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ABSTRACT

In a simple representative consumer model, vaccines and drug treatments yield the same revenue for a pharmaceutical manufacturer, implying that the firm would have the same incentive to develop either ceteris paribus. We provide more realistic models in which the revenue equivalence breaks down for two reasons. First, drug treatments are sold after the firm has learned who has contracted the disease; in the case of heterogeneous consumers who vary with respect to the probability of contracting the disease, there is less asymmetric information to prevent the firm from extracting consumer surplus with drug treatments than with vaccines. We prove that, due to this aspect of pharmaceutical pricing, the ratio of drug-treatment to vaccine revenue can be arbitrarily high; we calculate that the ratio is about two to one for empirical distributions of HIV risk. The second reason for the breakdown of revenue equivalence is that vaccines are more likely to interfere with the spread of the disease than are drug treatments, thus reducing demand for the product. By embedding an economic model within a standard dynamic epidemiological model, we show that the steady-state flow of revenue is greater for drug treatments than for vaccines.

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1 Introduction

It is conventionally believed that pharmaceutical manufacturers prefer to develop drug treatments (medicines administered after a disease has been contracted) rather than vaccines (medicines that prevent healthy people from ever contracting the disease). Patricia Thomas, journalist and author of a widely publicized book on the search for an AIDS vaccine (Thomas 2001), notes,

> Private companies find vaccines less financially rewarding than drugs. In 2001, the global marketplace for therapeutic drugs exceeded $300 billion, whereas worldwide vaccine sales were only about $5 billion . . . . It is not hard to understand why major pharmaceutical companies, capable of developing drugs and preventive vaccines, generally invest in drugs that patients must take every day rather than shots given only occasionally. Drug company executives have investors to answer to, after all. (Thomas 2002)

The case of HIV is consistent with this conventional belief that pharmaceutical firms are more inclined to invest in drug treatments than in vaccines: although it may certainly be in part due to differing degrees of scientific difficulty, drug treatments for HIV/AIDS have been developed, but as yet there is no HIV vaccine.

Thomas' explanation of why firms prefer drug treatments to vaccines—that is, that drug treatments are administered more frequently, allowing firms more opportunities to extract revenue—appears to be widely held (for example, see also Rosenberg 1999). Yet from the perspective of neoclassical economics, this explanation seems odd because a rational consumer would pay the expected present value of the stream of benefits in an up front lump sum for the vaccine, and thus by this argument vaccines and treatments should yield equivalent revenues.

While behavioral economics may provide reasons why people are willing to pay more for a cure than for prevention, in this paper we examine two ways in which the view that firms are biased toward developing drug treatments can be reconciled with standard neoclassical economics. In Section 2, we show that if one moves from a representative consumer model to a more realistic model with heterogeneous consumers, revenue equivalence between vaccines and treatments

breaks down. It is indeed realistic to suppose that consumers are heterogeneous in their *ex ante* probabilities of contracting the disease. Take as an example the case of HIV: people engaging in unprotected sex with many partners have a higher risk of contracting HIV than do those with few partners. We show in this paper that treatments extract revenue from heterogeneous consumers more effectively than vaccines. Since vaccines are administered before consumers contract the disease, there is no basis on which the firm can discriminate among the consumers. If the firm attempts to charge a high price for the vaccine, only consumers at high risk of contracting the disease will buy it, but this segment is often only a small fraction of the population. On the other hand, at the point when treatments are administered, the firm has better information about consumers; in particular, the firm at least knows which consumers have the disease and which do not. The firm can use this information to charge high prices to all consumers who contract the disease, regardless of whether they come from the small segment of the population at high risk or the large segment of the population at low risk.

A simple example suffices to illustrate this point. Suppose there are 100 total consumers, ninety of whom have a ten percent chance of contracting the disease and ten of whom have a 100 percent chance. Suppose consumers are risk neutral and are willing to pay 100,000 to be cured of the disease if they contract it. A monopolist selling a vaccine could either charge 100,000 and sell to the ten high-risk consumers or charge 10,000 and sell to all 100 of them. Either way, the monopolist's revenue is 1,000,000. A monopolist selling a treatment would, in expectation, sell to the nineteen consumers contracting the disease (all ten of the high risk consumers as well as an average of nine consumers from the low-risk group) at a price of 100,000 for a total revenue of 1,900,000, almost twice the revenue from a vaccine.

In Section 2.2 we develop a formal model in which the probability of contracting a disease for consumer i, x_i, is a random variable with distribution function $F(x_i)$. We prove that for any distribution with a non-trivial amount of consumer heterogeneity, a treatment yields more revenue than a similarly effective vaccine. We prove that there exist distributions of consumer

heterogeneity for which the ratio of treatment to vaccine revenue is arbitrarily high. While our results are proved in the simplest possible setting in which vaccines and drug treatments produce the exact same social benefits, given the substantial gap in revenue between the two, it is straightforward to argue by continuity that there will exist a broad range of cases in which the social benefit from a vaccine exceeds that from a drug treatment, yet the revenue advantage of the drug treatment will induce the firm to develop a drug treatment rather than a vaccine. In Section 2.3 we show how our results can be applied to estimates of two actual distributions of expected risk in populations to bound the treatment/vaccine revenue gap. Such estimates can be used to calculate the subsidies needed to induce firms to develop vaccines rather than treatments where the relative social benefit of vaccines is large relative to treatments.

In Section 3 we consider a dynamic model and reveal additional disadvantages of vaccines relative to drug treatments in terms of rent extraction. Because vaccines cause greater reductions in disease transmission than drug treatments, it is more difficult for developers to capture the full social benefit of their medicine. We examine the effects of disease transmission on pricing and research and development (R&D) decisions by embedding an economic model within a standard dynamic epidemiological model, which we use to solve for the optimal price and profits for both vaccines and drug treatments. We show that the steady-state flow of revenue for drug treatments is greater than for vaccines, and thus that R&D expenditures will be distorted towards drug treatments rather than vaccines. The fraction of social benefits that the private developer of a vaccine captures declines with disease prevalence.

Sections 2 and 3 focus on the case of private markets for pharmaceuticals; however, in practice, governments are often large purchasers. In Section 4, we argue that if the prices the government pays for vaccines and drug treatments are influenced by the threat point of profits the firm could realize on the private market if bargaining breaks down, then to the extent that vaccines are less profitable than drug treatments on the private market, they will also be less profitable when sold to the government.

It is worth noting that a preference for investing in drug treatments over vaccines will have particularly detrimental consequences for developing countries. Vaccines are more suited for use in developing countries with weak medical infrastructure: they do not require prior diagnosis; do not need to be taken on a long term basis but instead require only a few doses; do not typically have major side effects that need to be monitored; and can more easily be delivered by personnel with limited medical training. As an illustration, consider that while three-quarters of the world's children receive a standard package of cheap, off-patent vaccines through the World Health Organization's Expanded Program on Immunization (Kim-Farley *et al.* 1992), it is estimated that only 10,000 to 30,000 of the 25 million people infected with HIV in Africa have access to antiretroviral therapies, at least in part due to difficulties with safe and effective delivery of the drugs (World Health Organization 2001).

To our knowledge, our comparison of drug treatments and vaccines in the static model with heterogenous consumers is new in the literature.[1] Our analysis of the bounds on the profitability of drug treatments relative to vaccines in Propositions 5 and 6 also represents a contribution. One might look to the industrial organization literature for a related result since, as we argue, the relationship between drug treatments and vaccines in our model is analogous to the relationship between price discrimination and uniform pricing. However, the industrial organization literature provides bounds on the social welfare from price discrimination relative to uniform pricing (Malueg 1993) but not bounds on a monopolist's relative profits, to which our results apply. Our dynamic extension is based on a standard epidemiological model. In a related model, Geoffard and Philipson (1997) show that if a vaccine is produced by firms with market power and sold on the private market, the disease will not be eradicated in the steady state. Our work differs because we explicitly derive the optimal monopoly price and profits for vaccines, and the

[1] We have become aware of contemporaneous research by Kessing and Nuscheler (2002) that is related to our static model. Their analysis is quite different from ours since their underlying model involves income heterogeneity rather than disease-risk heterogeneity. In addition, they consider vaccines alone rather than compare vaccines to drug treatments.

fraction of vaccines' social value appropriated by developers. Furthermore, our analysis of drug treatments, our comparison of drug treatments to vaccines, and our result that R&D expenditures will be distorted towards drug treatments in a dynamic model are new.

2 Static Model

2.1 Homogeneous Consumers

A monopoly pharmaceutical manufacturer, called the firm, has the choice of developing alternative medicines for a disease affecting a population of consumers. The timing of the model is given in Figure 1. First, the firm chooses which of the alternative medicines to develop: a vaccine, the term we give to a medicine administered before consumers contract the disease, or a drug treatment, the term we give to a medicine administered after. To fix ideas, we will suppose the firm's choices are mutually exclusive: it will develop either a vaccine or a drug treatment but not both.[2] Let $k_j \in [0, \infty)$ be the present discounted value of the fixed cost of developing medicine j, where $j = v$ for the vaccine and $j = t$ for the drug treatment. Let $c_j \in [0, \infty)$ be the present discounted value of the cost of administering medicine j to an individual consumer. Note that the drug treatment may be administered later in a consumer's life than a vaccine, and so the nominal cost of the drug treatment may be discounted more heavily than the vaccine, but such discounting is reflected in the terms c_v and c_t since they are expressed as present discounted values. Let $e_j \in [0, 1]$ be the efficacy of medicine j, that is, the probability that medicine j prevents the consumer from experiencing any harm from the disease. Let $\sigma_j \in [0, 1]$ be the probability that a consumer experiences side effects from medicine j and $s_j \in [0, \infty)$ the present discounted value of the harm from the side effects conditional on experiencing them. Let $P_j \in [0, \infty)$ be the present discounted value of the price the firm receives for medicine j.

[2]Given the normalizations adopted later in the paper, we will show (Propositions 4 and 9) the firm does not prefer to develop both a vaccine and a drug treatment.

Interpreting P_j as a net price the firm receives for medicine j allows for a consistent representation of the legal/liability costs associated with side effects. Assuming a *caveat emptor* regime in which the consumer bears the liability for harm, consumers' willingness to pay will be reduced by the harm they expect from side effects, and P_j will reflect a discount for this lower willingness to pay. Assuming a *caveat venditor* regime in which the firm bears liability for harm, P_j can be interpreted as the price the firm receives after subtracting off payments it makes to consumers for damages. Other exogenous legal/liability costs can be embodied in k_j if the costs are fixed or in c_j if the costs vary with the number of consumers who receive the medicine.

Before pursuing any medicine, consumer i learns the probability that he or she will contract the disease, $x_i \in [0, 1]$. To capture the notion that consumers are homogeneous, we will assume that x_i takes on a single value, which is public information for consumers and the firm.[3] Whether or not consumer i contracts the disease is represented by Bernoulli random variable d_i, where $d_i = 1$ indicates i contracts the disease, an event which occurs with probability x_i, and $d_i = 0$ indicates i does not contract the disease, an event which occurs with probability $1 - x_i$. Without loss of generality, assume d_i is public information, observable not only to consumer i but also to the firm.[4]

As Figure 1 shows, the key difference between a vaccine and a drug treatment hinges on when the medicine is administered relative to the realization of d_i. A vaccine is administered before d_i is realized and a drug treatment is administered after.

Suppose consumers are risk neutral. If a consumer contracts a disease and has not had a vaccine or does not receive a drug treatment, he or she experiences harm $h \in [0, \infty)$ in present discounted value terms. Normalize the mass of consumers to unity.

[3]The case in which consumers are homogeneous but in which the firm does not know x is formally identical to the case of heterogeneous consumers drawn from a distribution known to the firm. We will treat this case in Section 2.2.

[4]To see that this assumption can be made without loss of generality, consider two cases. First, if the firm has developed a vaccine rather than a drug treatment, the firm does not make any decisions conditional on d_i, so it is immaterial whether it can observe d_i. Second, if the firm has developed a drug treatment rather than a vaccine, the firm can indirectly observe who has contracted the disease by observing who demands the drug treatment.

First, consider the firm's profit from a vaccine. A consumer's expected net surplus from a vaccine is $x_i h e_v - \sigma_v s_v - P_v$. That is, with probability e_v the vaccine is effective and provides a benefit to the consumer in that expected harm $x_i h$ is avoided. From this benefit, the expected harm from side effects $\sigma_v s_v$ and the price P_v have to be subtracted to yield net consumer surplus. The profit maximizing price extracts all this surplus; hence $P_v^* = x_i h e_v - \sigma_v s_v$. Since consumers are of unit mass, the firm's maximum profit from the vaccine is

$$P_v^* - c_v - k_v = x_i h e_v - \sigma_v s_v - c_v - k_v. \tag{1}$$

Next, consider the firm's profit from a drug treatment. The consumer will only purchase the drug treatment if he or she contracts the disease. Conditional on contracting the disease, the consumer's net consumer surplus from the drug treatment is $h e_t - \sigma_t s_t - P_t$. The profit maximizing price extracts all this surplus; hence $P_t^* = h e_t - \sigma_t s_t$. Since consumers are of unit mass, and a fraction x_i end up contracting the disease, the firm's maximum profit from the drug treatment is

$$x_i(P_t^* - c_t) - k_t = x_i(h e_t - \sigma_t s_t - c_t) - K_t. \tag{2}$$

Using expressions (1) and (2), we can characterize which medicine the firm chooses to develop.

Proposition 1. *In the homogeneous consumer model, the firm strictly prefers to develop the vaccine over the drug treatment if and only if (1) strictly exceeds (2), strictly prefers to develop a drug treatment over a vaccine if and only if (2) strictly exceeds (1), and is indifferent if (1) equals (2).*

In view of Proposition 1, it is straightfoward to perform comparative statics analyses on the various parameters. *Ceteris paribus*, the firm tends to prefer to develop a vaccine over a drug treatment if it is cheaper to develop (i.e., k_v is low relative to k_t) or cheaper to produce (c_v is

low relative to c_t). The firm tends to prefer a vaccine if it involves less severe side effects (σ_v and s_v are low relative to σ_t and s_t, respectively). The firm tends to prefer a vaccine if it is a more effective cure (e_v is high relative to e_t).

Obviously this model does not exhaust the list of factors that might lead the firm to prefer vaccines over drug treatments or vice versa. However, it would be straightforward to extend the model to consider alternative factors, and we will briefly mention a few here. First, if consumers were assumed to be risk averse, vaccines would become relatively more profitable, since they would provide insurance to consumers for which consumers would pay a premium. Second, the effect of assuming consumers face liquidity constraints is less clear, depending on the nature of the constraint assumed. If the liquidity constraint is a constraint on lifetime expenditures, say because the consumer has access to relatively efficient credit markets, then the liquidity constraint may bind less with vaccines than with drug treatments. To see this, recall that we found the equilibrium price for the vaccine to be $P_v^* = x_i h e_v - \sigma_v s_v$ and for drug treatment to be $P_t^* = h e_t - \sigma_t s_t$. Adopting the *ceteris paribus* assumptions that $e_v = e_t$, $\sigma_v = \sigma_t$, and $s_v = s_t$, it is evident that $P_v^* < P_t^*$ for all $x_i < 1$. Hence, conditional on contracting the disease, total payments are lower with vaccines. This type of lifetime liquidity constraint would bias the firm in favor of vaccines. If, on the other hand, the liquidity constraint were a per-period constraint, say because the consumer does not have access to credit, then the liquidity constraint may bind less with drug treatments since the total payment with drug treatments may be spread out in installments (with a payment for each separate treatment) whereas the total payment for the vaccine would need to be paid in a lump sum at the time the vaccine is administered. This type of liquidity constraint would bias the firm in favor of drug treatments.

The conclusions drawn from Proposition 1—that is, that the firm prefers cheaper, more effective medicines associated with fewer side effects—are both intuitive and well-known. To focus on the more subtle issues that are the focus of this paper, we will normalize certain variables so that the firm is indifferent between developing vaccines and drug treatments in the

homogeneous consumer model. In particular, throughout the remainder of the paper, we will normalize $k_j = c_j = \sigma_j = 0$ and $e_j = 1$ for $j = v, t$. That is, we will assume that both medicines are costless to develop and produce, have no side effects, and are perfectly effective. The following revenue-equivalence result for the case of homogeneous consumers is an immediate corollary of Proposition 1.

Proposition 2. *Assume $k_j = c_j = \sigma_j = 0$ and $e_j = 1$ for $j = v, t$. Then the firm is indifferent between developing the vaccine and the drug treatment in the homogeneous consumer model.*

We will show in the next subsection that drug treatments are more profitable than vaccines in a heterogeneous consumer model.

2.2 Heterogeneous Consumers

In this subsection, we will adopt the preceding model with one modification. As before, consumer i learns the probability that he or she will contract the disease, $x_i \in [0, 1]$, before pursuing any medicine. Now, however, we assume x_i is a random variable distributed according to a nontrivial cumulative distribution function $F(x_i)$. Each consumer in the population has a type given by an independent draw from this distribution. Variable x_i is private information for the consumer; the firm only knows the distribution from which x_i is drawn. We are attempting to capture the fact that the consumer's background and/or actions put him or her into a risk category that he or she can observe more accurately than can outsiders. For example, engaging in unprotected sex with multiple partners or in intravenous drug use would put a person at higher risk of contracting HIV, but such behaviors would be difficult for a firm to monitor accurately enough to be able to charge a discriminatory price. Likewise, frequenting mosquito-infested tropical regions increases the chance of contracting malaria, but again may be difficult to monitor accurately.

Normalize $k_j = c_j = \sigma_j = 0$ and $e_j = 1$ for $j = v, t$ as before. That is, both medicines are costless to develop and produce and both are perfectly effective. These normalizations allow us to concentrate on the revenue generated by each medicine in a heterogeneous consumer model.

Consider first the firm's profit maximization problem if it decides to develop a vaccine. Given that consumers' types x_i are private information, the firm is forced to charge a uniform price. Since consumers are risk neutral, consumer i will buy the vaccine if the price P_v is less than the expected harm from the disease, hx_i, which represents i's probability x_i of contracting the disease times the harm h from the disease conditional on contracting it. Thus there exists a cutoff type $\hat{x}_v = P_v/h$ such that consumer i weakly prefers to buy if and only if $x_i \geq \hat{x}_v$. The firm's expected revenue from the vaccine, also equal to its profit given the assumption of zero costs, is $\int_{\hat{x}_v}^{1} P_v dF(x_i)$. Substituting $P_v = h\hat{x}_v$ and rearranging, the firm's profit from the vaccine is $h\hat{x}_v[1-F(\hat{x}_v)]$. The firm will choose $\hat{x}_v$, which is equivalent to choosing P_v, to maximize profit; thus, we can write the monopoly profit from vaccine as

$$\Pi_v = \max_{\hat{x}\in[0,1]} \left\{h\hat{x}[1 - F(\hat{x})]\right\}. \tag{3}$$

Next consider the firm's profit maximization problem if it decides to develop a drug treatment. Any consumer who has contracted the disease (i such that $d_i = 1$) would be willing to pay a price up to the avoided harm h. The firm's optimal price for the drug treatment fully extracts consumer surplus: $P_t^* = h$. Of course consumers will only pay P_t if they happen to contract the disease, which occurs for consumer i with probability x_i. The maximum revenue (and, equivalently, the maximum profit) from the drug treatment is therefore

$$\Pi_t = \int_0^1 hx_i dF(x_i) = hE(x_i), \tag{4}$$

where $E(\cdot)$ is the expectations operator.

Before formally examining the profits from the vaccine, Π_v, and the drug treatment, Π_t, we can gain intuition by analyzing the graphical illustration in Figure 2. The vaccine involves charging a uniform price to all consumers. A price of $h\hat{x}$, for example, will induce only those consumers with $x_i \geq \hat{x}$ to purchase, so total revenue (and profit) would be given by the price

$h\hat{x}$ times the mass of consumers in $[\hat{x}, 1]$, which graphically is the probability-weighted area of rectangle B in the figure. Of course the firm would choose the price optimally, so Π_v can be seen in the figure as the rectangle B of greatest probability-weighted area that can be inscribed in the larger triangle ABC. On the other hand, Π_t is the probability-weighted area of the triangle ABC itself. To see this, note each type x_i pays h for the drug treatment conditional on contracting the disease, which occurs with probability x_i, thus producing an expected revenue of hx_i for each consumer. Integrating over consumers with respect to their density gives revenues (and, equivalently, profit) Π_t. Combining these figures, we can see Π_t exceeds Π_v by the probability-weighted area of A plus C. No matter how B is inscribed, triangles A and C will have positive area, and so $\Pi_t > \Pi_v$. Formally, we have the following proposition, proved in the Appendix.

Proposition 3. *If the population of consumers with a positive probability of contracting the disease is nontrivially heterogeneous (that is, at least two distinct subintervals of* $(0, 1]$ *have positive measure), then* $\Pi_t > \Pi_v$. *Hence the firm's profit from developing a drug treatment is higher than from developing a vaccine.*

A few remarks about the proposition are in order. First, note that the proposition holds for general distributions, including discrete, continuous, and mixed. Second, note that a two point distribution in which one of the points is $x_i = 0$ is effectively homogeneous, because the relevant population for revenue considerations includes only those consumers with a positive probability of contracting the disease, and this relevant population would in this case then have a single-point distribution.

Further intuition for Proposition 3 can be obtained by reconsidering the problem of medicine choice in terms of price discrimination. A vaccine constrains the firm to charge a uniform price both from an *ex ante* and an *ex post* perspective. A drug treatment also constrains the firm to charge a uniform price from an *ex post* perspective; that is, all consumers who contract the disease pay the same price. From an *ex ante* perspective, however, consumers' expected payments for a drug treatment are not uniform. High risk consumers will pay for the drug treatment with high probability, thus leading to a high expected payment from an *ex ante* perspective; the

opposite is true for low risk consumers. A drug treatment tailors the *ex ante* expected price to the value consumers place on avoiding the disease. From an *ex ante* perspective, drug treatments effectively allow the firm to engage in third degree price discrimination, wherease vaccines result in a uniform pricing situation. It is a general result in the industrial organization literature that monopolists are able to extract more rent from consumers using third degree price discrimination than using uniform prices (see, e.g., Varian 1989), just as illustrated by the firm considered here.

We have implicitly assumed that the firm develops one of the two medicines but not both. Given the normalization $k_v = k_t = 0$, implying that the medicines are costless to develop, it might be thought the firm could do better by developing both and using them in a complicated mixed-bundling scheme. In fact, as the next proposition shows, the firm does not prefer to develop both, justifying our focus on exclusive development. The proof of Proposition 4, provided in the Appendix, relies on the fact that the firm extracts 100 percent of social welfare with a drug treatment, so a vaccine would provide no additional benefit.

Proposition 4. *The firm does not strictly prefer developing both a drug treatment and a vaccine to developing a drug treatment alone.*

We have shown that the firm earns more revenue from drug treatments than from vaccines, raising the question of how much more revenue drug treatments can extract. We will answer this question in a series of propositions, starting with the case in which x_i is a discrete random variable of arbitrary form, and building from there.

Suppose that consumers fall into R risk classes indexed by $r = 1, \ldots, R$. Within each risk class r, consumers have the same probability x_r of contracting the disease. Consumers observe their risk class, but the firm cannot. We will arrange the risk classes without loss of generality such that $0 \leq x_1 \leq \cdots \leq x_R \leq 1$. Let $m_r \in (0, 1)$ be the mass of consumers in risk class r and normalize the mass of the total population such that $\sum_{r=1}^{R} m_r$ is equal to one. Note that this setup captures the case in which an individual i's probability of contracting the disease x_i is a discrete random variable of arbitrary form. The next proposition shows that the number of risk

classes determines a tight upper bound on the amount the profit from a drug treatment exceeds that from a vaccine, and this proposition will serve as a useful building block for subsequent results.

Proposition 5. *For any $\epsilon > 0$, there exist distributions of consumers in R risk classes such that $\Pi_t/\Pi_v > R - \epsilon$. That is, we can find distributions of consumers in R risk classes such that the profit from a drug treatment can be made arbitrarily close to R times the profit from a vaccine. Moreover, R is an upper bound on Π_t/Π_v.*

In the proof of Proposition 5, contained in the Appendix, we construct a distribution of consumers in which the masses of the R risk classes $\{m_r\}_{r=1}^R$ decline geometrically. Further, we specify probabilities $\{x_r\}_{r=1}^R$ such that the firm earns the same profit whether it sells to all consumers at a low price hx_1, to all consumers but the lowest risk class at a higher price hx_2, etc., on up to selling to the highest risk class alone at price hx_R.

We note that Proposition 5 has a straightforward corollary in the simplest possible case of consumer heterogeneity, that is, the two type case with a low risk class and a high risk class. The example from the Introduction (with 100 consumers, 90 of whom have a ten percent chance of contracting the disease and ten of whom have a 100 percent chance) is such a case. As noted in the Introduction, the drug treatment produces higher profit than the vaccine by a factor of 1.9. Proposition 5 implies that a drug treatment can be as much as twice as profitable as a vaccine in the two type case, but no more. The example given in the Introduction approaches our bound of two, and we can come closer to the bound with examples in which the size of the high risk pool as well as the probability of contracting the disease in the low risk pool are reduced. For example, consider a population of 100 consumers, 99 of whom have a one percent chance of contracting the disease, and one of whom has a 100 percent chance. Then it can be shown, given the assumption from the Introduction that the harm from the disease is 100,000, that a vaccine produces a profit of 100,000 while drug treatment produces a profit of 199,000, very nearly twice as much profit.

The two type case provides important insights into the settings in which firms will strongly

prefer drug treatments to vaccines. Skewed distributions in which there exist a large segment of the population with a very small probability of contracting the disease and a small segment of the population with a large probability of contracting the disease will create the largest relative incentives for the firm to develop drug treatments.

An obvious corollary of Proposition 5 is that there exist distributions of consumer types such that drug treatments are arbitrarily more profitable than vaccines. This can be seen by taking the limit as R approaches infinity in the proposition. Stated formally, we have the following proposition.

Proposition 6. *For any finite bound $M \in (0, \infty)$, there exist distributions of consumers such that $\Pi_t / \Pi_v > M$.*

By themselves, Propositions 3 and 6 do not raise public policy concerns. The propositions were proved under maintained assumptions which guarantee that the social benefit from vaccines and drug treatments are equal, so no problems arise if the firm is biased toward developing drug treatments because of better rent extraction properties. Given the substantial profit advantage that drug treatments potentially have over vaccines, it is easy to see by continuity that there will exist a broad range of cases in which vaccines are socially more beneficial than drug treatments and yet the firm is still biased toward developing drug treatments. Because a vaccine is administered at an early stage, it may be more effective in preventing the disease's spread, may reduce the harm the disease causes an individual, and indeed may increase the probability of curing the disease as compared to a drug treatment. Yet, if the revenue extraction advantage of a drug treatment is great enough, the firm will still have an incentive to develop a drug treatment rather than a vaccine.

Our model has considered the case where the only source of heterogeneity is in consumers' probability of contracting the disease. More realistically, people may differ in willingness to pay for a given reduction in their probability of infection either because they differ in income

or because they differ in the value they attach to prevention of the disease.[5] It is possible to imagine bivariate distributions for which vaccines could be more profitable than drug treatments. Suppose the chance of infection is perfectly inversely correlated with the willingness to pay for reductions in probability of infection, for example because individuals who are unconcerned about their health are the most likely to have multiple partners and the least likely to be willing to pay for per-unit reductions in the chance of infection. In this case, all consumers would have the same willingness to pay for a vaccine and the firm could extract all surplus with a vaccine but not with a drug treatment. However, this is unlikely, and we would conjecture that for most reasonable bivariate distributions of chance of infection and willingness to pay, vaccines will offer less opportunity for price discrimination than drugs.

2.3 Applications to Empirical Distributions

In this section, we apply our theoretical results to estimates of actual distributions of HIV risk in certain populations. We consider two examples, one using a nationally representative sample but containing only crude risk information, and another using a non-representative sample but containing more detailed information on risk. The first example uses nationally-representative data from the United States Center for Disease Control National Health and Examination Survey (NHANES) in 1999-2000 to divide the population into risk classes based on the number of sexual partners in a twelve month period.[6] The second example involves a smaller population for which we have more detailed data, data from a study of projected HIV risk which surveyed a random sample of individuals living in poor neighborhoods with high drug use in Houston, Texas (Bell and Trevino 1999). The result from the previous subsection that there are theoretical distributions of risk for which drug treatments generate considerably more revenue than vaccines is borne out

[5] Kessing and Nuscheler (2002) analyze a static model with income heterogeneity.

[6] We do not allow for separate risk factors based on sex of the respondent or of his or her partners and, due to data limitations, we assume that all men who reported having male partners had no female partners (and analogously for women with female partners).

for the actual distributions of risk analyzed in both examples.

For our first example, assume the risk of contracting a disease from one sexual partner is ϕ; thus, we treat risk of contracting the disease as a linear function of the number of sexual partners. Assume a unit mass of consumers with distribution of sexual partners as in NHANES (1999–2000), normalize the harm experienced conditional on contracting the disease to $h = 1$, and maintain all previous normalizations (that is, that medicines are costless to develop and produce, are perfectly effective, etc.). We will compute the revenue from a drug treatment and a vaccine and then compare the two figures. Given the normalizations, the revenue from a drug treatment is equal to the fraction of the population that is expected to contract the disease, which in turn is equal to ϕ times the mean number of sexual partners 1.666. Thus the revenue from a drug treatment is 1.666ϕ. To compute the revenue from a vaccine, we can compute (as in Table 1) the maximum price that induces each risk class to purchase (and strictly induces higher risk classes to purchase), and then find the highest revenue. Reading down the last column of Table 1, the highest revenue is gained from selling to the entire population that is sexually active at price ϕ, which yields 0.8991ϕ in revenue. Thus, the ratio of revenue from a drug treatment to revenue from a vaccine is 1.853, so a drug treatment would generate almost twice as much revenue as a vaccine.

In our second example, we consider a study that directly provides estimates of projected HIV risk, Bell and Trevino (1999). The authors collected quite detailed information on 270 subjects living in poor Houston neighborhoods, including records of all the subjects' sexual acts over a given thirty day period. The authors used the data from this survey to parametrize an epidemiological model of HIV risk which combines risk behaviors, prevalence rates, and transmission probabilities. The 270 individuals in Bell and Trevino's sample are not representative of the U.S. population as a whole. In particular, 14 percent could be expected to develop HIV within ten years, an order of magnitude notably higher than the national average. Assuming a static population with no change in the prevalence of HIV within the population as well as

no change in the risk level of new sexual partners over time, this model then allows them to compute an empirical distribution of the ten-year projected risk of contracting HIV for the given population. The resulting empirical distribution (based on data from Figure 1 in Bell and Trevino) is presented in the first two columns of Table 2.

Assuming a unit mass of consumers with the same distribution of HIV risk as in Table 2, normalizing the harm experienced conditional on contracting HIV to $h = 1$, and maintaining all the other previous normalizations, we can compute the potential revenue from an HIV vaccine and an HIV/AIDS drug treatment. The revenue from a drug treatment equals the expected number of infected individuals times the avoided harm $h = 1$, or 0.1424. To compute the revenue from a vaccine, we can compute (as in Table 2) the maximum price that induces each risk class to purchase (and strictly induces higher risk classes to purchase), and then find the highest revenue. Reading down the last column of the table, the highest revenue, 0.0694, is generated by charging a price that induces the 75 percent risk class and higher to purchase. Thus the ratio of drug treatment revenue to vaccine revenue is 2.052, so a drug treatment would again generate more than twice as much revenue as a vaccine.

Despite the fact that the distribution of HIV risk in Bell and Trevino's sample is likely to be less skewed than in the U.S. population as a whole, it is still somewhat skewed. Only nine percent of the mass of consumers have risks at or above 75 percent. Serving only these high risk consumers with a vaccine leaves a large mass of consumers from lower risk classes unserved, and thus leaves a great deal of unclaimed consumer surplus.

3 Dynamic Model

In this section we show that drug treatments are more profitable than vaccines even with a homogeneous population if vaccines cause greater reductions in disease transmission than drug treatments. Vaccines typically reduce disease transmission more than drug treatments for two

reasons. First, people often spread the disease before receiving treatment. For example, much transmission of HIV is believed to take place during the first few months of an individual's infection;[7] during this "window period," viral loads (and thus transmission rates) are high,[8] but the individual is not producing enough antibodies to test positive on standard HIV tests, and thus will not seek drug treatments such as the Highly Active Antiretroviral Treatments (HAARTs). Second, drug treatments sometimes treat symptoms rather than actually curing the disease, so even if a patient receiving a treatment is experiencing no harm from the disease, he or she may still be a carrier.

To examine the effect of disease transmission on pricing and R&D expenditure decisions, it is useful to embed the economic model within a standard dynamic epidemiological model. We will consider a non-fatal disease since this simplifies modeling by allowing us to consider a constant population. Assume that people are born into the population at rate δ and that both infected and uninfected individuals die at rate δ as well. Let S, I, and V represent the fractions of the population that are susceptible, infected, and vaccinated. Normalizing the mass of the consumer population to unity, $S + I + V = 1$. If no vaccine exists, $V = 0$ and $S + I = 1$.

The rate at which people become newly infected is βIS, where β depends on the rate at which susceptibles contact infecteds and the proportion of those contacts which lead to new infections. Let ξ denote the fraction of newborns who are vaccinated.[9] For now, we treat ξ as a parameter; later, we will solve for the equilibrium value of ξ and substitute that value back into this epidemiological model.

The rate of change of the susceptible population is equal to the birth rate times the non-

[7]Wawer *et al.* (2003) report that in their study approximately half of all HIV transmission was estimated to occur within the first five months of an individual's seroconversion (seroconversion usually takes place two to six weeks after acquisition of HIV).

[8]Wawer *et al.* (2003) show the rate of HIV transmission per coital act is highest in the first five months after seroconversion (0.0081 per coital act).

[9]Given the Poisson structure of the model, without loss of generality we can treat all vaccinations as if they are given to newborns.

vaccination rate, $1-\xi$, minus the loss of susceptibles to infection or death:

$$\dot{S} = \delta(1-\xi) - \beta IS - \delta S. \tag{5}$$

The rate of change of the infected population is

$$\dot{I} = \beta IS - \delta I \tag{6}$$

and the rate of change of the vaccinated population is

$$\dot{V} = \delta\xi - \delta V. \tag{7}$$

There is a trivial steady state in which $I^* = 0$ and $S^* = 1 - V^*$, but this is unstable for $\xi < 1 - \delta/\beta$. Setting $\dot{S} = \dot{I} = \dot{V} = 0$ in equations (5) through (7) gives the non-trivial steady state

$$S^* = \delta/\beta, \quad V^* = \xi, \quad I^* = 1 - \xi - \frac{\delta}{\beta} \tag{8}$$

for $\xi < 1 - \delta/\beta$. For brevity we will define $\lambda = \delta/\beta$. This term can be interpreted as the latent proportion of healthy individuals in the steady state before a vaccine is introduced, as can be seen by setting $\xi = 0$ in the equation for I^* in (8). With this notation, the steady-state rate at which new infections will occur if a vaccine is developed is thus

$$\beta I_v^* S_v^* = \delta(1 - \xi - \lambda) \tag{9}$$

and the steady-state rate at which new infections will occur if a drug treatment is developed is

$$\beta I_t^* S_t^* = \delta(1-\lambda). \tag{10}$$

We wish to consider a firm's incentives for developing either a vaccine or a drug treatment. (We will show below in Proposition 9 that the firm will not choose to develop both.) Once developed, we assume that either medicine can be produced at zero cost. We suppose that a person taking a vaccine does not contract the disease and is unable to transmit the disease to others. We assume that a single dose of a drug treatment perfectly relieves all symptoms permanently but still allows the treated individual to transmit the disease to others. These assumptions are clearly extreme, but results will be qualitatively similar as long as drug treatments interfere less with disease transmission than do vaccines.

We will consider the case as the discount rate goes to zero so that consumers only care about their probability of contracting the disease (not when they will contract it) and the firm wants to maximize the steady-state flow of revenue; this allows us to abstract from transitional dynamics. Assume consumers are risk neutral, and define h to be the fixed amount a consumer will be willing to pay in order to avoid infection.

Revenue (and profit since production costs have been normalized to zero), Π_j, will equal price, P_j, multiplied by quantity sold, Q_j, where $j = v$ if a vaccine is developed and $j = t$ if a drug treatment is developed. Let W_j denote social welfare. Let P_j^*, Q_j^*, Π_j^*, and W_j^* denote the equilibrium price, quantity, profit, and social welfare in the steady state, respectively.

We proceed by solving for the firm's profit-maximizing prices P_v^* and P_t^*, using these prices to compute the steady-state flow profits Π_v^* and Π_t^*, and then comparing these profits to determine which medicine is more profitable in the steady state. The results are contained in a series of propositions.

Proposition 7. *In the steady state of the dynamic model with a drug treatment, the equilibrium*

price is $P_t^* = h$*, quantity is* $Q_t^* = \delta(1-\lambda)$*, flow profit is* $\Pi_t^* = h\delta(1-\lambda)$ *and flow welfare is* $W_t^* = h\delta(1-\lambda)$.

The proof of Proposition 7 is straightforward. The firm sets a price extracting all the surplus from infecteds, $P_t^* = h$. Since we assumed that one dose of the drug treatment permanently relieves all symptoms, only newly infected consumers will purchase the drug treatment. In equilibrium, all newly infecteds buy the drug treatment at price $P_t^* = h$, so by equation (10), $Q_t^* = \delta(1-\lambda)$. The resulting flow profit is thus $\Pi_t^* = P_t^* Q_t^* = h\delta(1-\lambda)$. The social benefit of the drug treatment is that all newly infected individuals are completely relieved of the harm from the disease h, so $W_t^* = h\delta(1-\lambda)$.

It is more difficult to derive a rational-expectations equilibrium in the vaccine case because of the externality involved. The more consumers who are vaccinated, the lower the disease prevalence, thus reducing the incentives of consumers to be vaccinated. We will solve for the equilibrium of this system, drawn in Figure 3. The diagram is drawn for a given vaccine price P_v; below we will solve for the profit maximizing P_v. The solid line AA' represents consumer demand for vaccines as a function of the the overall infection level and the given price, $Q_v(I_v, P_v)$. As the line indicates, there is a cutoff level of infection prevalence $\hat{I}$ such that no consumer buys the vaccine below this cutoff, all consumers buy the vaccine above this cutoff, and consumers are indifferent exactly at this cutoff so that the fraction of newborns obtaining the vaccine is indeterminate. The dotted line BB' represents the infection level as a function of the quantity of vaccine consumed, $I_v(Q_v)$, which comes from the epidemiological model; in particular, this follows directly from the equation for I^* in (8). The equilibrium quantity as a function of price is given by the intersection of AA' and BB'. Note that an increase in price shifts AA' to the right, resulting in a lower intersection point and thus a lower equilibrium quantity—the familiar tradeoff for a monopolist. The next step is to compute the profit-maximizing price. The result of these calculations is provided by Proposition 8, proved in the Appendix.

Proposition 8. *In the steady state of the dynamic model with a vaccine, equilibrium price is*

$P_v^* = h(1-\sqrt{\lambda})$, quantity is $Q_v^* = \delta(1-\sqrt{\lambda})$, flow profit is $\Pi_v^* = h\delta(1-\sqrt{\lambda})^2$, and flow welfare is $W_v^* = h\delta(1-\sqrt{\lambda})$.

In view of Propositions 7 and 8, we can compare the firm's incentives to develop a drug treatment versus a vaccine:

Proposition 9. *In the steady state of the dynamic model, the firm's profit is higher with a drug treatment than a vaccine. The firm appropriates all the social surplus with a drug treatment but only a fraction $1-\sqrt{\lambda}$ with a vaccine. The firm does not strictly prefer developing both a drug treatment and a vaccine to developing a drug treatment alone.*

The proof is a simply corollary of Propositions 7 and 8; the details are provided in the Appendix. The drug treatment allows the firm to appropriate 100 percent of the social benefits since consumers can be charged their maximum willingness to pay and there are no externalities. With a vaccine, the firm does not serve all susceptibles since this would eradicate the disease and eliminate future demand. Instead, the vaccine is priced such that only a fraction of susceptibles are served. The unvaccinated susceptibles obtain a positive externality from other's vaccinations, and this benefit is not appropriated by the firm.

As Proposition 9 states, since the firm appropriates all social surplus with a drug treatment, there is no additional benefit from also developing a vaccine. This justifies our implicit assumption that the firm develops one medicine or the other but not both.

Analogous to the result in the static model of Section 2, we are able to obtain the result in the present dynamic model that the ratio of profit from a drug treatment to the profit from a vaccine is unbounded. The key parameter is λ, which recall is interpreted as the initial proportion of healthy individuals prior to the introduction of the vaccine. A disease that is initially quite rare can be represented by the limit as λ approaches one. For such diseases, a drug treatment is particularly profitable for the firm relative to a vaccine, and the fraction of social benefits the vaccine producer is able to appropriate is particularly small.

Proposition 10. *In the limit as the initial prevalence of the disease approaches zero, the ratio of profit from drug treatment to vaccine grows without bound, i.e., $\lim_{\lambda\to 1}(\Pi_t^*/\Pi_v^*) = \infty$, and the ratio of profit to social welfare from a vaccine goes to zero, i.e., $\lim_{\lambda\to 1}(\Pi_v^*/W_v^*) = 0$.*

There is reason to think that, in practice, externality benefits may be quite large relative to direct benefits. For example, in a randomized evaluation of a project in Kenya, Miguel and Kremer (2003) find that school-based mass treatment with deworming drugs created substantial externalities among both untreated students in the treatment schools and among children in neighboring schools; the share of disease burden averted due to externalities in their study is estimated at about 76 percent.[10]

4 Government Purchases

The previous sections have focused on the case of pharmaceutical sales on private markets. However, at least in the case of vaccines, governments are the main purchasers, not private parties. We argue in this section that our results are still applicable to the case of government procurement as long as price negotiations between the firm and the government are influenced by the threat point of what profits the firm would realize with private sales if negotiations with the government broke down.

Suppose the firm and government engage in Nash bargaining over the sale of medicine j. Assume they bargain after the firm has decided which medicine ($j = v$ for vaccine, $j = t$ for drug treatment) to develop and has sunk its investment in R&D. For ease of comparison, we will assume that this sunk cost is the same for either medicine. Assume the government's objective is to maximize consumer surplus and the firm's is to maximize profit.[11]

Given these objectives, the "pie" over which the parties bargain equals social welfare at socially efficient prices, denoted $\tilde{W}_j$. Note the difference between $\tilde{W}_j$ and W_j defined earlier: $\tilde{W}_j$ is social welfare when the medicine is consumed at the socially efficient level, whereas W_j is social welfare given the amount of medicine that will be consumed at monopoly prices. Let

[10] See also the theoretical analysis of vaccine externalities in Boulier, Datta, and Goldfarb (2002).

[11] Assuming alternatively the government's objective is to maximize social welfare, with equal weights given to producer and consumer surplus, Nash bargaining would trivially result in all surplus being allocated to the firm.

Π_j be the monopoly profit and CS_j the consumer surplus from the private sale of medicine j at monopoly prices. Let Φ_j be the firm's threat point in Nash bargaining and Γ_j be the government's. Then the Nash bargaining formula yields the following expression for the firm's surplus:

$$\frac{1}{2}(\tilde{W}_j + \Phi_j - \Gamma_j). \tag{11}$$

It is plausible to assume that the firm's threat point is given by what it would earn if it sold to the private market rather than the government.[12] Under this assumption, $\Phi_j = \Pi_j$ and $\Gamma_j = CS_j$. Substituting these threat points into equation (11), we have that the firm prefers to develop a drug treatment to a vaccine if and only if $(\tilde{W}_t + \Pi_t - CS_t)/2 > (\tilde{W}_v + \Pi_v - CS_v)/2$, or upon rearranging,

$$\Pi_t - \Pi_v > \tilde{W}_v - \tilde{W}_t - CS_v. \tag{12}$$

We have substituted $CS_t = 0$ in condition (11), consistent with the fact that the firm ends up extracting all consumer surplus in both the static model of Section 2 and the dynamic model of Section 3.

Condition (12) shows that, even if medicines are procured by the government, there is a wedge between social and private incentives that possibly distorts the firm's development decision. There is a range of cases in which $\tilde{W}_v > \tilde{W}_t$, so it is socially beneficial for the vaccine to be developed, yet (12) holds so the firm instead develops the drug treatment. This range of cases may be broad for two reasons: as shown in Propositions 6 and 10, the ratio Π_t/Π_v is unbounded, and so the left-hand side of (12) may be large; furthermore, subtraction of the term CS_v reduces the right-hand side of (12) below $\tilde{W}_v - \tilde{W}_t$.

[12] There are of course other possibilities. For example, the government could hypothetically refuse to grant approval for private sales of the medicine in the event of bargaining breakdown, implying $\Phi_j = 0$. However, at least in the United States (by far the largest single market), once approval is granted the U.S. government would not stop private sales of the product.

Our conclusions are essentially an instance of the familiar hold-up problem (Williamson 1975). The firm decides which medicine to develop prior to negotiating with the government. Recognizing that it does not appropriate all the surplus in bargaining, the firm may distort its decision to appropriate more surplus; thus the firm is concerned over how profitable the medicines are relative to each other in the threat point, i.e., on the private market.

The analysis can be repeated assuming that vaccines are procured by the government but drug treatments are sold on the private market. The firm would then compare the Nash bargaining surplus from the vaccine $(\tilde{W}_v + \Pi_v - CS_v)/2$ to the drug treatment profit Π_t. After rearranging and noting $W_v = \Pi_v + CS_v$, we see that the firm would prefer to develop a drug treatment to a vaccine if and only if

$$\Pi_t - \Pi_v > \frac{1}{2}(\tilde{W}_v - W_v). \tag{13}$$

The right-hand side of (13) is the difference between social welfare given the socially efficient level of consumption and social welfare at the monopoly-price level of consumption, divided by two. The left-hand side is again the relative profit advantage of a drug treatment, which all our preceding results were directed toward showing can be large. Again, we have the result that the firm may be biased against developing a vaccine even though vaccine development may be more socially desirable.

One policy implication that emerges from this section is that there are advantages to the government bargaining with the firm as early as possible in the development process, since this will of course help protect the firm's R&D from hold up by the government and thus enhance investment. Our point here is that this will also encourage the firm to make the socially efficient decision regarding which medicine to develop. In the model, if the bargain takes place before the firm decides which medicine to develop, in equilibrium the firm will develop the vaccine precisely when it is socially efficient to do so, i.e., when $\tilde{W}_v > \tilde{W}_t$. This provides one justification for

advance purchase commitment programs of the type described by Kremer (2001).

5 Conclusions

Numerous potential factors could induce firms to develop a drug treatment (administered after patients contract the disease) rather than a vaccine (administered before), or vice versa, for a given disease. One or the other may involve "easier science," be cheaper to produce once developed, or have fewer or less severe side effects. The interests of both consumers and firms are likely to be aligned concerning all of these preceding factors: that is, consumers and firms are likely to agree that a cheaper treatment is better as is one with fewer side effects. In this paper, we identified more subtle issues that are present even if one abstracts away from all these preceding factors. Drug treatments turn out to be better tools to extract consumer surplus than vaccines.

- Drug treatments emerge as better rent extraction tools than vaccines in a static model since drug treatments are administered after consumers have contracted the disease and thus the firm has more information about individual consumer's valuations.

- Drug treatments emerge as better rent extraction tools than vaccines in a dynamic model if vaccines are more likely to interfere with disease transmission than are drug treatments. Since the people who benefit from the positive externalities of vaccination do not compensate the firm for the benefits they receive from the vaccine, the firm earns more revenue from drug treatments than from vaccines.

We showed that in both the static and dynamic models, the firm can make arbitrarily higher revenue in percentage terms with drug treatments than with vaccines. Fitting two actual estimates of the *ex ante* distribution of HIV risk—one a nationally-representative survey of HIV risk, the other a detailed survey of individuals in several poor Houston neighborhoods—into our theoretical framework, we demonstrated the empirical relevance of our theoretical results. In both samples,

we calculated that the revenue-extraction properties of drug treatments would allow the firm to earn considerably more, around twice the revenue, compared to vaccines. Incorporating dynamic considerations suggests the ratio is likely to be even larger. Given the importance of technological advances to public health, and the particular importance of vaccines for fighting disease in developing countries, these results suggest a justification for public policies to increase investment in vaccine R&D.

Appendix

Proof of Proposition 3

Define

$$\hat{x}_v^* = \underset{\hat{x}\in[0,1]}{\operatorname{argmax}} \left\{ h\hat{x}[1 - F(\hat{x})] \right\}.$$

Then, in view of equations (3) and (4),

$$\begin{aligned} \Pi_t - \Pi_v &= h\int_0^1 x_i dF(x_i) - h\int_{\hat{x}_v^*}^1 \hat{x}_v^* dF(x_i) \\ &= h\int_0^{\hat{x}_v^*} x_i dF(x_i) + h\int_{\hat{x}_v^*}^1 (x_i - \hat{x}_v^*) dF(x_i). \end{aligned} \tag{A1}$$

Both terms in expression (A1) are nonnegative. There cannot be a measure one of consumers at $\hat{x}_v^*$ by maintained assumption. Thus there must be a positive measure on either a subset of $(0, \hat{x}_v^*)$, in which case the first term in (A1) is positive, or on a subset of $(\hat{x}_v^*, 1]$, in which case the last term in (A1) is positive. In either case, $\Pi_t - \Pi_v > 0$. *Q.E.D.*

Proof of Proposition 4

Curing the disease generates gross social welfare $hE(x_i)$ from an *ex ante* perspective. This is also the revenue from a drug treatment, and profit since costs have been normalized to zero, by equation (4). Hence the addition of a vaccine cannot increase the firm's profit. *Q.E.D.*

Proof of Proposition 5

A distribution of consumers into R risk classes involves parameters $\{m_r\}_{r=1}^R$ and $\{x_r\}_{r=1}^R$. These $2R$ parameters can be freely chosen to generate as high as possible a value of Π_t/Π_v subject to $m_r \in (0,1)$ for all $r = 1, \ldots, R$; $\sum_{r=1}^R m_r = 1$; and $0 \le x_1 \le \cdots \le x_R \le 1$. Let $\theta \in (0, 1/2)$. Define

$$m_r = \begin{cases} \theta^{r-1} & \text{if } r > 1 \\ 1 - \sum_{r=1}^{R-1} \theta^r & \text{if } r = 1. \end{cases} \tag{A2}$$

The definition of risk-class masses in equation (A2) produces a geometrically declining sequence. As is easily seen, this definition respects the constraints $m_r \in (0,1)$ for all $r = 1, \ldots, R$ and $\sum_{r=1}^R m_r = 1$. Next, we set the risk-class probabilities $\{x_r\}_{r=1}^R$. We will set them so that the firm makes the same revenue regardless of which risk class it decides to target with its vaccine

pricing. Specifically, we will set $x_R = 1$ and define the rest, $\{x_r\}_{r=1}^{R-1}$, recursively by

$$hx_r \sum_{i=r}^{R} m_i = hx_{r+1} \sum_{i=r+1}^{R} m_i. \tag{A3}$$

The left-hand side of equation (A3) is the revenue (and profit) from charging a price hx_r and selling the vaccine to risk classes r and higher. The right-hand side is the revenue (and profit) from charging a price hx_{r+1} and selling to risk classes $r+1$ and higher. As is easily seen, our definition of $\{x_r\}_{r=1}^{R}$ respects the constraint $0 \leq x_1 \leq \cdots \leq x_R \leq 1$. From equation (4), we have $\Pi_t = \sum_{r=1}^{R} hm_r x_r$. By construction implicit in (A3), we have $\Pi_v = hx_1$; that is, it is weakly most profitable to charge hx_1 for the vaccine and sell to all consumers. Thus

$$\begin{aligned}
\frac{\Pi_t}{\Pi_v} &= \frac{\sum_{r=1}^{R} hm_r x_r}{hx_1} \\
&= m_1 + \sum_{r=2}^{R} \frac{m_r x_r}{x_1} \\
&= m_1 + \sum_{r=2}^{R} \frac{m_r}{m_r + \cdots + m_R} \\
&= 1 - \sum_{r=1}^{R-1} \theta^r + \sum_{r=2}^{R} \frac{\theta^{r-1}}{\theta^{r-1} + \cdots + \theta^{R-1}}.
\end{aligned}$$

We provided an argument previously for the first line. The second line holds by simple algebra. The third line holds since it is equally profitable to sell the vaccine to all consumers at price hx_1 or to consumers in risk classes r and above at price hx_r, so that $hx_1 = hx_r(m_r + \cdots + m_R)$, implying $x_r = x_1/(m_r + \cdots + m_R)$. The last line holds by substituting for $\{m_r\}_{r=1}^{R}$ from equation (A2). Taking limits,

$$\lim_{\theta \to 0} \left(\frac{\Pi_t}{\Pi_v} \right) = 1 - 0 + \sum_{r=2}^{R} 1 = R.$$

This shows that for any $\epsilon > 0$, and for the definitions of the parameters in (A2) and (A3), we can find $\theta > 0$ such that $\Pi_t/\Pi_v > R - \epsilon$. To prove $\Pi_t/\Pi_v \leq R$ for all distributions of consumers

into R risk classes, note

$$\begin{aligned} R\Pi_v &= R \max_{r\in\{1,\ldots,R\}} \left\{ hx_r \left(1 - \sum_{i=1}^{r-1} m_i\right)\right\} \\ &\geq R \max_{r\in\{1,\ldots,R\}} \{hx_r m_r\} \\ &\geq \sum_{r=1}^{R} hx_r m_r \\ &= \Pi_t. \end{aligned}$$

Hence $\Pi_t/\Pi_v \leq R$. *Q.E.D.*

Proof of Proposition 8

As stated in the text, for a given price P_v, the rational-expectations equilibrium vaccine quantity is given by the intersection of lines AA' and BB' in Figure 3. First we will compute the vaccine demand correspondence AA'. The probability a newborn will ever become infected if he or she is not vaccinated is $\beta I_v/(\beta I_v + \delta)$. Thus a consumer's maximum willingness to pay for the vaccine is $h\beta I_v/(\beta I_v + \delta)$. Consumers are indifferent between buying a vaccine and not if $P_v = h\beta I_v/(\beta I_v + \delta)$, an equation which can be inverted to yield the cutoff infection level $\hat{I} = \delta P_v/[\beta(h - P_v)]$. Thus AA' is given by

$$Q_v(I_v, P_v) = \begin{cases} 0 & \text{if } I_v < \hat{I}_v \\ [0,1] & \text{if } I_v = \hat{I}_v \\ 1 & \text{if } I_v > \hat{I}_v. \end{cases} \tag{A4}$$

Next, we will compute BB', the infection level from the epidemiological model. By the equation for I^* in (8), we have $I_v = 1 - \xi - \lambda$. But $Q_v = \delta\xi$, implying

$$I_v(Q_v) = 1 - \frac{Q_v}{\delta} - \lambda. \tag{A5}$$

Solving (A4) and (A5) simultaneously yields

$$Q_v = \delta\left[1 - \lambda\left(1 + \frac{P_v}{h - P_v}\right)\right]. \tag{A6}$$

Maximizing flow profit $P_v Q_v$ with respect to P_v, where Q_v is given by (A6) yields a first-order condition, which can be expressed as

$$P_v^2 - 2P_v h + h^2(1 - \lambda) = 0.$$

This is a quadratic equation with two solutions: $P_v = h(1+\sqrt{\lambda})$ and $P_v = h(1-\sqrt{\lambda})$. The first solution exceeds h and thus would result in zero demand. We will thus use the second solution, $P_v^* = h(1-\sqrt{\lambda})$. By (A6), $Q_v^* = \delta(1-\sqrt{\lambda})$. Hence $\Pi_v^* = P_v^* Q_v^* = h\delta(1-\sqrt{\lambda})^2$. The flow social benefit from the vaccine, W_v^*, equals the foregone harm from the disease h times the flow of newborns δ times the reduction in the proportion of infecteds in the population. From the equation for I^* in (8), the proportion of the population that is infected in the steady state with a vaccine is $1-\xi-\lambda$ and without a vaccine is $1-\lambda$, the latter found by substituting $\xi = 0$ in (8). Thus,

$$\begin{aligned} W_v^* &= h\delta\xi \\ &= h\delta\frac{Q_v^*}{\delta} \\ &= h\delta(1-\sqrt{\lambda}). \end{aligned}$$

Q.E.D.

Proof of Proposition 9

We have

$$\begin{aligned} \Pi_t^* &= h\delta(1-\lambda) \\ &= h\delta(1-\sqrt{\lambda})(1+\sqrt{\lambda}) \\ &> h\delta(1-\sqrt{\lambda})(1-\sqrt{\lambda}) \\ &= \Pi_v^*. \end{aligned}$$

The first line holds by Proposition 7, the second line by simple algebra, the third line by $\sqrt{\lambda} > 0$ and the fourth by Proposition 8. Thus $\Pi_t^*/W_t^* = 1$ but $\Pi_v^*/W_v^* = 1-\sqrt{\lambda}$. To complete the proof, note 100 percent of gross consumer surplus is extracted by the drug treatment, so there is no additional benefit from also developing a vaccine. *Q.E.D.*

Proof of Proposition 10

To compute the first limit in the proposition,

$$\begin{aligned} \lim_{\lambda\to 1}\frac{\Pi_t^*}{\Pi_v^*} &= \lim_{\lambda\to 1}\frac{h\delta(1-\lambda)}{h\delta(1-\sqrt{\lambda})^2} \\ &= \lim_{\lambda\to 1}\frac{(1-\sqrt{\lambda})(1+\sqrt{\lambda})}{(1-\sqrt{\lambda})(1-\sqrt{\lambda})} \\ &= \lim_{\lambda\to 1}\frac{1+\sqrt{\lambda}}{1-\sqrt{\lambda}} \\ &= \infty. \end{aligned}$$

The first line holds by the expressions for profits in Propositions 7 and 8 and the remainder by simple algebra. The second limit in the proposition is $\lim_{\lambda \to 1}(\Pi_v^*/W_v^*) = \lim_{\lambda \to 1}(1 - \sqrt{\lambda}) = 0$, where the first equality holds by Proposition 9. *Q.E.D.*

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Table 1: Calculations of Vaccine Revenue for NHANES Sample

Number of Partners (n)	Fraction of Population in Risk Class	Maximum Price Inducing Purchase ($= \phi n$)	Quantity Sold	Vaccine Revenue
0	0.1007	0ϕ	1.0000	0.0000ϕ
1	0.7232	1ϕ	0.8991	0.8991ϕ
2	0.0845	2ϕ	0.1759	0.3518ϕ
3	0.0369	3ϕ	0.0914	0.2742ϕ
4	0.0162	4ϕ	0.0545	0.2180ϕ
5	0.0128	5ϕ	0.0383	0.1915ϕ
6	0.0075	6ϕ	0.0255	0.1530ϕ
7	0.0008	7ϕ	0.0180	0.1260ϕ
8	0.0033	8ϕ	0.0172	0.1376ϕ
9	0.0008	9ϕ	0.0139	0.1251ϕ
10	0.0029	10ϕ	0.0131	0.1310ϕ
12	0.0012	12ϕ	0.0102	0.1224ϕ
13	0.0004	13ϕ	0.0090	0.1170ϕ
14	0.0004	14ϕ	0.0086	0.1204ϕ
15	0.0025	15ϕ	0.0082	0.1230ϕ
19	0.0004	19ϕ	0.0057	0.1083ϕ
20	0.0025	20ϕ	0.0053	0.1060ϕ
27	0.0004	27ϕ	0.0028	0.0756ϕ
30	0.0004	30ϕ	0.0024	0.0720ϕ
50	0.0004	50ϕ	0.0020	0.1000ϕ
100	0.0004	100ϕ	0.0016	0.1600ϕ
111	0.0004	111ϕ	0.0012	0.1332ϕ
150	0.0004	150ϕ	0.0008	0.1200ϕ
255	0.0004	255ϕ	0.0004	0.1020ϕ

Table 2: Calculations of Vaccine Revenue for Bell and Trevino Sample

Ex ante Risk Class	Fraction of Population in Risk Class	Maximum Price Inducing Purchase	Quantity Sold	Vaccine Revenue
0.0000	0.5852	0.0000	1.0000	0.0000
0.0625	0.1296	0.0625	0.4148	0.0259
0.1250	0.0667	0.1250	0.2852	0.0356
0.1875	0.0444	0.1875	0.2185	0.0410
0.2500	0.0185	0.2500	0.1741	0.0435
0.3125	0.0037	0.3125	0.1556	0.0486
0.3750	0.0185	0.3750	0.1519	0.0569
0.4375	0.0185	0.4375	0.1333	0.0583
0.5000	0.0185	0.5000	0.1148	0.0574
0.5625	0.0037	0.5625	0.0963	0.0542
0.6250	0.0000	0.6250	0.0926	0.0579
0.6875	0.0000	0.6875	0.0926	0.0637
0.7500	0.0148	0.7500	0.0926	0.0694
0.8125	0.0037	0.8125	0.0778	0.0632
0.8750	0.0148	0.8750	0.0741	0.0648
0.9375	0.0148	0.9375	0.0593	0.0556
1.0000	0.0444	1.0000	0.0444	0.0444

Figure 1: Timing of Static Model

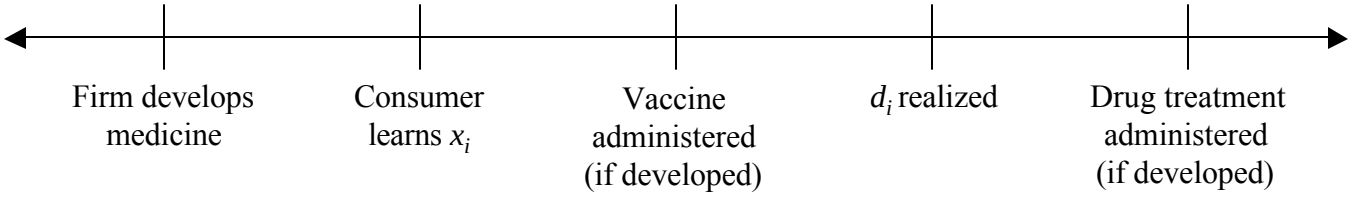

Figure 2: Geometric Comparison of Profit from Vaccine Versus Drug Treatment

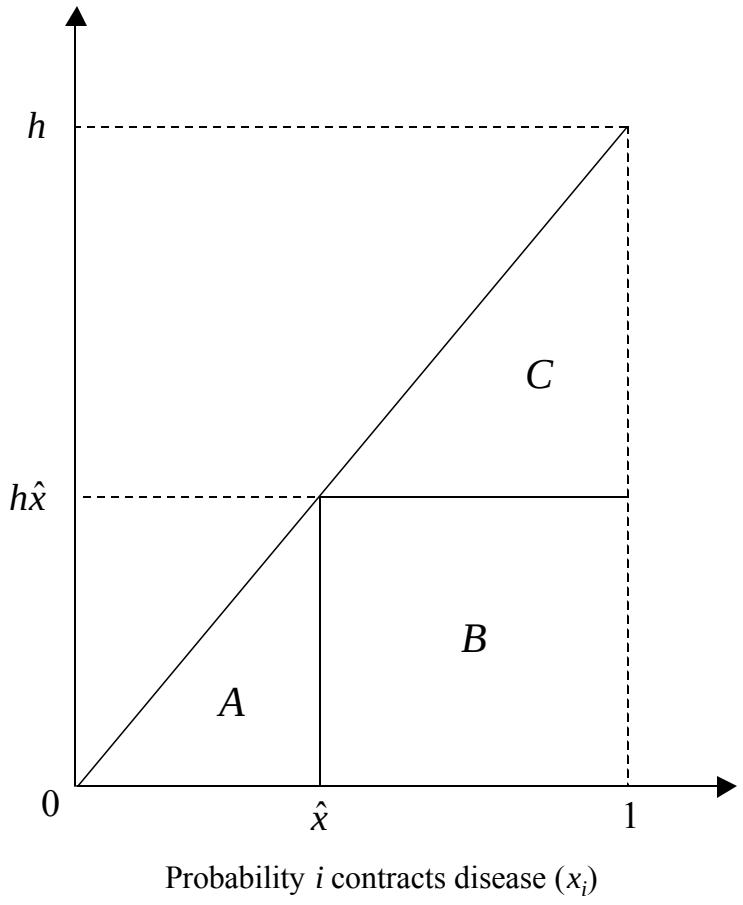

Figure 3: Equilibrium in Dynamic Model for Given Vaccine Price