

The Revenue Consequences of Vaccines Versus Drug Treatments

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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*. In a more realistic model with heterogeneous consumers who vary with respect to the probability of contracting the disease, the revenue equivalence between vaccines and treatments breaks down. Treatments are sold after the firm has learned who has contracted the disease; there is less asymmetric information to prevent the firm from extracting consumer surplus than with vaccines. We show there exist distributions of consumer types such that the firm earns arbitrarily more revenue with a treatment than a vaccine. Empirical distributions of AIDS risk exhibit characteristics of such distributions. We identify further advantages of drug treatments over vaccines in terms of surplus extraction that arise in a dynamic extension of the model.

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1 Introduction

It is conventionally believed that pharmaceutical manufacturers prefer to develop treatments (medicines that cure a disease or ameliorate the harm from the disease after it has been contracted) rather than vaccines (medicines that prevent healthy people from ever contracting the disease). The case of HIV is consistent with this conventional belief: treatments have been developed, but as yet there is no vaccine. A naive view is that firms prefer treatments to vaccines since a vaccine often cures after a single dose, only allowing one chance to extract revenue from a consumer, whereas a treatment typically involves multiple doses over an extended period of time, allowing a firm to extract revenue from a consumer repeatedly. This view is of course naive since a rational consumer would pay the expected present value of the stream of benefits in an up front lump sum for the vaccine, so vaccines and treatments should yield equivalent revenues.

In this paper, 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: in the case of HIV for example, people engaging in unprotected sex with multiple partners or intravenous drug use with shared needles have a higher risk of contracting the disease than those not engaging in similar behaviors. 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 them. 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 contracting the disease, 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 the point. Suppose there are 100 total consumers, 90 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 would be willing to pay 100,000 to be cured of the disease once they have contracted it. A monopolist selling a vaccine could either charge 100,000 and sell to the ten high-risk consumer or charge 10,000 and sell to all of them. Either way, the monopolist's revenue is 1,000,000. A monopolist selling a treatment would, in expectation, sell to 19 consumers contracting the disease (all the high risk consumers plus nine consumers on average 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.

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 be 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 induces the firm to develop it rather than a vaccine.

We show how our results can be applied to estimates of the actual distribution of expected HIV incidence in a population 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. Extending the model to a dynamic setting reveals more disadvantages of vaccines relative to treatments for rent extraction. Vaccines do not allow firms to price discriminate intertemporally. Further, a vaccine may end up

eradicating a disease, providing a benefit to future generations for which they cannot compensate the firm.

In this paper, we deal only with private markets for pharmaceuticals. One claim that is often made about the revenue consequences of vaccines versus drug treatments is that governments are often the purchaser of vaccines on behalf of their citizens, whereas the market for drug treatments is largely private (at least in some cases where pharmaceuticals are unregulated). It is further observed that governments do not commit to pay high prices for vaccines that would induce sufficient development but instead use their bargaining power as exclusive buyer or regulatory power to extract low prices. In this light, one could interpret our research as showing what would happen if governments left the purchase of vaccines to the private market, paralleling what is more commonly done with drug treatments. We show that having private vaccine purchases rather than government would not completely solve the problem of inducing vaccine development since there is an inherent bias on the private market toward the development of drug treatments instead. The policy conclusion is that the private market for vaccines may potentially fail to produce the social optimum and thus the potential roles of governments, coalitions of governments, and non-government organizations in remedying these market failures through direct purchase, subsidies, and/or prizes for vaccine development (see, e.g., Glennerster and Kremer 2000).

2 Homogeneous Consumer Model

A monopoly pharmaceutical manufacturer, called the firm, has the choice of developing alternative therapies 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 therapies to develop: a vaccine, the term we give to a therapy administered before consumers contract the disease, or a drug treatment, the term we give to a therapy 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. Let

$K_j \in [0, \infty)$ be the present discounted value of the fixed cost of developing therapy j , where $j = v$ for the vaccine and $j = t$ for the drug treatment. Assuming K_v and K_t are sufficiently high ensures the firm does not have an incentive to develop both alternative therapies. Let $c_j \in [0, \infty)$ be the present discounted value of the cost of administering therapy 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 therapy j , that is, the probability that therapy 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 therapy 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 therapy j .

Interpreting p_j as a net price the firm receives for therapy 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 therapy.

Before pursuing any therapy, consumer i learns the probability that he 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. (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 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. 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.

As Figure 1 shows, the key difference between a vaccine and a drug treatment hinges on when the therapy 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.

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

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

$$p_v^* - c_v - K_v = x_i h e_v - \sigma_v s_v - c_v - K_v. \quad (1)$$

Next, consider the firm's profit from a drug treatment. The consumer will only purchase the drug treatment if he contracts the disease. Conditional on contracting the disease, the consumer's

net consumer surplus from the drug treatment is $he_t - \sigma_t s_t - p_t$. The profit maximizing price extracts all this surplus; hence $p_t^* = he_t - \sigma_t s_t$. 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

$$x_i(p_t^* - c_t) - K_t = x_i(he_t - \sigma_t s_t - c_t) - K_t. \quad (2)$$

Using expressions (1) and (2), we can characterize which therapy 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 straightforward 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 (i.e., 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).

The model does not exhaust the list of factors that might lead the firm to prefer vaccines over drug treatments or vice versa. It would be straightforward to extend the model to consider alternative factors. We will briefly mention a few here. 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. The effect of assuming consumers face a liquidity constraint 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 drug treatments. To see this, note 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 the firm prefers cheaper, more effective therapies associated with fewer side effects—are well-known. To focus on more subtle issues that are the focus of our paper, we will normalize certain variables so that the firm is indifferent between vaccines and drug treatments in the homogeneous consumer model. We will show in the next section that drug treatments will be more profitable than vaccines in a heterogeneous 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 $j = v$ and $j = t$. That is, we will assume that therapies 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 $j = v$ and $j = t$. Then the firm is indifferent between developing the vaccine and the drug treatment in the homogeneous consumer.

3 Heterogeneous Consumer Model

We will adopt the model from the preceding section with one modification. As before, consumer i learns the probability that he will contract the disease, $x_i \in [0, 1]$, before pursuing any therapy.

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 trying to capture the fact that the consumer's background and/or actions put him into a risk category that he can observe better than 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/AIDS, but such behaviors would be difficult for a firm to monitor sufficiently well to condition a discriminatory price on it. Frequenting mosquito-infested tropical regions increases the chance of contracting malaria, but again may be difficult to monitor well.

We will continue to maintain the normalizations $K_j = c_j = \sigma_j = 0$ and $e_j = 1$ for $j = v$ and $j = t$. That is, both vaccines and drug treatments are costless to develop and produce and both are perfectly effective. We will concentrate on the revenue generated by each 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 , equaling i 's probability of contracting the disease x_i times the harm from the disease conditional on contracting it, h . 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 $\int_{\hat{x}_v}^1 p_v dF(x_i)$. It turns out to be convenient to express profit in terms of a single choice variable \hat{x}_v . Substituting $p_v = h\hat{x}_v$ and rearranging, the firm's profit from vaccine, conditional on \hat{x}_v , 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;

so we can write the monopoly profit from vaccine as

$$\Pi^v = \max_{\hat{x} \in [0,1]} \{h\hat{x}[1 - F(\hat{x})]\}. \quad (3)$$

Next consider the firm's profit maximization problem if it decides to develop a drug treatment. Any consumer that 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 maximum profit) from the drug treatment is, therefore,

$$\Pi^t = \int_0^1 hx_i dF(x_i) = hE(x_i), \quad (4)$$

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

The profits from vaccine, Π^v , and drug treatment, Π^t , can be compared using graphical arguments. Refer to Figure 2. The vaccine involves a uniform price charged 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 $[\hat{x}, 1]$, or graphically as 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 . 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 if it contracts the disease, which occurs with probability x_i , producing expected revenue hx_i for each consumer. Integrating over consumers with respect to their density gives revenues (and profit) Π^t . Putting these figures together, 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.

Proposition 3. If the population of consumers with a positive probability of contracting the disease is nontrivially heterogeneous (i.e., 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 a vaccine.

The proof Proposition 3 is in the Appendix. 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. This is because the relevant population for revenue considerations includes only those consumers with a positive probability of contracting the disease, and this relevant population would have a single-point distribution in this case.

Further intuition for Proposition 3 can be obtained by reconsidering the problem of therapy 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. 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 have to pay for the drug treatment with high probability, 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, whereas vaccines result in a uniform price. 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 the firm under our consideration earns more revenue from a drug treatment than from a vaccine.

We have shown that the firm earns more revenue from drug treatments than from vaccines. This raises the question of how much better drug treatments can be than vaccines. We will answer this question in a series of propositions. We will start from the case in which x_i is a

discrete random variable of arbitrary form, and build from there.

Suppose that consumers fall into R risk classes indexed by $r = 1, \dots, R$. 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 so that $0 < x_1 < \dots < x_R < 1$. Let $m_r \in (0, 1)$ be the mass of consumers in risk class r and normalize the mass of the total population, $\sum_{r=1}^R m_r$, to be 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. This proposition will serve as a useful building block for subsequent results.

Proposition 4. 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. R is an upper bound on Π^t/Π^v .

In the proof of Proposition 4, 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 .

Of course Proposition 4 has a simple corollary in the simplest possible case of consumer heterogeneity, 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 10 of whom have a 100 percent chance, is such a case. As noted in the Introduction, drug treatment produced higher profit than a vaccine by a factor of 1.9. Proposition 4 implies that drug treatment can be as much as twice as profitable as a vaccine in the two type case, but no more. The example from the Introduction came close to this bound of two. One can get closer to the bound of two with examples in which the size of the high risk pool is reduced along

with the probability of contracting the disease in the low risk pool. 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 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, with 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 will create the largest relative incentives for the firm to develop drug treatments.

An obvious corollary of Proposition 4 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 5. 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 5 do not raise public policy concerns. The propositions were proved under maintained assumptions guaranteeing that the social benefit from vaccines and drug treatments are equal, so no problem is raised 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 yet the firm is still biased toward developing drug treatments. Because it is administered at an early stage, a vaccine 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 compared to a drug treatment. Still, if the revenue extraction advantage of drug treatment is great

enough, the firm will have an incentive to develop it rather than a vaccine.

4 Application to Empirical Distribution of HIV Risk

In this section, we apply our theoretical results to estimates of the actual distribution of HIV risk in certain populations. A number of studies (see Anderson and May 1991, Laumann *et al.* 1994, Michael *et al.* 1994, Anderson *et al.* 1999) provide information on the distribution of risk factors in the population including the number of sex partners, incidence of same sex contact, use of injected drugs, etc. If one had information about how these risk factors translated into probabilities of contracting HIV, or were willing to make assumptions, these studies could be used to construct empirical distributions of ex ante HIV risk.

There is one study that directly provides such an estimate of the projected HIV risk, Bell and Trevino (1999). The authors surveyed a random sample of 270 individuals living in poor neighborhoods with high drug use, predominately crack cocaine, in Houston, Texas. The survey includes quite detailed information on subjects, for example collecting information on all subjects' sexual acts over the past 30 days. The authors used the data from this survey to parametrize an epidemiological model of HIV risk combining risk behaviors, prevalence rates, and transmission probabilities. Assuming a static population with no change in the prevalence of HIV within the population and no change in the risk level of new sexual partners over time, the model allows them to compute an empirical distribution of the ten-year projected risk of contracting HIV for the population. The resulting empirical distribution (based on data from Figure 1 in Bell and Trevino) is presented here in Figure 3.

The 270 individuals in Bell and Trevino's sample are not representative of the U.S. population as a whole. Fourteen percent could be expected to develop HIV within ten years, an order of magnitude higher than the national average. The data are still useful for our purposes, however. First, we are concerned with diseases of the developing world in addition to the developed world.

The frequency of HIV may be more representative of certain populations in the developing world (although there transmission by intravenous drug use, as was important in Bell and Trevino's sample, is less important than transmission by sexual contact). Furthermore, to the extent that the distribution of risk is less skewed in Bell and Trevino's sample than in the overall population, we would expect our results based on Bell and Trevino's sample would be a conservative bound on what we would find using a more representative sample.

Assuming a unit mass of consumers with the same distribution of HIV risk as in Figure 3, normalizing the harm if they contract HIV to $h = 1$, and maintaining the previous normalizations that therapies are costless to develop and produce and are perfectly effective, we can compute the potential revenue from an HIV vaccine and a drug treatment. As mentioned previously, 14 percent of the sample is predicted to contract HIV (a fraction 0.142 of the population to be precise). Given the preceding normalizations, the revenue from a drug treatment is thus 0.142. To compute the revenue from a vaccine, we first compute the price that just induces a risk class to purchase (and strictly induces higher risk classes to buy) and do this for each risk class. The results are presented in Figure 4. It is clear from the figure that the highest revenue is generated by charging a price that induces the 75 percent risk class and higher to purchase. The associated revenue is 0.069. The ratio of drug treatment revenue to vaccine revenue, Π^t/Π^v , is $0.142/0.069 = 2.05$. Hence, a drug treatment would 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, still, it exhibits some skewness. 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, thus leaving a great deal of unclaimed consumer surplus.

5 Dynamic Model

In this section, we show that drug treatments have further advantages over vaccines in terms of rent extraction: namely, for communicable diseases, drug treatments are also better at dynamic rent extraction. By curing the disease, vaccines tend to reduce its spread. In particular, administering a vaccine to the current generation of living individuals will tend to reduce its prevalence in future generations, including generations of as yet unborn. Drug treatments tend to have less of an effect on the spread of a disease for several reasons. First, by our definitions of drug treatments here, being administered after the disease has been contracted, the individual has the chance to spread the disease before receiving treatment, and so there is greater potential for current generations to spread the disease to future ones. Second, drug treatments often treat symptoms rather than actually curing the disease, so that even if a patient receiving a treatment is experiencing no harm from the disease himself, he may still be a carrier, as is the case with drug treatments for HIV/AIDS currently available, for example. In the extreme, vaccines have the potential to eradicate a disease entirely, a potential that may not be available with drug treatments.

If the pharmaceutical manufacturer could sign a complete contract with future generations of as yet unborn to receive compensation for the benefits the vaccine offers them, then vaccines would not have a disadvantage in terms of dynamic rent extraction. It seems unlikely that such contracts would be possible on the private market. Absent such contracts, vaccines would reduce the amount of rent that can be extracted from future generations by curing the disease in present generations and thus reducing its spread to future generations. A drug treatment, on the other hand, ensures that the firm has the opportunity to extract rent from each subsequent generation of consumers. It might be possible for a government to sign a contract for a vaccine on behalf of future generations, and our results in this section will point toward this as a solution. However, our caveat from the Introduction—that governments often find it difficult to commit to pay high prices for vaccines once they are developed—applies strongly in the context of this section as

well.

To develop these ideas more formally, consider an overlapping generations model in which each generation, indexed by τ , lives for two periods, the first period of life labeled “young” and the second period labeled “old.” The timing for a consumer in a given generation τ is similar to Figure 1: a consumer learns his type x_i , which is the probability he will contract the disease, and then may be administered the vaccine if applicable, when he is young. He learns whether he has contracted the disease, and then may be administered the drug treatment if applicable, when he is old. The firm decides to develop a vaccine or a drug treatment at the outset, before the birth of the first generation.

To fix attention to the new issues raised by the dynamic model rather than the issues of consumer heterogeneity raised in the previous section, we will make assumptions ensuring the consumer population is effectively homogeneous. Specifically, assume there are two types of consumer in the first generation. A fraction x will contract the disease with probability one; the remaining $1 - x$ will not contract the disease. Consumers know their types when young, and the firm knows the proportion of types in the first generation. The heterogeneity we have assumed here—two types, but one of which has zero probability of contracting the disease—turns out not to generate any advantage of drug treatments over vaccines in the ability to extract rent in a static model. As the discussion following Proposition 3 indicates, it is the population of consumers who have a positive probability of contracting the disease that is relevant for revenue considerations; this population has a trivial, single point distribution given the preceding assumptions.

We will assume a simple disease transmission mechanism for generations $\tau > 1$. Each young member of generation τ meets one old member of generation $\tau - 1$; the young member eventually develops the disease if the consumer it meets has the disease and not otherwise. For simplicity we will assume that, prior to purchasing any therapy, the young learn the type of person they have met with, and thus know with certainty whether they will develop the disease if they do not receive therapy. Given this transmission mechanism, in the absence of a cure, the fraction of

consumers with the disease in any generation is stationary at x .

We will maintain all the normalizations adopted before, namely, $K_j = c_j = \sigma_j = 0$ and $e_j = 1$ for $j = v$ and $j = t$, or in words that both therapies are costless to develop and produce, have no side effects, and are perfectly effective. We will suppose that vaccines cure the disease in the sense that a person taking a vaccine both suffers no harm from the disease and cannot transmit the disease to future generations. Drug treatments are perfectly effective in relieving the symptoms of the disease, so that the treated individual suffers zero harm from it, but they do not cure the disease in that the treated individual can still transmit the disease to future generations. Normalize the mass of consumers to unity. Let h be the present discounted value of future harm from the disease from a young person's perspective. Let $\delta \in (0, 1)$ be the per-period discount factor. Thus the nominal harm to an old person from contracting the disease is h/δ , where the present value of harm for a young person, h , has been rescaled by $1/\delta$ to translate it into a nominal harm for an old person.

Assume that the firm can only enter into contracts with the currently living generations and that it cannot commit to a price schedule for future generations. We proceed by calculating the profit from a vaccine and from a drug treatment and then comparing the two figures.

First, consider a vaccine in this dynamic context. One strategy is for the firm to charge h for the vaccine to the first generation of consumers. The mass x of consumers who will definitely contract the disease will purchase the vaccine and the rest will not. The disease is then eradicated from the population from then on since there are no longer carriers to pass the disease on to future generations. The firm earns hx from this strategy. As Proposition 6 shows, this is the unique equilibrium conditional on the firm's developing a vaccine. Next, consider a drug treatment in this dynamic context. In nominal terms, the firm can charge h/δ to the mass x of each generation's old who contract the disease. The firm's revenue is

$$x \left(\frac{h}{\delta} \right) (\delta + \delta^2 + \dots) = \frac{hx}{1 - \delta}. \quad (5)$$

Comparing the two expressions for profit yields the following proposition.

Proposition 6. Assume $K_j = c_j = \sigma_j = 0$ and $e_j = 1$ for $j = v$ and $j = t$. In the dynamic model considered in this section, assuming a vaccine cures the disease and prevents the inoculated person from spreading it to future generations, the ratio of the present discounted value of the stream of profits from a drug treatment to that from a vaccine, Π^t/Π^v , equals $1/(1 - \delta)$. This ratio becomes arbitrarily large as $\delta \rightarrow 1$.

6 Conclusions

There may be potentially many factors inducing firms to develop a drug treatment, administered after patients contract the disease, rather than a vaccine, administered before, for a given disease, or vice versa. One or the other may involve “easier science” or may be cheaper to produce once developed. One or the other may 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: 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 a more subtle issue that is present even if one abstracts away from all these preceding factors.

- Drug treatments may facilitate the firm’s extraction of surplus from consumers. 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 one assumes that vaccines cure the disease, preventing the vaccinated person from transmitting it to others, whereas drug treatments only reduce the harm from a disease’s symptoms but the treated person is still a carrier. Drug treatments allow the firm to extract rent from the whole stream of future generations; vaccines end up reducing the prevalence of the disease among future generations, in the extreme eradicating the disease from the population.

Since future generations are not around to compensate the firm for the benefits they receive from the vaccine, the firm earns more from drug treatments.

We showed that in both the static and dynamic models, the firm can make arbitrarily higher revenue in percentage terms with drug treatments than vaccines. Applying the theoretical work to actual estimates of the ex ante distribution of HIV risk from Bell and Trevino (1999), we calculated that the revenue-extraction properties of drug treatments would generate more than twice the revenue than vaccines for the sample the authors surveyed. We argued that this may be a conservative estimate for the larger population.

Appendix

Proof of Proposition 3

Define

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

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

$$\begin{aligned} \Pi^t - \Pi^v &= h \int_0^1 x_i dF(x_i) - h \int_{\hat{x}_v^*}^1 \hat{x}_v^* dF(x_i) \\ &= h \int_0^{\hat{x}_v^*} x_i dF(x_i) + h \int_{\hat{x}_v^*}^1 (x_i - \hat{x}_v^*) dF(x_i). \end{aligned} \quad (\text{A1})$$

Both terms in expression (A1) are nonnegative. There cannot be a measure one of consumers at \hat{x}_v^* by maintained assumption, so there must be a positive measure on other $x_i > 0$ as well. If there is a positive measure on a subset of $(0, \hat{x}_v^*)$, then the first term in (A1) is positive. If there is a positive measure on a subset of $(\hat{x}_v^*, 1]$, then the last term in (A1) is positive. In either case, $\Pi^t - \Pi^v > 0$. *Q.E.D.*

Proof of Proposition 4

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 $r = 1, \dots, R$; $\sum_{r=1}^R m_r = 1$; and $0 \cdot x_1 \cdot \dots \cdot x_R \cdot 1$.

Let $\theta \in (0, 1)$. Define

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

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 $r = 1, \dots, R$ 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

$$hx_r \sum_{i=r}^R m_i = hx_{r+1} \sum_{i=r+1}^R m_i. \quad (\text{A3})$$

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 $0 \cdot x_1 \cdot \dots \cdot x_R \cdot 1$.

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

$$\begin{aligned} \frac{\Pi^t}{\Pi^v} &= \frac{\sum_{r=1}^R hm_r x_r}{hx_1} \\ &= m^1 + \sum_{r=2}^R \frac{m_r x_r}{x_1} \\ &= m^1 + \sum_{r=2}^R \frac{m_r}{m_r + \dots + m_R} \\ &= 1 - \sum_{r=1}^{R-1} \theta^r + \sum_{r=2}^R \frac{\theta^{r-1}}{\theta^{r-1} + \dots + \delta^{R-1}}. \end{aligned}$$

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 $hx_1 = hx_r(m_r + \dots + m_R)$, implying $x_r = x_1/(m_r + \dots + m_R)$. The last line holds by substituting for $\{m_r\}_{r=1}^R$ from equation (A2).

Taking limits,

$$\lim_{\delta \rightarrow 0} \left(\frac{\Pi^t}{\Pi^v} \right) = 1 - 0 + \sum_{r=2}^R 1 = R.$$

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 $\Pi^t/\Pi^v \cdot R$ for all distributions of consumers into R risk classes, note

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

Hence $\Pi^t/\Pi^v \cdot R$. *Q.E.D.*

Proof of Proposition 6

The text preceding the statement of the proposition establishes that the profit from a drug treatment is $hx/(1 - \delta)$. It also establishes that the firm can earn at least hx from a vaccine by selling it at a price h and having all infected consumers purchase, eradicating the disease from the population so that the vaccine cannot be sold to future generations. We show here that this is the maximum profit the firm can earn from a vaccine, so that this outcome is associated with a unique equilibrium.

More generally, equilibrium with a vaccine may involve the firm's selling at price h but only selling to a fraction $\phi_\tau \in [0, 1]$ of the generation- τ young. Since consumers are indifferent between buying and not, such a mixed strategy equilibrium can be supported. The firm's profit is

$$hx \sum_{i=1}^{\infty} \left[\delta^{i-1} \phi_i \prod_{k=1}^{i-1} (1 - \phi_k) \right]. \quad (\text{A4})$$

In the equilibrium maximizing the firm's profit, $\{\phi_\tau\}_{\tau=1}^{\infty}$ is set to maximize (A4). The first-order condition associated with ϕ_τ is

$$\left[hx \prod_{i=1}^{\tau-1} (1 - \phi_i) \right] \left\{ \delta^{\tau-1} (1 - \phi_{\tau-1}) - \sum_{i=0}^{\infty} \left[\prod_{k=\tau+1}^{\tau+i} (1 - \phi_k) \right] \right\} = 0. \quad (\text{A5})$$

It is apparent that equation (A5) is stationary in τ , so that we can take ϕ_τ to be a constant ϕ for all τ . Making this substitution in the objective function (A4) yields

$$hx[\phi + \delta(1 - \phi)\phi + \delta^2(1 - \phi^2)\phi + \dots] = \frac{hx\phi}{1 - \delta(1 - \phi)}. \quad (\text{A6})$$

It is easily seen that (A6) is increasing in ϕ , so that the optimum involves $\phi = 1$. That is, the firm sells to all infected consumers in the first generation and eradicates the disease.

This is the unique equilibrium. Consider a proposed equilibrium in which the firm earns less than hx , say $hx - \epsilon$ for some $\epsilon > 0$ by selling to less than 100 percent of the infected consumers. The firm could profitably deviate by charging $hx - \epsilon/2$ and selling to all of them. Note that all consumers would strictly prefer to purchase at this price, so they would indeed all purchase. *Q.E.D.*

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Figure 1: Timing of Model

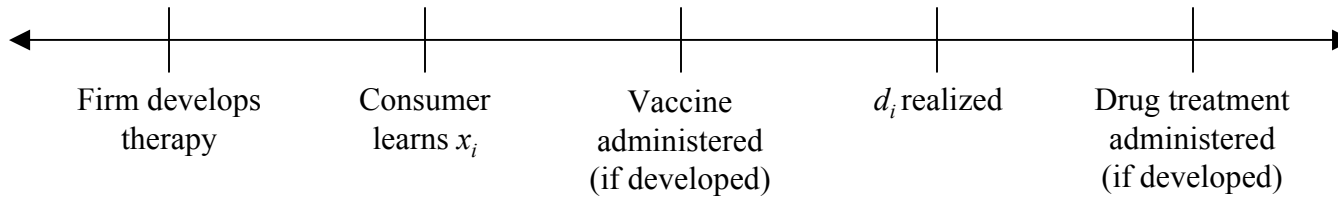


Figure 2: Geometric Comparison of Profit from Vaccine Versus Drug Treatment

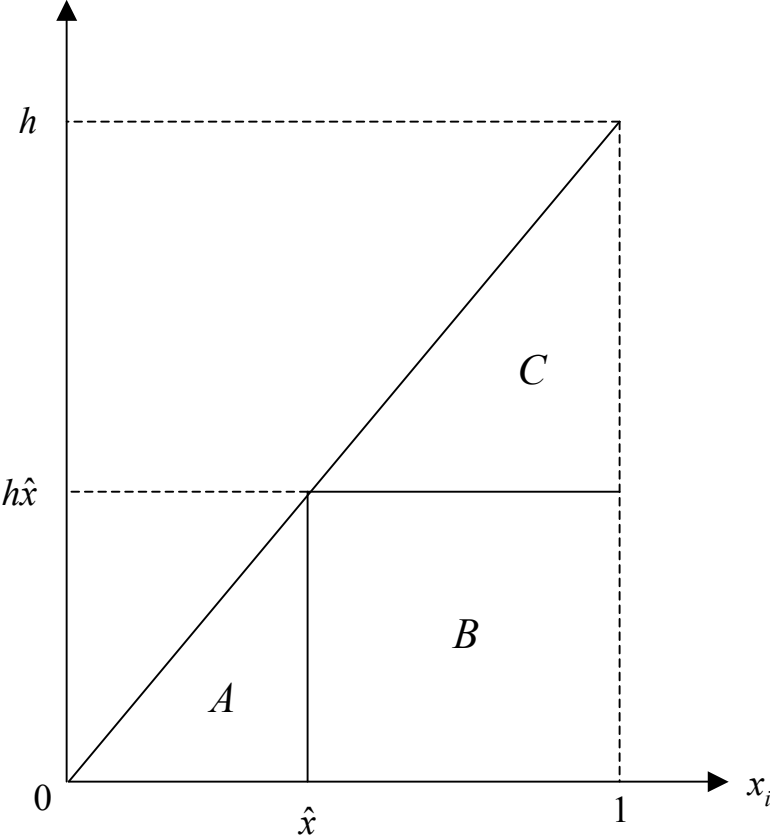


Figure 3: Bell and Trevino's (1999) Estimated Distribution of HIV Risk

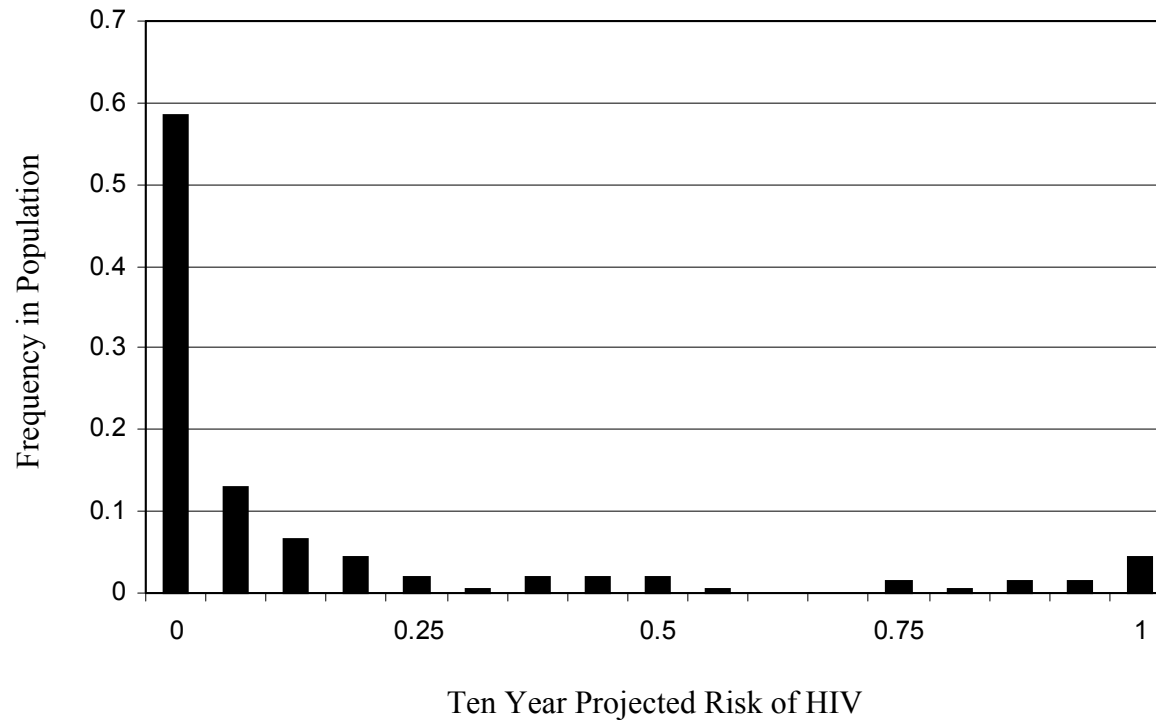


Figure 4: Vaccine Revenue Given Empirical Distribution

