Research incentives in competing markets: A model of the development of new vaccines

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Abstract

This paper tries to find an economic explanation to the fact that vaccines for death-causing diseases such as AIDS, malaria and tuberculosis, have not been discovered yet. We argue that private laboratories do not have proper incentives to invest in research due to three reasons: 1) the vast majority of demand comes from poor countries who cannot afford a price high enough to compensate research costs, 2) international pressure to reduce vaccine prices once discovered will be high and successful, and 3) laboratories act as monopolists in the competing market of treatments for already infected patients and the appearance of a vaccine will, in the short run, lower the price of treatments while, in the longer run, make the treatment market disappear. We first present a static model to show why laboratories may under-invest in vaccines. We extend the model to a dynamic context to endogenize how the infection rate. Finally, we discuss some mechanisms to provide incentives for private research in vaccines.

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"Most experts agree a vaccine will be a crucial part of the anti-AIDS arsenal. Unfortunately, hardly any money is being spent on developing one."

The Economist, 29 April 2000.

1 Introduction

Nearly 5 million people die each year from AIDS, malaria and tuberculosis. Yet, although the medical community agrees that vaccines would be the best solution to the problem, almost no private research is being carried out to find them.[1] According to the World Health Organization (WHO), only 10% of medical research is conducted against diseases which cause 90% of world deaths. The lack of incentives for private laboratories to invest in vaccines could be behind this lack of private research.

Research costs are high, and pharmaceutical companies fear that they would not be able to sell enough vaccines at a high enough price to recoup their investments. Low revenue might come from the fact that these diseases affect primarily poor countries, which cannot afford high prices for vaccines, but also because laboratories fear that, once vaccines are developed, international pressure will be so high that they will not be able to price discriminate, selling vaccines more expensively only to rich countries. We argue that firms may not even be able to set vaccine prices. Finally, the fact that most firms competing to create a vaccine market already sell a treatment product for infected patients, gives additional incentives for not developing a vaccine,

[1] Although there exists a vaccine against tuberculosis, due to its characteristics and price, it is not suitable for the biggest demanders of it, i.e. the developing countries.

which, in the long run, could make the treatment market disappear.

Laboratories have their own incentives which differ from those of health institutions. Nadiri (1993) estimated that the social returns to research and development (R&D) are typically twice the return to private developers. Kremer (2000) finds a much greater gap in the vaccines market of ten times the private returns, due partially to the possibility of designing around vaccine patents which will drive prices down.[2] Additionally, vaccine research is subject to a time consistency problem because regulators have a double objective. On the one hand, they would like to guarantee a high price for the vaccine in order to provide incentives for research. On the other hand, once discovered, they would prefer low prices so more people can vaccinate.

These facts create distortions in the market of research for vaccines. Moreover, vaccine markets are also distorted, since individuals have inadequate incentives to take vaccines because those who take them not only benefit themselves, but also benefit others by breaking the cycle of infection.

A clarifying example of the distortions in these markets is that although there are 80 different products against hypertension or 200 different pain relief drugs, private investment still focuses on new drugs for these illnesses, while laboratories cut off their investment in malaria in the mid-nineties. Only 8% of resources spent against AIDS are devoted to finding a vaccine, which could cut the increasing flow of people from low income countries who get infected. In 1999, there were 33.6 million people infected with AIDS, 95% of them in developing countries, and the infection rate has risen to 16,000

[2]The recent case of the South African government using non-patented copies of some AIDS treatments has forced some laboratories to offer lower prices to developing countries.

new cases of people infected daily.

This combination of huge need and market failure could be relieved if the incentives of laboratories were directed properly. Although bigger public resources against these diseases were announced for 2000, especially for AIDS,[3] correct regulation can help these budgets being used more efficiently. In this sense, as vaccines are an international public good, no single country has incentives to spend resources encouraging research on its own. As it has been shown recently in South Africa, international patent protection is a complicated issue, since once the vaccine is discovered, other countries could easily free-ride. Therefore, global public action is recommended. Two kinds of mechanisms have been put forward: *push mechanisms*, which basically subsidize the costs of research, and *pull mechanisms*, which pay for innovation once the discovery has been reached. Here, we will discuss some different incentive programs and we will argue that pull mechanisms are more appropriate for a vaccine to appear.

To study the different incentives of private laboratories, public institutions and individuals considered as consumers,[4] we introduce a game theoretic model where these three agents interact. We first present a static version of the model to explain why laboratories lack incentives to invest in vaccines, especially when they already sell a treatment product for infected patients. The main reason is that they would need to price the vaccine high enough to recover research costs and, due to government regulation and the

[3]The US Administration announced in April 2000 $1 billion tax credit aid for HIV investment, and both the World Bank and the European Union have announced similar plans.

[4]It is remarkable that the World Trade Organization (WTO) considers food as a basic good while pharmaceuticals, even vaccines, have a consumption good consideration.

characteristics of the demand, they will not be able to do it. We then present a dynamic version of this model to show that, when taking into account the relationship between treatment prices, vaccine prices and the infection rate in a dynamic context, laboratories have even lower incentives to find a vaccine. The cause is that the discovery of the vaccine can make the disease disappear, causing the extinction of the markets for both treatment and a vaccine. We additionally show the infection rate path both before and after the discovery of a vaccine. We will conclude with a discussion of different incentive programs in a more general setting, finding that a combination of push and pull mechanisms would be socially desirable. Although push programs can be a good companion measure, public resources should focus on pull programs. The reason is that an ex-post payment to buy the vaccine by a public institution can maintain or increase firms' profits attracting private resources to vaccine research, while also allowing to set a price for the vaccine equal to marginal cost. As in our model marginal cost equals zero, all individuals could vaccinate and the disease would disappear.

The paper is organized as follows. Section 2 contains the static model. Section 3 presents the dynamic version of the model. Section 4 discusses the policy implications of the results. Proofs appear in the Appendix.

2 The static model

2.1 Description of the model

Consider a game with three types of agents: 1) A firm F developing a vaccine for a particular disease through its R&D program, and already selling a

treatment for infected patients at a monopoly price p. 2) A continuum of risk neutral consumers C with exogenous income y uniformly distributed in the interval [0,1]. Non-vaccinated consumers will be infected with probability i.[5] Infected consumers decide whether to buy the treatment or not. 3) A government G whose only task is to set the price q of the vaccine in case it is discovered, to maximize social welfare.

The timing of the game is as follows. Firm F decides how much resources I it is going to invest in the development of the vaccine. The discovery of the vaccine is determined by a probability function $h(I)$ increasing in the amount of investment I. If research fails, the vaccine is not found and the firm decides the price p_f of the treatment, while infected consumers decide, at this price, if they get treated or not. If research succeeds, the vaccine is found, and government G decides the price q of the vaccine, firm F decides the price p_s of the treatment, and infected consumers decide whether to vaccinate or to be exposed to the disease which will infect them with probability i. Infected consumers will then decide to get treated or not.[6] The extensive form of the game is shown in Figure 1.

Consumers' payoffs are the net income they get after paying for the products (treatment or vaccine) they buy. Non-infected consumers will enjoy their full income y. If a consumer vaccinates she never gets infected and she obtains her income y minus the price of the vaccine q. If an infected consumer buys the treatment she obtains her income y, minus a proportion δ of what

[5] The probability of infection will be endogeneized in section 3.

[6] A justification of the timing of the model and how the agents take pricing decisions is contained in section 4.

she will not earn because of being infected,[7] minus the price p_f or p_s (depending on the existence or otherwise of a vaccine) she pays for the treatment. Infected consumers who do not buy the treatment die, therefore obtaining zero net income. Firm F's payoff is the revenue from the products it sells. Government G obtains social welfare, defined as the sum of consumers' and firms' payoffs.

For simplicity we additionally assume that production costs of both the treatment and the vaccine are zero.[8]

Given these assumptions, we next find the subgame perfect equilibrium of the model by backwards induction.

2.2 Equilibrium analysis of the static model

To begin with, we consider the market for treatment when a vaccine does not exist.

Lemma 1: *The equilibrium price of the treatment when a vaccine does not exist is* $p_f^* = \frac{1-\delta}{2}$, *which yields equilibrium demand for treatment* $T_f^* = \frac{i}{2}$.

Only infected consumers have to decide whether to buy the treatment at price p_f or not, given the expected payoffs they may get. All infected consumers would prefer to get treated if they could buy the treatment, because in our model, if they do not get treated they die; but only those with

[7] Even though δ is interpreted here as the proportion of labour income a consumer will not earn because of having the disease, δy could also be interpreted in a more general setting as the utility cost of being infected. For the labour income justification lets remember what happened to the fired lawyer played by Tom Hanks in Jonathan Demme's film "Philadelphia".

[8] In the pharmaceutical industry, production costs once the product is discovered represent only a small fraction of the higher R&D costs of discovering it.

enough income to buy it will get treated. Laboratory F will choose equilibrium monopoly price for treatment p_f^* to maximize its revenue, and given the equilibrium price, demand for treatment follows. Notice that the equilibrium price of the treatment does not depend on the infection rate i, while demand for treatment T_f does.

Next, we consider the market for treatment when a vaccine is discovered. We need to remark that, in this case, only consumers who did not buy the vaccine face now the probability i of getting infected,[9] and consequently, the demand for treatment depends on the price of the vaccine q.

Lemma 2: *The equilibrium price of the treatment when a vaccine exists at a price* q is $p_s^*(q) = \frac{(1-\delta)q}{2i}$, *which yields equilibrium demand for treatment* $T_s^*(q) = \frac{q}{2\delta}$ *and equilibrium demand for vaccine* $V^*(q) = 1 - \frac{(1+\delta)q}{2i\delta}$.

Given the probability i of getting infected, each consumer will vaccinate if the net income she gets when vaccinating is bigger than her expected net income when not vaccinating. The existence of the vaccine will determine that the price the firm F sets for treatment will be lower when the vaccine exists than when it does not. On the other hand, the higher the price of the treatment $p_s^*(q)$ the more consumers will be willing to vaccinate. Therefore markets of treatment and vaccine compete. Demand for treatment comes from infected consumers who cannot vaccinate but can get treated, i.e., those consumers with income y higher than $\frac{p_s}{1-\delta}$ but lower than $\frac{q(1+\delta)}{2i\delta}$. Demand for the vaccine comes from all consumers with high enough income to vaccinate, i.e., with income higher than $\frac{q(1+\delta)}{2i\delta}$, as it is shown in Figure 2.

[9] We are assuming for simplicity that the preventive vaccine being investigated will be 100% effective. If the vaccine is successful only in some percentage of cases, less consumers would be willing to vaccinate, but qualitative results would be the same.

Government G decides the price for the vaccine q once the vaccine has been discovered, to maximize social welfare, defined as the sum of the net income of the pool of consumers C plus total revenue of laboratory F.

Proposition 1: *If Government G decides the price of the vaccine after it has been discovered, it sets $q^* = 0$. Anticipating this, laboratory F does not invest in the vaccine, $I = 0$.*

Prices p_s and q are just a transfer from consumers to the laboratory. G chooses $q = 0$ to make sure that if a vaccine exists, every consumer vaccinates and the disease disappears. Thus, G avoids the loss of welfare $i\delta y$ coming from infected consumers who receive treatment and the zero net income suffered by infected consumers who cannot afford the treatment.[10] Anticipating that G will set $q = 0$, F will not invest any resources in the development of the vaccine, $I = 0$, both because investment is costly for the laboratory and because $q = 0$ will leave it with zero revenue if a vaccine is discovered. Therefore, the uncertainty about the success of the investment, the uncertainty on the revenue F will be able to get if it discovers a vaccine, and the certainty that the markets of both treatment and vaccine will disappear if a vaccine is discovered, makes the laboratory reject the investment, and the vaccine not being discovered with probability one ($h(I) = 0$).

Notice that the results do not depend on the form of the probability function $h(I)$. In what follows, we assume that $h(I)$ is concave, so that marginal returns to investment decrease with resources allocated to it. We also assume that, no matter how much investment I is carried out, the probability

[10] Notice that the same argument applies when G is an international public institution such as the World Health Organization (WHO) who cares only about consumers and not about laboratories' profits.

of success will never be one, as there is always a chance of failure. Finally, if investment I is zero, the probability of finding the vaccine will then be zero, $h(0) = 0$. A simple parametrization that incorporates these assumptions is

$$h(I) = \frac{I}{a + I} \ ,$$

where a is a positive parameter.

2.3 Policy analysis

In this section we propose some mechanisms to increase firms' incentives to invest in vaccines. We focus in four categories: monopoly pricing in the vaccine market, bargained prices, research subsidies (push mechanisms) and ex-post payments made by the government to buy the vaccine and freely distribute it (pull mechanisms). We find that pull mechanisms are the most appealing solution. As a benchmark we consider the price F would set if G would let him behave also as a monopolist in the vaccine market.

2.3.1 Monopoly price

Proposition 2: *A monopolist F sets $q = q^M = \frac{2i\delta}{1+3\delta}$, and invests positive resources I^M in vaccine research, for a high enough value of the slope of the investment function.*

A monopolist laboratory F sets a positive price $q^M > 0$ for the vaccine expecting to have bigger revenue from both the vaccine and treatment markets when the vaccine exists than only from the treatment market when the vaccine does not exist. Consequently F invests positive resources I^M to develop a vaccine for the disease.

The problem of monopoly pricing regarding social welfare is that, even though investment is positive and consequently the probability of finding the vaccine $h(I)$ is positive, the monopoly price of the vaccine q^M is high, and thus the price of the treatment p_s is also high. Consequently only a small proportion of consumers can afford vaccination, and only a small fraction of infected consumers can get treatment.

2.3.2 Bargaining solution

An alternative to monopoly pricing is to let G and F bargain a price between zero and q^M once the vaccine has been developed. Under a high enough bargained price there will be incentives to ex-ante invest on the vaccine. For simplicity we adopt a bargaining solution similar to Hart-Moore (1998),[11] where G and F have probabilities $1-\gamma$ and γ, respectively, of making a *take-it-or-leave-it offer*[12] of the vaccine price. Under the agreed price for the vaccine q^γ, investment I^γ can still be positive (though no bigger than I^M). An advantage of the bargained price is that it makes the vaccine available for a wider group of consumers than under the monopoly price.

Proposition 3: *The bargaining solution yields a price $q^\gamma = \gamma q^M$, and F will invest no more than I^M.*

Figure 3 illustrates the bargaining solution.[13] When firm F has all the bargaining power ($\gamma = 1$), the bargained price will be the same as the

[11] We prefer this approach to the standard Nash Bargaining Solution. Qualitative results would be similar.

[12] Parameter γ would then be interpreted as F's bargaining power, $1-\gamma$ being G's bargaining power.

[13] Figure 3 holds for any $\delta \geq \frac{1}{3}$, which is reasonable in our context given that δ is the proportion of earnings that a consumer loses because of having a disease like AIDS.

monopoly price $q^\gamma = q^M$, yielding monopoly revenue equal to $\frac{i\delta}{1+3\delta}$. When government G has all the bargaining power ($\gamma = 0$), it will choose $q = 0$ which yields social welfare equal to $\frac{1}{2}$ and zero revenue to firm F. The bargaining solution yields positive investment while making the vaccine available to more consumers than in the monopoly case. Additionally, F's revenue is higher than without the vaccine.[14]

2.3.3 Push incentives

Traditionally, subsidies have been a popular mechanism to encourage R&D. In our model, subsidies need to be combined with other mechanisms as firms have no incentives to develop a vaccine. Here the problem is not only that investment is costly but that successful research implies the disappearance of the treatment market. Therefore we consider a combination of research subsidies with a bargaining price for the vaccine. The aim is to lower the private cost of investment while keeping firm's revenue positive.

Under these combination of mechanisms, F's investment decision is

$$\underset{I}{Max}\ h((1+\alpha)I)R_s^\gamma + (1 - h((1+\alpha)I)R_f^\gamma - I$$

where α is the proportional subsidy paid by G,[15] and $R_s^\gamma = \gamma R_s^M$and $R_f^\gamma =$

[14]The *status quo* situation (SQ) occurs when no agreement is reached and therefore, the vaccine is not sold in the market. In this case, firm F sells only the treatment. It could be argued that when G has high bargaining power ($\gamma \to 0$), the price q^γ will be so low that F's revenue will be lower when a vaccine exists than when it does not exist, and therefore, F will not recognize that they have discovered the vaccine. To avoid this, in our bargaining model, F first announces if it has the vaccine, and afterwards bargaining takes place. On the other hand, if we assume that bargaining occurs before the announcement, the only change is that the minimum price for the vaccine ($\gamma = 0$) is the one that makes F's revenue equal to the situation where there's not a vaccine ($R_f = \frac{(1-\delta)i}{4}$) instead of zero.

[15]And not by F, so total investment is $(1+\alpha)I$, while F only spends I.

$R_f^M = \frac{(1-\delta)i}{4}$ are firm's revenues if a vaccine exists and if it does not, respectively. In this case investment I is higher than in the case where there is only a bargaining price for the vaccine as F's revenue does not change and the investment cost goes down.

2.3.4 Pull incentives

Subsidies can also be paid ex-post, i.e., once the vaccine has been developed. Due to G's double objective, it turns out that pull mechanisms are more suitable than push mechanisms. The reason is that they increase investment and make the vaccine available to a wider group of consumers.[16] G can buy the future distribution of the vaccine by an amount that compensates investment costs and the disappearance of the treatment market. Once G owns the patent of the vaccine, it can freely distribute it in the case of success, which will now occur with higher probability. At $q = 0$ all consumers vaccinate and the disease disappears.[17]

Under pull mechanisms, F's investment decision is

$$\underset{I}{Max}\ h(I)B + (1 - h(I))R_f^\gamma - I,$$

where B is the amount of resources paid by G to F to compensate the investment costs and the disappearance of the treatment market, and R_f^γ is F's monopoly revenue when the vaccine does not exist. Paying B increases the probability of discovering the vaccine. For high enough B, investment

[16] In the case where the infection rate is endogenous and depends on variables such as preventive behavior or income, G could establish target groups of consumers (drug addicts, prostitutes, hemophiliacs...) to be the first vaccinated.

[17] This mechanism is similar to the "patent-buy-outs" proposed in Kremer (1998). We will further comment on this in section 4.

could be greater than under the monopoly price q^M.[18]

To sum up, in this section we have studied four different types of mechanisms which could increase investment in our model. We will extend in policy implications in section 4.

3 The dynamic model

3.1 Description of the model

In this section we introduce a dynamic model to study some of the issues not covered by the static approach. In particular, we use an overlapping generations model (OLG) to endogenize the infection rate i_t, which now depends on the proportion of consumers infected in the previous period.[19] Thus, prices p_t and q_t and investment I_t may vary with time.[20] We try to study how pricing decisions affect the equilibrium rate of infection and how agents change their decisions when they know that present decisions are going to affect them in the future. Otherwise, the timing of the model is the same as in the static one.

In the OLG model, we assume that generations of consumers live for two periods, while G and F live forever. Each generation of young consumers receives income y, which is distributed uniformly in the interval [0,1]. We also assume that G and F behave myopically, i.e., thinking only about next period payoffs, while consumers decide on vaccination taking into account

[18] The amount B that G must pay F to reach the monopoly investment level is $B = \frac{i\delta}{1+3\delta}$.

[19] We use *period* to refer to the time interval before and after consumers face the probability of infection.

[20] For simplicity, we will suppose that the probability of finding the vaccine $h(I_t)$ does not accumulate over periods. Therefore, previous investment does not help to discover the vaccine in the current period.

the posterior probability of being infected. Payoffs are the same as in the static model but, logically, they now depend on time.

3.2 Equilibrium without a vaccine

If a vaccine does not exist, each generation of young consumers born in period $t-1$, faces a probability of getting infected i_{t-1}. In period t, young consumers born in $t-1$ will then be old. Old infected consumers take the decision of get treated or not. Consumers who have survived (the proportion of consumers treated, the others will die), will infect the next generation at rate i_t, which is the probability of the consumers born in t getting infected. Figure 4 illustrates the dynamics of contagion.

The next step is to specify the determinants of the probability of infection i_t. We assume that only consumers infected in $t-1$ who could buy the treatment (those with income higher than $\frac{p_{f,t}}{1-\delta}$) live in period t. Non-treated infected consumers die. Only treated infected consumers infect the next generation. Additionally we address the possibility of progressive learning on the risk of the disease. Consequently, new generations will protect themselves more against the infection.[21] Probability of infection is specified as follows

$$i_{f,t} = \left[(1 - \frac{p_{f,t}}{1-\delta})i_{f,t-1}\right]^{\frac{1}{2}}.$$

Notice that due to the normalization of population of consumers to one, when there is no vaccine the probability of infection i_t is the same as the proportion of consumers infected in period t.

[21] Obviously, we assume a very simplified infection function. Epidemiology studies show than infection rates depend in patients' preventive behavior and we only address this issue partially.

Lemma 3: *The equilibrium price of treatment when a vaccine does not exist is* $p_{f,t} = \frac{1-\delta}{2}$.

As F decides myopically, the price of treatment $p_{f,t}$ does not depend on the probability of infection as long as a vaccine does not exist. Notice that the equilibrium price of treatment when a vaccine does not exist is the same as in the static model. Substituting the result in Lemma 3 into the probability of infection function implies the following dynamic equation for infection

$$i_{f,t} = \left[\frac{1}{2} i_{f,t-1}\right]^{\frac{1}{2}}.$$

Hence the infection rate converges to the long-run equilibrium $i_f^* = \frac{1}{2}$.[22] The convergence path, depending on the initial conditions i_{0_H} and i_{0_L}, is shown in Figure 5.

3.3 Equilibrium with vaccine

If a vaccine exists, a proportion of the young consumers born in period $t-1$ vaccinate, paying q_{t-1} and thus protecting themselves against the disease. Non-vaccinated consumers confront a probability $i_{s,t-1}$ of getting infected. z_{t-1} is the proportion of non-vaccinated consumers who get infected. Infected consumers will decide at t whether to get treated or not. Non-treated consumers will die. Treated consumers will infect next generation with probability $i_{s,t}$. Figure 6 illustrates the dynamics of contagion.

As before, we assume that firm F decides the monopoly price $p_{s,t}$ myopically, i.e., from the moment a vaccine exists F takes into account only the

[22] It is obvious that our infection function does not yield a realistic equilibrium (with half the population infected) but we are more interested in how the convergence path will change when a vaccine appears than in the numerical value of the long-run equilibrium.

revenue it will get in the next period. Also G sets price q for the vaccine myopically. We next analyze F's incentives to invest in the vaccine.

Lemma 4: *The probability of infection at time t when a vaccine exists is given by*

$$i_{s,t} = \left[\left(\frac{q_{t-1}}{i_{s,t-1}} - \frac{p_{s,t}}{(1-\delta)}\right)\frac{z_{t-1}}{\delta}\right]^{\frac{1}{2}},$$

where the proportion of people infected is

$$z_{t-1} = i_{s,t-1}\left(1 - \frac{q_{t-1}}{\delta i_{s,t-1}} - \frac{p_{s,t}}{\delta}\right).$$

The argument is the same as in the static model and it is explained in the proof. Figure 7 shows the proportion of consumers vaccinated and treated.

We next study the pricing decision of the firm in the market of treatment when a vaccine exists. First we need to derive the demand for treatment at time t. Treatment will be demanded by the consumers infected at time $t-1$ who have survived and therefore, can receive treatment at t, which is

$$T_{s,t} = \frac{z_{t-1}}{\delta}\left[\frac{q_{t-1}}{i_{s,t-1}} - \frac{p_{f,t}}{1-\delta}\right].$$

The equilibrium price for treatment, decided myopically, will be the result of

$$\underset{p_{s,t}}{Max}\ p_{s,t}\frac{z_{t-1}}{\delta}\left[\frac{q_{t-1}}{i_{s,t-1}} - \frac{p_{s,t}}{1-\delta}\right],$$

which yields equilibrium monopoly price $p^*_{s,t}$. This price depends on the price of the vaccine in the previous period q_{t-1}, the probability of infection in the previous period $i_{s,t-1}$, and the proportion of consumers infected in the previous period z_{t-1}.[23]

[23] As qualitative results do not depend on the expression of prices, and such expression are complex, we do not write the explicit forms for prices.

Finally, government G decides the price q_t of the vaccine. Following the discussion in the previous section, and assuming myopic decision making, we obtain that once the vaccine is developed G will set $q = 0$. The reason is, again, that at a zero price every consumer gets vaccinated in period t and the disease disappears in period $t + 1$.

As in the static model, the problem with this solution is the lack of incentives for F to invest in the development of the vaccine. Thus, there is no investment and the vaccine is never discovered.

The incentive problem is more serious in the dynamic than in the static model. If $q = 0$ and a vaccine already exists, every consumer is vaccinated and, with the disappearance of the disease, both the vaccine and treatment market disappear for the remaining infinite periods. Therefore, F will never invest in vaccines in a dynamic context if it anticipates that its markets are going to disappear forever.

4 Discussion of results

The main result of our model is that private laboratories do not have incentives to invest in vaccines for diseases in which they already sell a treatment product. However, our results may seem to depend too much on an assumption which has not been properly justified: government decides the price of the vaccine but lets the firm set the price of the treatment. We argue that government uses its purchase power more strongly to reach its real objective, the vaccine, than to lower the price of the treatment, as treatment does not solve the problem, it only alleviates it.

To justify this, we note that the government has purchasing power in

the pharmaceutical industry due to three reasons: 1) in most countries, the government acts as the main buyer of pharmaceuticals from private laboratories, 2) the government regulates property rights such as patents, and 3) the government decides whether to allow the distribution of drugs in its territory through its health departments. But the government[24] knows that taking advantage of its purchasing power decreases private incentives to invest in new and more efficient products. Therefore, if the government wants new drugs in the market, it needs to build up a reputation that it will not use its power heavily when new vaccines appear.

In the disease market, the real objective for the government is the development of a vaccine. But not long after diseases such as AIDS were discovered, it was clear that a vaccine was biologically much more difficult to develop than treatment products. Consequently, in a historic perspective, governments could have decided not to regulate treatment prices to give incentives to develop efficient treatments as a first step. We argue that both because of this commitment and because research was easier and cheaper, treatment products were developed. It was not until 1996 that AZT and other retrovirals proved to be very useful in increasing infected patients' life quality. But the main objective, the vaccine, has not been discovered yet. Therefore, governments still need to maintain their reputation that they are not going to set low prices. In our simple model, where the only problem government has is the disease, once the vaccine is discovered, reputation is no longer valuable, and that is why it is difficult for government to commit credibly to

[24] We interpret "government" as countries' health departments. Alternatively it could be addressed as an international health institution such as the World Health Organization..

let laboratories set vaccine prices. Once the vaccine exists, need of vaccination in poor countries (the ones with higher infection rates) creates so much pressure, that the temptation to lower prices wins, and the commitment is no longer credible.

In a more general setting, governments would also be worried about other problems, some of them also related with pharmaceutical companies. For example, if the government thinks there is positive probability for a new infection even worse than AIDS to appear, it will try to maintain its credibility in the future because it will also want to provide incentives for firms to develop a new cure for the new epidemic. Therefore, the higher the probability firms and governments assign to future problems, the more credible present commitments will be.

Additionally, we argue that even if laboratories could set vaccine prices, there are also two other obstacles to investment in vaccines. The main one is that these diseases affect mostly poor countries, which cannot pay for research costs. 95% of AIDS patients live in developing countries and the rate is increasing. Malaria and tuberculosis hardly affect developed countries but are still a huge problem in poor ones. As Sala-i-Martín (2000) notes, between 1975 and 1997, 1,233 new drugs were patented, but only 13 of them were addressed to tropical diseases. Even more shocking, Kremer (2000) finds that only 4 of these 13 drugs were developed by private laboratories. In our model, a possible solution is to let the laboratory price discriminate between rich and poor consumers. In the real world, price discrimination between countries is complicated. Poor countries' governments usually face serious corruption problems and vaccines sold to poor countries at a low price could

be resold to richer ones.

Our model also shows that competition between treatment and vaccine markets decreases incentives to develop vaccines. The main result shows that the discovery of a vaccine lowers the price of the treatment and threatens the existence of both treatment and vaccine markets for future periods as the epidemic will progressively disappear.[25] A simplified version of our model were F sets the price of the vaccine shows that, even in this case, when the laboratory already sells treatment, incentives to develop a vaccine are scarce.

Our model points out that vaccine markets, as they are currently designed, suffer distortions. Much can be done to approach social and private returns. As Kremer (2000) argues, social returns exceed by a factor of ten private returns and therefore, private companies do not have the right incentives to invest in research as much as would be socially desirable.

There are some other issues in our model that should be briefly discussed. For simplicity, we assumed that consumers' payoffs are monetary and that they are risk neutral. We define the disutility of having a disease only by the proportion of earnings the consumer cannot obtain because of being infected. Although it is clear that the problem of an infected consumer is not only monetary, the simplification fits well with other global costs of diseases like AIDS. When we argue that G will set $q = 0$ to avoid the inefficiency coming from the existence of the disease, we are implicitly assuming that the parameter δ represents that inefficiency. In this sense, economic consequences of epidemics are huge: for example, AIDS mainly kills young and

[25] In our simple model, the disappearance occurs right at the moment the vaccine appears because all consumers of the present generation vaccinate.

most productive workers, and, by lowering life expectancy, reduces incentives to invest in education.

Another assumption of our model is that there exists only one monopolistic laboratory in both the markets of treatment and vaccine. In the real world, there are currently six private laboratories investing in anti-AIDS products, and roughly, they only dedicate 6% of research budgets in AIDS to the development of a vaccine, as Kremer (2000) notes. Most of their budget is spent on increasing the quality of treatment products, which is also important to fight the disease. In the malaria market, there is no single private laboratory at the moment investing in vaccines, as almost happens in the tuberculosis market. The introduction of competition between different laboratories to find a vaccine will not be very important for our model since no single laboratory which also sells treatment products has incentives to invest in vaccines. Of course, the appearance of a new laboratory without a treatment product to sell would affect positively investment in vaccine research. In any case, notice that established laboratories selling the treatment are the only ones with competitive knowledge to start a race to discover the vaccine, due to the specific characteristics of epidemic markets. New laboratories would need to get this knowledge before investing in vaccines, and it seems like investment in treatment is the best way to learn about the characteristics of the infection. Consequently, we have serious doubts that new laboratories without a treatment product will appear in this market to invest in vaccines. This is an interesting issue for future research.

We now discuss some proposed incentive programs to bring private returns closer to social returns and therefore, increase investment and thus, the

probability of discovering a vaccine. The literature on R&D distinguishes between push and pull programs. Push programs provide ex-ante funding for vaccine research. Some examples are grants to academics, public equity investments in vaccine development and research tax credits. Pull programs increase ex-post rewards for development of a vaccine. The example we analyze is the commitment to purchase a vaccine if it is developed, at an agreed price, setting the standards the developed vaccine needs to fulfill. Roughly, the distinction is between paying for research inputs and paying for research outputs. As we have seen in section 2, a credible pull program is better than a push mechanisms in the case of vaccines. The reason is that it allows to fix a price low enough so most consumers can vaccinate, and thus it extinguishes the epidemic, while keeping, if the ex-post payment is high enough, laboratories' revenues high.

We agree with Kremer (2000) that a so-called pull mechanism of "patents buy-outs", where government G commits credibly to buy the patent of the vaccine once developed to freely distribute it afterwards, will provide the best incentives to vaccine development.[26] A discussion of other pull mechanisms such as patent extensions, cash prices, research tournaments or pricing existing vaccines higher as a signal of a high price in the future for the new vaccine can be found in Kremer (2000).

Finally, our model assumes that government G has enough bargaining power to set vaccine prices. It seems obvious that G could also have enough

[26] It can be argued that, under risk neutrality, this "patent buy-out" mechanism will be equivalent to commit ex-ante to set a price $q > 0$ for vaccines. The problem will then be to subsidize vaccination. The advantage of Kremer's mechanism in the real world is that patents are more credible, as they are more legally protected.

power to impose on laboratory F an investment rate I, solving by compulsory regulation the lack of incentives of F to invest. We have decided to solve the model only with price regulation because we think it fits better with reality. In an R&D intensive industry such as the pharmaceutical one, investment rates will be difficult for government to verify due to the obscurity of investment budgets. As we have argued in this paper, we believe that the main problem is not to regulate or subsidize research, but to provide the right incentives to laboratories to invest. Money spent in subsidies or regulation can be ineffective for a vaccine to appear if laboratories can deviate it to other programs (including additional research on treatments) when they do not have the right incentives to invest in vaccines.

5 Appendix

Proof of Lemma 1: An infected consumer gets net income $(1-\delta)y - p_f$ if she buys the treatment, and gets 0 if she does not. Therefore, she will buy it if and only if $(1-\delta)y - p_f \geq 0$, which implies the condition

$$y \geq \frac{p_f}{(1-\delta)}.$$

Given that income is uniformly distributed in [0,1], and only infected consumers get treated, it follows that the demand for treatment is

$$T_f(p_f) = i\left(1 - \frac{p_f}{1-\delta}\right).$$

The monopolist firm sets p_f to maximize $p_f T_f(p_f)$, which yields the result.

Proof of Lemma 2: A consumer will buy the vaccine if her net income after vaccinating is greater than her net expected income if she does not buy it and gets infected with probability i, that is if $y - q \geq (1-i)y + i\left[\max\left\{(1-\delta)y - p_s, 0\right\}\right]$ which implies $q \leq i\left[y - \max\left\{(1-\delta)y - p_s, 0\right\}\right]$. There are two cases to consider.

1. If $\frac{p_s}{1-\delta} > \frac{q}{i}$ no consumer has enough income to get treated, so there is no demand for treatment and the demand for vaccine is $V = 1 - \frac{q}{i}$.

2. If $\frac{p_s}{1-\delta} \leq \frac{q}{i}$, the proportion $x = \frac{1}{\delta}(\frac{q}{i} - \frac{p_s}{1-\delta})$ of consumers have enough income to buy the treatment but not the vaccine. Therefore,the demand for treatment comes from infected consumers who can afford the treatment but not the vaccine. Therefore the demand for treatment is $T_s = \frac{i}{\delta}(\frac{q}{i} - \frac{p_s}{1-\delta})$. Consequently, the demand for vaccine comes from

all consumers who can afford it. Due to the uniform distribution of income, the demand for vaccine is $V = 1 - \frac{p_s}{1-\delta} - \frac{1}{\delta}(\frac{q}{i} - \frac{p_s}{1-\delta})$.

The monopolist firm sets p_s to maximize $p_s T_s(p_s)$, which yields

$$p_s^*(q) = \frac{(1-\delta)}{2i} q$$

Notice that $\frac{p_s}{1-\delta} = \frac{q}{2i} < \frac{q^*}{i}$ so only case 2 is relevant.

Substituting the equilibrium price for the treatment we obtain equilibrium demands for treatment and vaccine

$$T_s^*(q) = \frac{q}{2\delta}$$

$$V^*(q) = 1 - \frac{(1+\delta)q}{2i\delta}.$$

Proof of Proposition 1: G chooses the price of the vaccine q to maximize social welfare, defined as the sum of consumers' net income plus firms' F revenue. Consumers' net income depends on the proportion of consumers who can buy treatment or vaccine, depending on their prices. F's revenue comes from infected treated consumers plus vaccinated consumers. Notice that for G, the prices paid for treatment and vaccine are only a transfer of welfare from C to F, and therefore, cancel in the social welfare function.

Government's decision problem is then

$$\underset{q}{Max} \int_0^{\frac{q}{2i}} i0dy + \int_0^{\frac{q}{2i}} (1-i)ydy + \int_{\frac{q}{21}}^{\frac{q(1+\delta)}{2i\delta}} i(1-\delta)ydy +$$

$$+ \int_{\frac{q}{21}}^{\frac{q(1+\delta)}{2i\delta}} (1-i)ydy + \int_{\frac{q(1+\delta)}{2i\delta}}^{1} i(1-\delta)ydy.$$

It is immediate to show that this problem reduces to

$$\underset{q}{Max}\ \frac{1}{2} - (\frac{2i\delta + 3i\delta^2}{8i^2\delta^2})q,$$

so G sets $q = 0$. At this price, all consumers vaccinate and therefore the price of the treatment is irrelevant and F's revenue when the vaccine exists will be equal to zero. F's revenue when the vaccine does not exist $R_f = p_s^* T_f^* = \frac{(1-\delta)i}{4}$ is positive for $i > 0$. Therefore, F's revenue is always higher when the vaccine does not exist so $I = 0$.

Proof of Proposition 2: First, the monopolist firm F sets vaccine price q to maximize its revenue

$$\underset{q}{Max} \int_{\frac{q}{2i}}^{\frac{q(1+\delta)}{2i\delta}} i\frac{(1-\delta)q}{2i}dy + \int_{\frac{q(1+\delta)}{2i\delta}}^{1} qdy,$$

which reduces to

$$\underset{q}{Max}\ q - \frac{(1+3\delta)}{4i\delta}q^2,$$

so the solution is

$$q^M = \frac{2i\delta}{1+3\delta}.$$

F decides vaccine investment to maximize expected revenue when a vaccine exists and when it does not

$$\underset{I}{Max}\ h(I)\left[q^M - \frac{(1+3\delta)}{4i\delta}q^{M^2}\right] + (1-h(I))\left[\frac{(1-\delta)i}{4}\right] - I.$$

The first order condition is

$$h\acute{(}I) = \frac{2i\delta - i + 3i\delta^2}{4+12\delta}.$$

Given $h(I) = \frac{I}{a+I}$, we obtain

$$I = I^M = -a + 2\sqrt{a(\frac{1+3\delta}{2i\delta - i + 3i\delta^2})} > 0 \text{ for } a < \frac{4+12\delta}{2i\delta - i + 3i\delta^2}.$$

That is, for positive investment to occur the slope of the probability of success function $h(I)$ must have a big enough slope for small resources I invested, i.e., for small investment, the probability of success must be high enough.

Proof of Proposition 3: We define the following *status quo* in the case agreement is not reached. If there is no agreement G will not allow the vaccine to be distributed in the drugs market. G's payoff in the *status quo* is the social welfare when there is no vaccine in the market (SW_f^{SQ}). F's *status quo* payoff is revenue when it does not sell the vaccine (R_f^{SQ}).

$$SW_f^{SQ} = \int_0^1 (1-i)ydy + \int_{\frac{1}{2}}^1 i(1-\delta)ydy = \frac{1}{2} - \frac{i+3i\delta}{8}$$

$$R_f^{SQ} = \frac{(1-\delta)i}{4}.$$

If $\gamma = 0$, G has all the bargaining power, $q = q^G = 0$, every consumer vaccinates and F does not obtain revenue. Therefore payoffs are

$$SW_s^G = \int_0^1 ydy = \frac{1}{2}$$

$$R_s^G = 0.$$

If $\gamma = 1$, F has all the bargaining power, and sells the vaccine at monopoly price $q = q^M = \frac{2i\delta}{1+3\delta}$. Payoffs are

$$SW_s^M = \int_0^{\frac{\delta}{1+3\delta}} (1-i)ydy + \int_{\frac{\delta}{1+3\delta}}^{\frac{1+\delta}{1+3\delta}} i(1-\delta)ydy + \int_{\frac{\delta}{1+3\delta}}^{\frac{1+\delta}{1+3\delta}} (1-i)ydy + \int_{\frac{1+\delta}{1+3\delta}}^1 ydy =$$

$$= \frac{1}{2} - \frac{i\delta + 3i\delta^2}{2(1+3\delta)^2}$$

$$R_s^M = \frac{i\delta}{1+3\delta}.$$

The expected price of the vaccine is proportional to bargaining power γ and moves linearly from $q^G = 0$ to $q^M = \frac{2i\delta}{1+3\delta}$

$$q^\gamma = \gamma q^M = \frac{\gamma 2i\delta}{1+3\delta}.$$

The expected payoffs of the bargaining solution are

$$SW^\gamma = \gamma\left[\frac{1}{2} - \frac{i\delta + 3i\delta^2}{2(1+3\delta)^2}\right] + (1-\gamma)\left(\frac{1}{2}\right) = \frac{1}{2} - \frac{\gamma(i\delta + 3i\delta^2)}{2(1+3\delta)^2}$$

$$R^\gamma = \gamma\left[\frac{i\delta}{1+3\delta}\right] + (1-\gamma)0 = \frac{\gamma i\delta}{1+3\delta}.$$

Consequently, F's investment decision solves

$$\underset{I}{Max}\ h(I)\left[\frac{\gamma i\delta}{1+3\delta}\right] + (1-h(I))\left[\frac{(1-\delta)i}{4}\right] - I$$

the solution is

$$I = I^\gamma = -a + \sqrt{a(\frac{4\gamma i\delta - i - 2i\delta + 3i\delta^2}{4+12\delta})} > 0 \text{ for } a < \frac{4\gamma i\delta - i - 2i\delta + 3i\delta^2}{4+12\delta},$$

which proves the result.

Proof of Lemma 3: If a vaccine does not exist and F is myopic, its revenue will be the price $p_{f,t}$ that F charges in t times the demand of treatment, which will be the proportion of people infected in $t-1$ who can treat in period t. Therefore, the monopolist firm chooses $p_{f.t}$ to maximize $p_{f,t} i_{f,t-1}\left(1 - \frac{p_{f,t}}{1-d}\right)$, which yields the result. Notice that price $p_{f,t}$ is constant for every i_t.

Proof of Lemma 4: At period $t-1$ a consumer will vaccinate if her net income after vaccinating is greater than her net expected if she does not buy it, and gets infected with probability $i_{s,t-1}$, that is $y - q_{t-1} \geq (1 - i_{s,t-1})y + i_{s,t-1}\left[\max\left\{(1-\delta)y - p_{s,t}, 0\right\}\right]$ which implies

$$q_{t-1} \leq i_{s,t-1}\left[y - \max\left\{(1-\delta)y - p_{s,t}, 0\right\}\right].$$

As in the static model, we identify the proportion of consumers who can not treat nor vaccinate, the infected consumers treated and the fraction of consumers vaccinated at $t-1$, in Figure 7. Notice that x is the proportion of consumers who did not vaccinate at $t-1$ who can treat at t, i.e., $x = \frac{1}{\delta}\left[\frac{q_{t-1}}{i_{t-1}} - \frac{p_{f,t}}{1-\delta}\right]$. As before, the probability of infection at time t, $i_{s,t}$, is the square root of the proportion of infected consumers at $t-1$ who could treat at t

$$i_{s,t} = \left[\left(\frac{q_{t-1}}{i_{s,t-1}} - \frac{p_{s,t}}{(1-\delta)}\right)\frac{z_{t-1}}{\delta}\right]^{\frac{1}{2}}$$

and the proportion of infected consumers at time t is the proportion of consumers who did not vaccinate $(1 - \frac{q_t}{\delta i_{s,t}} - \frac{p_{s,t}}{\delta})$ (vaccinated consumers are protected against the disease) times the probability of the infection at time t, $i_{s,t}$:

$$z_t = i_{s,t}\left(1 - \frac{q_t}{\delta i_{s,t}} - \frac{p_{s,t+1}}{\delta}\right).$$

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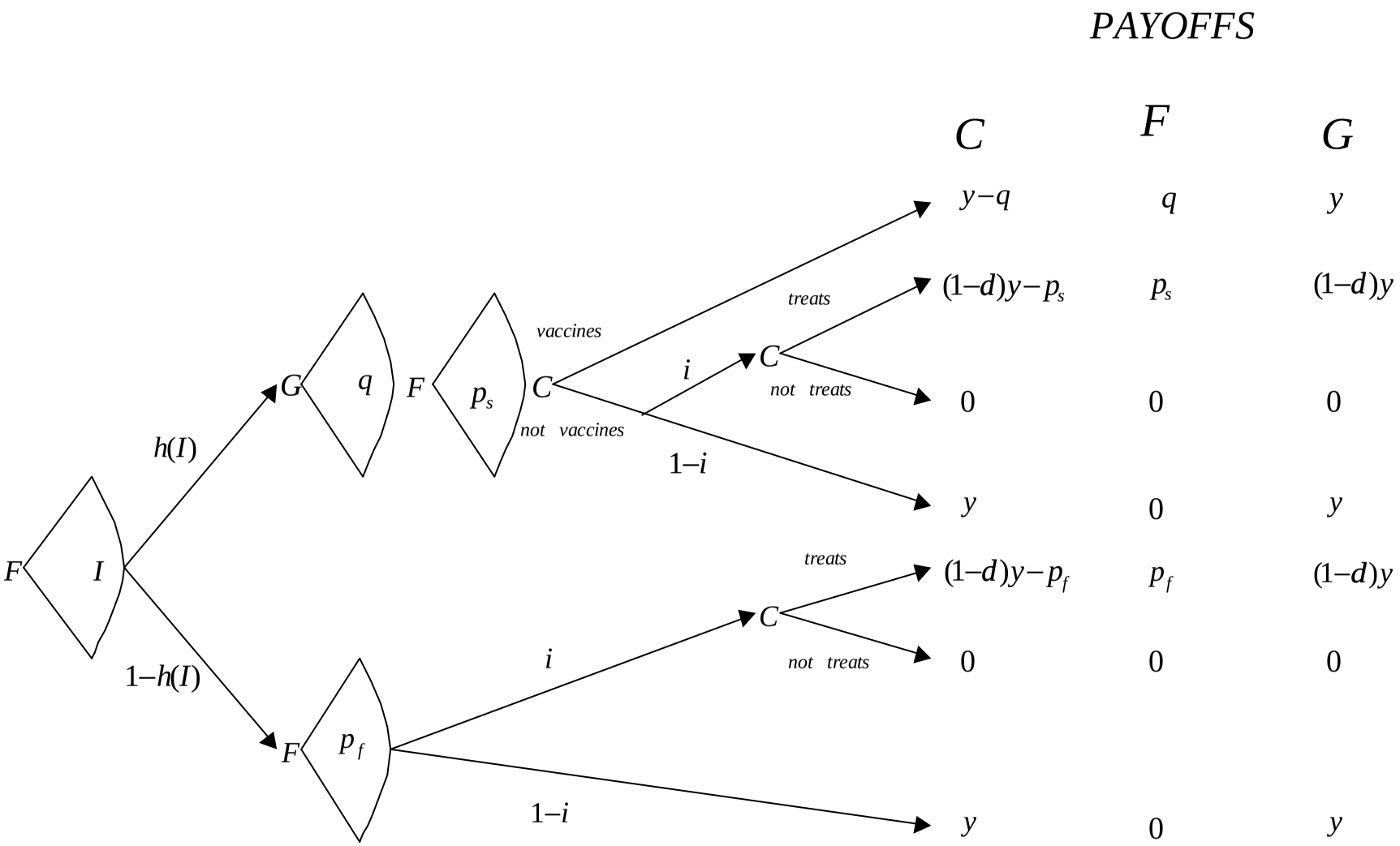

Figure 1: The extensive form of the game

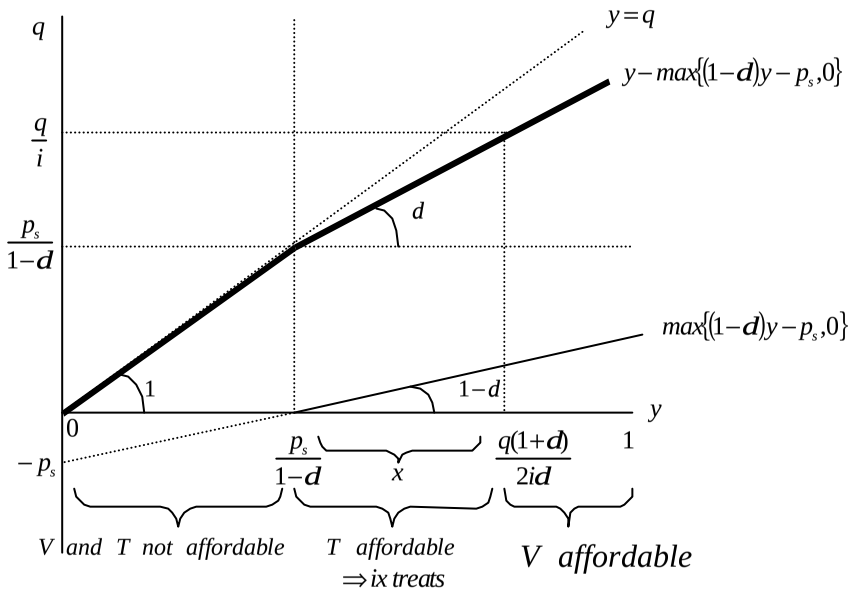

Figure 2: Demands for treatment and vaccine

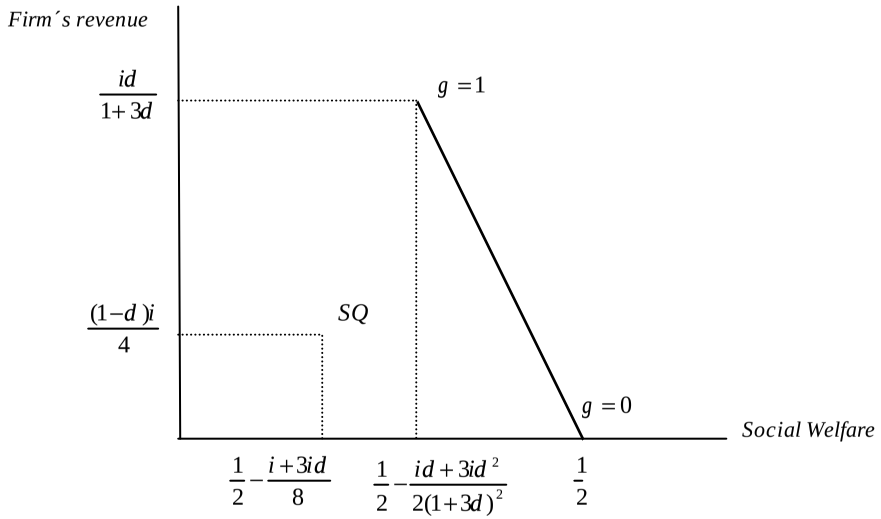

Figure 3: Bargaining solution

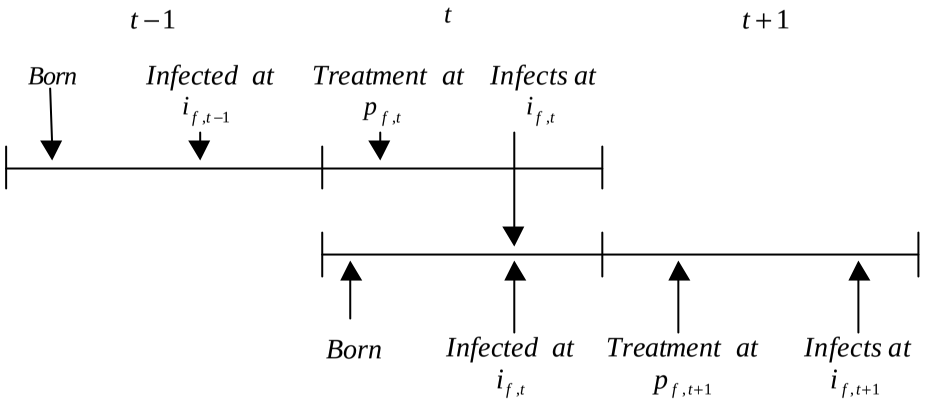

Figure 4: Dynamics of contagion without vaccine

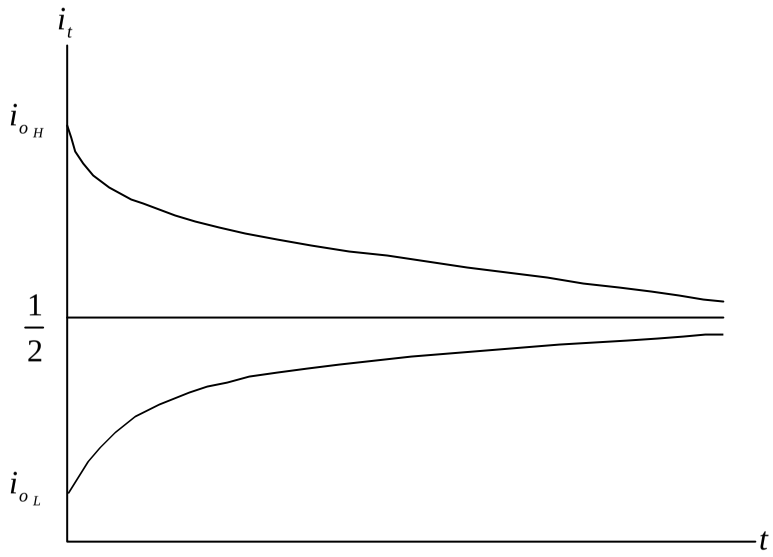

Figure 5: Infection rate without vaccine

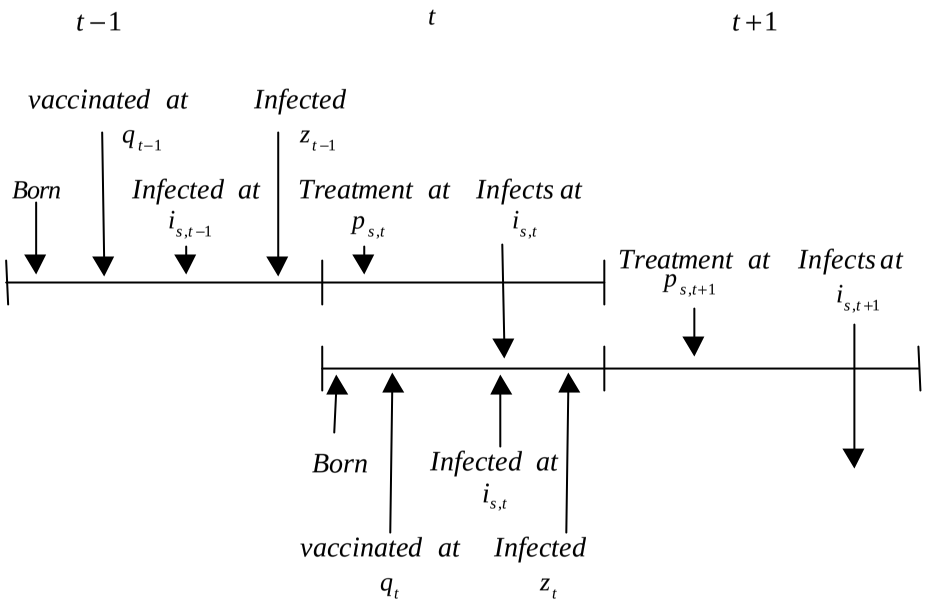

Figure 6: Dynamics of contagion with vaccine

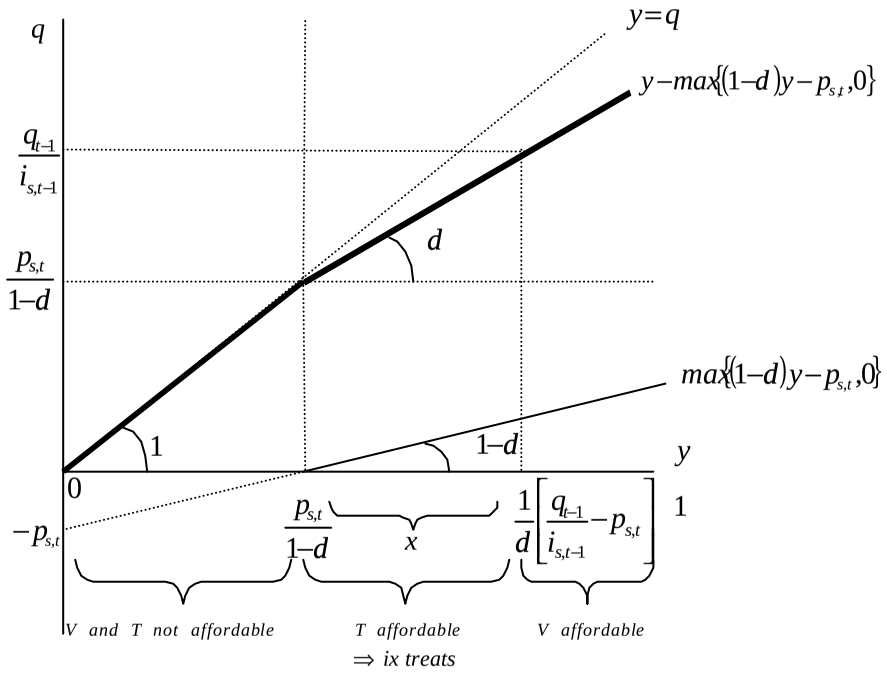

Figure 7: Dynamic demands for treatment and vaccine