

GLOBAL DISEASE ERADICATION

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Abstract. An infectious disease can only be eradicated globally if it is eliminated in every country. But does this require only international coordination, or does it require cooperation? Using a model that blends epidemiology, economics, and game theory, this paper shows that coordination will not always suffice, even when the global benefits of eradication exceed the costs. In general, eradication will require strong international institutions.

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1. Introduction

The eradication of smallpox stands as one of the greatest achievements of international cooperation—ever. It is also a singular event in the history of public health. Earlier attempts to eradicate other diseases—hookworm, yellow fever, yaws, and malaria—all failed. Today, public health officials are trying to eradicate the global scourge, poliomyelitis, and the tropical disease, guinea worm (dracunculiasis). Other candidates for eradication have been proposed to follow on these efforts—including measles, which kills almost a million children a year. This paper is a preliminary investigation into the reasons for the success and failure of international disease eradication programs.

Though the public health literature has addressed this subject at length, eradication is more than a problem for epidemiology. Being a global public good, it also poses problems for incentives and the design of institutions. This paper examines the latter aspects of eradication, but in a way that builds upon the public health literature. In particular, key parameters for eradication found in the mathematical epidemiology literature also feature in my analysis. Of course, economists have examined the eradication problem previously. However, this earlier work has either ignored the international dimension (Geoffard and Philipson, 1997) or focused on only part of the problem (Cooper, 1989) or been discursive (Sandler and Arce, 2001). This paper builds a more complete picture. I also derive results that question some of the received views about eradication.

Perhaps even more surprising than the fact that the smallpox eradication campaign succeeded is that it nearly failed for lack of international support. As I show in this paper, even if epidemiology favors eradication—indeed, even if cost-benefit analysis overwhelmingly approves of the eradication goal—eradication may yet fail for reasons of poor institutional design. Implementation of some (but not all) eradication programs requires international enforcement, and enforcement powers at the international level are notoriously weak.

2. Epidemiology

A key parameter in mathematical epidemiology is the basic reproductive rate of a disease, R_0 : the average number of secondary infections produced when one infected individual is introduced into a host population where everyone is susceptible (Anderson and May, 1991). Obviously, for a disease to spread, it is necessary that $R_0 > 1$.

The value of R_0 varies with the disease. For polio, $R_0 \approx 6$; for measles, R_0 can be more than twice as large (Anderson and May, 1991: 70). The value of R_0 also depends on local factors. Some diseases are spread by means of reasonably close human contact, for example, making population density a determinant of R_0 . It was partly for this reason that smallpox was harder to eliminate on the Indian subcontinent than in Africa (Anderson and May, 1991: 89-90). In this paper I take the value of R_0 to be the same for all countries.

If a population is homogeneously mixed, the number of secondary infections produced by the introduction of a single infected person, R , will be linearly proportional to the probability that a susceptible person comes into contact with an infected person. Let x denote the fraction of a

population that is susceptible.¹ Then $R = xR_0$. This relationship tells us that, if policy can control x , it can reduce R below one and so make the disease disappear—locally if not globally.

Note that, for a disease to be endemic, it is essential that the country's population be large enough. That is, the population must give birth to enough new susceptibles every year that R is kept above one. Measles, for example, is endemic only in countries with a population of at least half a million (Black, 1966). In the analysis to follow, I assume that the disease subject to control is endemic in every country.

I shall further take it that x can be controlled by means of vaccination, and that a fully effective vaccine exists.² Let p denote the fraction of the population that is immunized. Then we have $R = (1 - p)R_0$. Elimination of a disease thus requires that the vaccination level be at least as great as the *critical level* p^c where

$$p^c = 1 - \frac{1}{R_0}. \quad (1)$$

We can now offer precise definitions for two important concepts from epidemiology:

Definition 1: A disease is *eliminated* in country i if and only if $p_i \geq p^c$.

Definition 2: A disease is *eradicated* if and only if $p_i \geq p^c \forall i = 1, \dots, N$.

In these definitions, p_i represents the fraction of the population in country i that is immunized, and N denotes the total number of countries in which the disease is endemic. Together, these definitions tell us that an infectious disease is eradicated if and only if it is eliminated in every country. By definition, eradication is an outcome requiring international action.

Notice that, with international homogeneous mixing, eradication and elimination are one in the same, since every country's immunization level would, under this assumption, be equal to the global average. In general, however, this will be too strong an assumption. And, without international homogeneous mixing, it is obvious that a global eradication campaign succeeds or fails depending on whether the condition $\min(p_1, p_2, \dots, p_N) \geq p^c$ holds.

Eradication is thus a “weakest link” game in the sense that, “the overall success of global measures to eradicate a disease hinges on the country that does the least” (Sandler and Arce, 2001: 20). For weakest link games, the full cooperative outcome is often a Nash equilibrium. However, it need not be and—as I shall show later—in the case of eradication it often will not be. That is, coordination may not suffice to eradicate an infectious agent; international enforcement of an agreement to eradicate may be needed.

¹ Where convenient, I adopt the symbolic representations used by Anderson and May (1991).

² This assumption is adopted purely for convenience. And it should be noted that the assumption will not always hold; the measles vaccine, for example, is about 80% effective (Haggett, 2000: 126).

3. Economics

Though the focus of my inquiry is at the international level, it will help to begin by considering disease control within an isolated country (disease autarky), so that elimination and (local) eradication are equivalent. Though not a realistic situation, it will provide a benchmark for later work. It will also connect the present paper to the earlier literature.

3.1 Competitive equilibrium

Within a representative country, assume that all individuals are symmetric and that each person has a binary choice: to get vaccinated or not to get vaccinated. Vaccination costs an individual an amount c , and since the vaccine offers full immunity (by assumption), the payoff to a person who gets vaccinated is $\Pi = -c$.

Note that c is not simply the direct cost of the vaccine (some vaccines cost just pennies per dose). The full costs of vaccination include the probability of an adverse reaction to the vaccine. For every million people given the smallpox vaccine, for example, a few will die and many others will suffer severe reactions (Altman, 2002).

What happens to a person who decides not to get vaccinated? Let λ denote the “force of infection,” or the probability that a given susceptible host will become infected. Assuming a linear relationship (Anderson and May, 1991: 91) we have:

$$\lambda = \mu R_0 \alpha (p^c - p) \text{ for } p^c \geq p; \lambda = 0 \text{ otherwise.} \quad (2)$$

The parameter μ converts the RHS of (2) into a probability and can be eliminated by normalization. The only novelty in expression (2), as compared with the epidemiology literature, is the parameter α , which reflects the degree to which the disease can be transmitted internationally. The importance of this parameter will be examined in Section 4.

Notice from (2) that, as p increases, the unvaccinated are also protected to some extent. Vaccination confers “herd immunity,” a positive externality. It is because of herd immunity that a disease can be eliminated without every person being vaccinated.

Letting b denote the economic cost of an infection (if the disease were lethal, b would reflect the “value of life”), a person who chooses not to get vaccinated gets a payoff of $\Pi = -bR_0\alpha(p^c - p)$. An individual will prefer to be vaccinated provided $bR_0\alpha(p^c - p) \geq c$. Substituting for p^c using (1) and rearranging gives (assuming an interior solution) the competitive equilibrium rate of vaccination:

$$p^o = 1 - \frac{(b\alpha + c)}{bR_0\alpha}. \quad (3)$$

It follows immediately that:

Proposition 1: For $c > 0$, $p^c > p^o$; the disease will not be eliminated in a competitive equilibrium under disease autarky.

Obviously, if $c = 0$, every person will get vaccinated so long as there exists a benefit to vaccination, and this will be true so long as there is any risk of infection. For $c > 0$, however, it may be privately irrational for some individuals to get vaccinated, even when all individuals are symmetric, because of herd immunity.³ At the same time, herd immunity may make greater vaccination *collectively* desirable. Herd immunity makes the private and social benefits of vaccination diverge. It is the reason that the control of infectious agents requires public intervention.

Before turning to public policy, we can add a final definition:

Definition 3: A disease is *controlled* in country i if and only if, for $c > 0$, $p^c > p_i > p^o$.

Obviously, individuals take actions to limit their exposure to a disease in the Nash equilibrium. But control refers to a public policy, one that achieves a higher level of aggregate protection than in the competitive equilibrium but that falls short of elimination.

3.2 Policy

The payoff to society as a whole is

$$\Pi = -cpn - bR_0\alpha(p^c - p)(1 - p)n \quad \text{for } p < p^c, \quad (4a)$$

where n denotes the country's population, and

$$\Pi = -cpn \quad \text{for } p \geq p^c. \quad (4b)$$

Assuming $p^c > p > 0$, maximization of (4a) yields:

$$p'' = 1 - \frac{(b\alpha + c)}{2bR_0\alpha}. \quad (5)$$

In comparing (5) and (1), it is obvious that p'' could be greater than or less than p^c . It is easy to show that $p'' < p^c \Leftrightarrow b\alpha < c$. Hence, a sufficient condition for (local) eradication to be optimal

³ My approach here is static, and in this sense akin to the approach taken by Brito, Sheshinski, and Intriligator (1991). Francis (1997) studies a special case in which, in a dynamic context, the externality disappears. I am grateful to Timo Goeschl for pointing this out to me.

under disease autarky is $b\alpha \geq c$. If this condition is satisfied, the optimal vaccination rate will be p^c . That is, policy should shoot for elimination, not control.

However, this condition is not necessary because eqs. (4a) and (4b) are not directly comparable. Under the assumption of disease autarky, elimination and eradication are equivalent, and eradication is permanent. Once the vaccination rate reaches p^c , however, the disease is eradicated (locally), and there is no need to vaccinate again in the future. A sufficient condition for (local) eradication to be optimal, as compared with a policy for control under disease autarky, is:

$$-cp^cn \geq -\int_0^\infty [cp^un + bR_0\alpha(p^c - p^u)(1 - p^u)n] e^{-rt} dt, \quad (6)$$

where r is the rate of discount. The LHS of (6) is the payoff to (local) eradication (assuming disease autarky). This is incurred once, in period 0. Thereafter, this country receives a payoff of 0 indefinitely (no risk of infection and no need to vaccinate). The RHS of (6) is the comparable present value payoff associated with the optimal disease control policy (p^u obeys eq. (5)). Eradication is optimal if the former payoff exceeds the latter.

Combining this result with the sufficiency condition derived earlier, a one time vaccination coverage of p^c is optimal if either (i) $b\alpha \geq c$ or (ii) $b\alpha < c$ and

$$\frac{cp^un + bR_0\alpha(p^c - p^u)(1 - p^u)n}{r} \geq cp^cn, \quad (7)$$

where (7) is found by solving the integral in (6) and rearranging. Condition (7) says that elimination/eradication is optimal if the benefit of elimination/eradication (the present value of the costs *avoided*) by elimination/eradication is at least as great as the cost.

It is easy to show that the competitive equilibrium can diverge sharply from the social optimum. Indeed, if $\frac{1}{(R_0-1)} > \frac{b\alpha}{c}$, then no individual will get vaccinated in the competitive equilibrium—and yet condition (7) may nonetheless be satisfied, implying that eradication is socially optimal.

Let p^* denote the optimal vaccination rate with disease autarky. Then we have:

Proposition 2: $p^* = p^o = p^c$ for $c = 0$. For $c > 0$, $p^* > p^o$; $p^* = p^c$ if and only if either $b\alpha \geq c$ or $b\alpha < c$ and

$$\frac{1}{(1 - \frac{1}{R_0})} \left[1 - \frac{(b\alpha + c)^2}{4cbR_0\alpha} \right] \geq r. \quad (8)$$

The latter condition is found by substituting for p^u and p^c in (7).

Note that the first term on the LHS of (8) decreases in R_0 while the second term increases in R_0 . On the one hand, a higher R_0 means a higher p^c , raising the cost of eradication. On the other hand, a higher value for R_0 (more specifically, $R_0\alpha$) increases the force of infection—and, hence, the benefit of eradication. The epidemiology literature draws attention only to the first effect—arguing that the best candidates for eradication have a low R_0 (and smallpox has an especially low R_0 ; see Anderson and May, 1991). In this model, however, the second effect dominates; that is, the LHS of (8) increases in R_0 for $b\alpha < c$.

4. International policy

Disease autarky is only a hypothetical concept. Diseases easily cross borders. After smallpox was eliminated from Botswana, for example, it was reintroduced from South Africa (Fenner *et al.*, 1988: 1349). Hence, our analysis needs to take account of the risk of importing infections.

Assume that, with microbial “free trade,” the probability than an unvaccinated person in country i becomes infected depends on a weighted average of the potentially infectious populations both at home and abroad. Then the payoff to country i can be written:

$$\Pi_i = -cp_i n - bR_0 \left[\alpha(1 - p_i) + (1 - \alpha) \sum_{j \neq i} \frac{(1 - p_j)}{(N - 1)} \right] (1 - p_i) n \quad (9a)$$

for $1 > \alpha > 0$ if $p_j < p^c$ for some $j \neq i$;

$$\Pi_i = -cp_i n - bR_0 \alpha (p^c - p_i) (1 - p_i) n \quad (9b)$$

for $\alpha = 1$ or for $1 > \alpha > 0$ if $p_j \geq p^c$ for all $j \neq i$ and $p_i < p^c$; and

$$\Pi_i = -cp_i n \quad (9c)$$

for $\alpha = 1$ if $p_i \geq p^c$ or for $1 > \alpha > 0$ if $p_j \geq p^c$ for all $j \neq i$ and $p_i \geq p^c$.

Obviously, the pair (9b) and (9c) are identical to (4a) and (4b); once the disease has been eliminated elsewhere, the last country is essentially operating under conditions of disease autarky.

As noted earlier, the parameter α reflects the ability of disease to travel internationally. The smaller is α the more porous is every country as regard infections. Though a parameter in this

model, the substantial increase in both air transport and international trade has reduced α very considerably in the last 50 years (Haggett, 2000: 93-95).

The symmetric Nash equilibrium corresponding to (9a) is:

$$p^+ = 1 - \frac{c}{bR_0(\alpha + 1)} \quad (10a)$$

Eq. (10a) can only be an equilibrium if $p^+ < p^c \Leftrightarrow c > (\alpha + 1)b$. Note that vaccination is a strategic substitute in this model. When countries other than i increase their vaccination rates, herd immunity is imported, and country i 's "best response" is to lower its vaccination coverage.

The symmetric full cooperative outcome corresponding to (9a) is:

$$p^{++} = 1 - \frac{c}{2bR_0} \quad (10b)$$

and, again, this only holds for $p^{++} < p^c \Leftrightarrow c > 2b$.

Obviously, since (9a) requires $1 > \alpha$, $p^{++} > p^+$. So one possible international situation is where, from the perspective of global welfare, every country under protects its population because of the international externality of herd immunity.

Suppose, however, that every other country eradicates the disease. Will each country then want to eradicate the disease? Maximization of (9b) yields (5). A sufficient condition for eradication to be a Nash equilibrium is thus $p^u \geq p^c \Leftrightarrow c \leq b\alpha$. As shown in the previous section, however, this condition is not necessary. Country i will eliminate the disease at home, given that every other country has eliminated the disease, if (8) holds.

To summarize:

Proposition 3: *If $c > (\alpha + 1)b$ and (8) also holds, then there exist two symmetric equilibria in pure strategies. In one, every country vaccinates to the level p^+ and the disease is controlled but not eradicated. In the other, every country vaccinates to the level p^c and the disease is eradicated.*

Notice that, in this model of symmetric countries, there does not exist an equilibrium in which some countries eliminate a disease and others do not. As noted by Hinman (1999: 225), "Although eradication may be a good economic investment, the same cannot necessarily be said for elimination, because of the extremely high cost of maintaining zero incidence while having to continue applying the intervention."

When will eradication be favored?

Proposition 4: *The equilibrium in which the disease is eradicated will be preferred by all countries to the equilibrium in which every country vaccinates to the level p^+ provided*

$$\frac{1}{(1 - \frac{1}{R_0})} \left[1 - \frac{\alpha c}{bR_0(\alpha + 1)^2} \right] \geq r. \quad (11)$$

Condition (11) is found by substituting p^c in (9c), substituting p^+ in (9a), and showing that the former value is at least as large as the latter, divided by r .

Presumably, if condition (11) is satisfied, countries will try to coordinate on the preferred equilibrium. But will coordination suffice to sustain full cooperation?

Full cooperation will demand eradication if $2b \geq c$ or $2b < c$ and

$$-cp^c n \geq -\int_0^\infty [cp^{++}n + bR_0(1 - p^{++})^2 n] e^{-rt} dt, \quad (12)$$

or

$$\frac{1}{(1 - \frac{1}{R_0})} \left[1 - \frac{c}{4bR_0} \right] \geq r. \quad (13)$$

It is easy to see that (13) may hold even while (8) does not hold (the LHS of (13) exceeds the LHS of (8)), and so there will exist situations in which eradication is globally optimal and yet coordination among countries will not suffice to achieve eradication. Formally:

Proposition 5: *Coordination will not always suffice to sustain full cooperation.*

The reason that coordination will not always suffice to sustain full cooperation is that eradication is a global public good. When the last country eliminates the disease, it eradicates the disease globally, and yet the last country will only take into account the benefit of this action for itself. Worse, as other countries eliminate the disease, the risk of infection in the last country is reduced by the externality of herd immunity, making elimination by this country even less attractive.

5. Conclusions

The analysis presented here, though preliminary, suggests that eradication will sometimes require very strong international institutions. Of course, strong institutions are not enough. Many other factors shape success, including key epidemiological ones such as that a disease not have a non-human reservoir. But even when epidemiology favors eradication—indeed, even when the

global benefits of eradication far exceed the costs—an eradication program may fail for institutional reasons.

In the case of smallpox, the epidemiological environment was favorable, as were the economics; using information supplied by Fenner *et al.* (1988), it can be shown that the benefit-cost ratio for smallpox eradication was about 90:1 (see Barrett, 2002). And yet, as noted by D.A. Henderson, the man who led the smallpox eradication effort, “smallpox eradication succeeded... by only the narrowest of margins” (Henderson, 1992: 233). The initial vote by the WHO to approve a budget of just \$50,000 for each country where an eradication program was needed passed by only two votes. Moreover, contributions to the eradication programs were miserly. “During the first seven years of the program, the combined cash contribution of all donors amounted to less than \$200,000 per year” (Henderson, 1992: 230). To be sure, the initial reluctance to support the eradication goal was influenced by the earlier eradication failures—especially the failure of malaria eradication. However, contributions remained small even after the feasibility of smallpox eradication had been demonstrated. According to Fenner *et al.* (1988: 1358), “A deficiency of resources was a continual problem, which seriously jeopardized the international effort. Despite the importance of global smallpox eradication for all countries, support for the programme was barely adequate to sustain it, even during the last months before transmission was stopped.” This suggests an institutional failure. Happily, the international system was able to overcome this problem in the case of smallpox. It remains to be seen, however, whether the initiatives now underway and being contemplated will be as fortunate.

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