously. With antibiotics, due to the abundance of generics in the market, and the fact that many drugs, particularly those with a broad spectrum of activity, may have some effectiveness in treating any number of conditions. However, those broad-spectrum antibiotics might have more side effects or a lower success rate at treating an infection than a more specialized treatment. Given the price difference between a generic drug compared to a newly developed drug that is still under patent protection, physicians, operating under the price-sensitive preferences of patients, may initially opt for the more cost-effective treatment. Given that the price of name-brand medications can be several orders of magnitude higher than generics, the cost effectiveness of a more effective, but many times more expensive medication can be much lower than the alternatives. Because of this, simply extending patent length might not be sufficient to spur enough innovation, particularly when taking into account the time value of money. However, with contracts that guarantee the use of a new medication when treating a condition, the innovator will

be receiving more revenues early in the product lifecycle, even when competitors release fast-follower drugs to treat the same condition.

There are, however, some limitations of this model. Perhaps the most obvious is ignoring how the reduced number of agents will negatively impact the realized values of innovation and costs because those are randomly drawn from distributions. Also, the model ignores the dynamic multi-period effects that might be able to account for endogenous entry into R&D and exit from R&D during the innovation period when research doesn't look promising. We also make the assumption that the true value, inclusive of an innovations effectiveness, is verifiable at the end of the innovation period. With pharmaceutical R&D, innovations that haven't completed clinical trials won't have verifiable data regarding effectiveness, and doing such verification is likely to be time consuming. Furthermore, additional information that may affect the true value of an innovation may not be apparent until long after the drug has been used in the general population. Given the various hurdles any individual R&D project may face, it isn't necessarily a realistic assumption that all projects will have done clinical trials at the end of the innovation competition. Additionally, we assume that all of the firms also have the means to manufacture their innovations. In reality, there are many small start-up biotech companies that primarily do research and rarely engage in manufacturing. These small companies either sell the rights to their innovations or the companies get acquired by larger firms.

5.0 Conclusion

The purpose of this paper is to suggest the use of procurement contracts to as a means to encourage innovation in sectors where the rate of innovation is insufficient. In particular, we adapted a model to suit the particular characteristic of the pharmaceutical industry where costs related to testing and verification are likely to be very significant. We find that, through the adaptation of Che et al. (2017)'s model, administration costs can have quite a few negative effects on the results of procurement auctions.

Finally, it should be noted that public procurement, though a largely untapped source for demand-side innovation incentives, isn't meant to replace direct funding of basic biomedical research such as what is often researched at universities. It is that basic public research that often attempts to better understand diseases and other biological mechanisms is the basis of what pharmaceutical researchers build upon to guide the development of treatments. However, this can potentially be an effective way to encourage innovation other than extending patent protections.

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7.0 Appendix A

Figure 2: Definition of Symbols

Symbol	Definition
$\rho_1(v)$	the transfer to firm the innovating agent
$i = 1$	the agent that provides the innovation
$\beta(v)$	the incentive benefit to the innovator that results from an increase in the prize
p_i	the cost faced by the principal for each agent in the procurement auction
b_i	the lowest winning bid in the entry auction
v	the value of the innovation firm i proposed
$\hat{v}$	threshold value for offering a monetary prize
n	the initial number of agents prior to the entry auction
$\hat{n}$	the number of agents after the entry auction
θ_i	firm i's true manufacturing cost
θ_i'	firm i's report of a cost other than the true cost
$\underline{\theta}$	the lowest cost in the distribution of θ
$\bar{\theta}$	the highest cost in the distribution of θ
e	the effort firm 1 expends toward innovation
$c(e)$	the cost of effort
$x_i(v, \theta)$	the probability that agent i will receive the contract given the value v of the innovation from firm 1 and the distribution of costs θ
$t_i(v, \theta)$	the transfer to agent i given the value v of the innovation from firm 1 and the distribution of costs θ
$U_i(v, \theta_i)$	the utility of firm i when bidding θ_i

Symbol	Definition
$w(v, \theta)$	the utility of the principal given the value of the innovation and the distribution of costs
$J_i(\theta_i)$	the virtual costs of firm i
$K_i(v, \theta_i)$	the shadow cost for firm i to implement the project
λ	the value of relaxing the moral hazard constraint