Using Private Demand Studies to Calculate Socially Optimal Vaccine Subsidies in Developing Countries

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Abstract

Although it is well known that vaccines against many infectious diseases confer positive economic externalities via indirect protection, analysts have typically ignored possible herd protection effects in policy analyses of vaccination programs. Despite a growing literature on the economic theory of vaccine externalities and several innovative mathematical modeling approaches, there have been almost no empirical applications.

The first objective of the paper is to develop a transparent, accessible economic framework for assessing the private and social economic benefits of vaccination. We also describe how stated preference studies (for example, contingent valuation and choice modeling) can be useful sources of economic data for this analytic framework. We demonstrate socially optimal policies using a graphical approach, starting with a standard textbook depiction of Pigouvian subsidies applied to herd protection from vaccination programs. We also describe nonstandard depictions that highlight some counterintuitive implications of herd protection that we feel are not commonly understood in the applied policy literature.

We illustrate the approach using economic and epidemiological data from two neighborhoods in Kolkata, India. We use recently published epidemiological data on the indirect effects of cholera vaccination in Matlab, Bangladesh (Ali et al., 2005) for fitting a simple mathematical model of how protection changes with vaccine coverage. We use new data on costs and private demand for cholera vaccines in Kolkata, India, and approximate the optimal Pigouvian subsidy. We find that if the optimal subsidy is unknown, selling vaccines at full marginal cost may, under some circumstances, be a preferable second-best option to providing them for free. © 2009 by the Association for Public Policy Analysis and Management.

INTRODUCTION

It is well known that many vaccines provide indirect protection to the unvaccinated. These "herd immunity" or "herd protection" effects[1] have long been recognized in economics and policy. Economists will be familiar with the implications of this positive externality: Individual vaccine purchasing decisions do not consider

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[1] Many authors use the term "herd immunity" to refer specifically to the conferral of immunity to another person through the shedding of the live, attenuated virus. For example, the brother of a child who received a live attenuated polio vaccine may be exposed to the attenuated virus through normal contact with his sibling and indirectly receive the vaccine. We use "herd protection" in this paper to denote the population-level indirect protection that occurs when vaccination removes susceptible individuals from the population and impedes disease transmission.

community-level benefits, and vaccines will be under-provided in a competitive private market. The textbook remedy is a Pigouvian subsidy that equates the marginal cost of providing an additional vaccine with the marginal social, rather than marginal private, benefits of an additional vaccine (Pigou, 1920).

The theoretical literature on vaccine pricing and policy is robust, and growing. Economists starting with Francis (1997) began to examine vaccination policies with the standard models used in mathematical epidemiology (SIR, or Susceptible-Immune-Recovered; see Anderson & May, 1991). Extending earlier work by Brito, Sheshinski, and Intriligator (1992), Francis argued that in some cases there might be no vaccination externalities, although Gersovitz (2003) showed that more plausible modeling assumptions guarantee some level of externality. Most of these mathematical economic-epidemiology models tend, however, to make fairly restrictive assumptions (for example, the vaccine is 100 percent effective with unlimited duration, and in Francis [1997] no one in the population ever dies). Boulier, Datta, and Goldfarb (2007) use an SIR framework coupled with an analytical economic framework to provide empirical estimates of externalities in measles and influenza vaccination, and show how the magnitude of externalities varies with infectiousness parameters, the number of vaccinations, and the efficacy of vaccination. Another key theoretical insight is a call for standard mathematical models to account for agents' reactions to rising (or falling) prevalence (Geoffard & Philipson, 1996; Kremer, 1996; Philipson, 2000). The evidence for this "prevalence elasticity" is growing. Using panel data on flu vaccine demand among the elderly, Li, Norton, and Dow (2004) find that demand increases following years with increased flu mortality, a result paralleling earlier work on flu by Mullahy (1999), on AIDS and condoms by Ahituv, Hotz, and Philipson (1996), and on measles by Philipson (1996). Another focus of this theoretical literature is on whether it is feasible and socially optimal to (globally) eradicate a disease (Barrett & Hoel, 2003; Barrett, 2004).

Despite the theoretical appeal of this literature on vaccine policy modeling, very few people besides economists use or cite this work. Epidemiologists have typically been concerned with finding the critical vaccination coverage rate that will drive a disease to eradication (Becker & Starczak, 1997; Fine, 1993; Longini, Ackerman, & Elveback, 1978; Patel, Longini, & Halloran, 2005). They have also used models to find the allocation of a fixed supply of vaccines that maximizes the number of cases avoided (Becker & Starczak, 1997; Patel, Longini, & Halloran, 2005). Galvani, Reluga, and Chapman (2007) expand upon this theme by embedding an epidemiological model into a game theoretic framework. They find that although the elderly receive a higher utility from receiving a flu vaccine than children, society would be better off by preferentially vaccinating children, who have a lower utility of vaccination but higher transmission rates than adults.

The most common types of economic evaluations of vaccination programs (cost effectiveness or cost utility analysis) often omit herd protection effects (Beutels et al., 2002). The few existing analyses that do model herd protection assume a constant uptake rate per year in infants or very young children and estimate indirect effects in the population as coverage of young children gradually increases with time (Lloyd et al., 2008; Welte et al., 2004; Lee et al., 2007). Accounting for herd protection effects can make flu vaccination programs much more cost-effective, especially when incidence is indirectly reduced for elderly age groups (Reichert et al., 2001; Lee et al., 2007; Lloyd et al., 2008; Patel, Longini, & Halloran, 2005).[2] We know of no empirical economic evaluations that use a social cost-benefit framework to account for the full range of social benefits that arise from herd protection.

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[2] However, herd protection effects can also be detrimental if vaccine protection wanes with age and if the disease is more serious for adults than children, such as the varicella vaccine (Edmunds et al., 2002).

This paper seeks to bridge this gap and has three objectives. The first is to present a simple and accessible economic framework for thinking about private benefits, social benefits, and vaccination externalities. The second objective is to illustrate several implications of herd protection that are not commonly recognized in the applied vaccine policy literature, using a graphical approach. The third objective is to demonstrate how epidemiological field data on the indirect protection of cholera vaccines might be combined with economic field data on private stated demand for cholera vaccines to approximate the socially optimal user fee. The intent is not to provide a detailed economic evaluation and policy prescription for the site we evaluate (two slums in Kolkata, India): We point out several limitations and data gaps along the way and suggest ways in which our approach could be made more rigorous for just such a policy study.

We acknowledge from the outset what some may perceive as a weakness: Our analysis is not grounded in the mathematical language of SIR models but instead takes a different approach. It is a one-period static model (that is, vaccinate today and count benefits and costs that accrue during the periods in which the cohort of vaccines are effective).[3] We do this to avoid as many restrictive assumptions as possible and begin with the most flexible possible model of observed behavior (economic demand functions for cholera vaccines). We prefer to use general functional forms that are more accessible to readers who are unfamiliar with SIR models to describe the epidemiology of indirect effects. As we will discuss in the final section, however, our simple approach gives similar epidemiological predictions to those from a full SIR model of cholera transmission (Longini et al., 2007).

MODEL

We begin by developing a static (i.e., one-period) model of vaccine costs and benefits that incorporates both the direct and indirect effects of a one-time mass vaccination program against some infectious disease such as cholera. The program would target both adults and children. The vaccine thus protects recipients and nonrecipients for a period corresponding to the duration of its effectiveness. For ease of exposition, we assume the program targets a homogenous population of size N with an average incidence rate of I (annual cases per 1000 people). We assume that the government may ask users to share some or all of the cost of the program through a user fee p.

Private Demand

Vaccines reduce a person's risk of infection.[4] As with other goods and services, people value the risk reductions obtained from vaccination differently. Some may place little value on the vaccine because they feel that the disease itself is not serious or dangerous. Some may place a very high value on the vaccine because they believe their risk of infection is high, either because the disease is very prevalent in their community and/or because their behavior puts them at higher risk. Others may have had a case or death in their families and know the pain and suffering firsthand. Some people may be more risk-averse than others (or less able to cope with

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[3] Although a dynamic model would be of great interest, a credible model would need data on how demand changes with prevalence over time (data not currently available). Also, demand in the first period may in fact be more representative of the true private economic benefits because prospective purchasers might be less likely to take into account the potential for indirect protection when they make their decision to purchase the vaccine.

[4] Unlike an SIR framework, we assume that everyone who is infected with the contagion contracts the illness.

the financial costs incurred if they fall ill). Others might be primarily concerned with reducing their risk of dying: In one stated preference study in Beira, Mozambique, 54 percent of respondents told researchers that reducing their risk of dying from cholera was the most important benefit of vaccination (28 percent reported avoiding "pain and suffering," and only 18 percent cited avoided treatment costs or lost wages) (Lucas et al., 2007).

We assume individuals will maximize their utility subject to a budget constraint. The utility function might have arguments for any or all of the above considerations, and the budget would constrain spending on the vaccine as well as all other non-vaccine expenditures (including other risk reduction strategies) to the individual's income and assets. Unfortunately, there are few empirical data on how private demand for vaccines is affected by most of the factors in the preceding paragraph.

Rather than focus on the analytical details of this utility maximization framework, we assume that agents are rational decision makers (perhaps using a health production function approach [Grossman, 1972]), and move straight to an observable Marshallian demand relationship. We restrict the arguments of the function to only two parameters: the user fee (p) and incidence (I) of the disease. The probability that an individual will choose to be vaccinated is:

$$P(p, I) = Pr\ (\text{Vacc} = 1 |\ p,\ I) \tag{1}$$

In a population with homogenous preferences for vaccines, this will also correspond to the fraction of the population that chooses to be vaccinated, or the "coverage rate."

The demand function $D(p, I)$ maps user fees and incidence levels to the total number of people vaccinated by multiplying this coverage rate with the population size N:

$$D(p, I) = N \cdot P(p, I) \tag{2}$$

Where would one find these Marshallian demand functions? We begin by focusing only on estimating $D(p, \cdot)$, or the relationship between price and demand, holding incidence constant. Estimating $D(p, \cdot)$ from revealed-preference market data would require that some nonzero price was charged for vaccines and that these prices varied over time or space. One could then map changes in the quantity of vaccines demanded (or the total coverage rate) to the exogenous price changes and, controlling for other confounders, estimate a demand relationship. However, vaccine user fees are uncommon, especially in developing countries, and policy analysts have so far been unable to find such price variation.

A second approach for estimating $D(p, \cdot)$ is a travel cost approach. Even where vaccines are provided free, users may incur financial travel costs (e.g., fuel or bus fare) as well as the economic costs of time spent traveling to the vaccination site and waiting to be seen. Jeuland, Lucas, et al. (2008) estimate demand and willingness-to-pay for cholera vaccines with a travel cost approach, using data from a vaccine trial and in-person interviews in Beira, Mozambique.

A third option for estimating $D(p, \cdot)$ is stated preference (contingent valuation or conjoint/choice experiment) studies. Stated preference studies have been routinely used in environmental economics for nonmarketed goods or services (see Venkatachalam, 2004, for a useful literature review of the method and its strengths and weaknesses) and have more recently been used for vaccines that are either locally unavailable, for example, a cholera vaccine in Kolkata (see Canh et al., 2006; Cook et al., 2007; Lucas et al., 2007; Islam et al., 2008; Kim et al., 2008; Whittington

et al., 2008), or have not yet been invented (for example, an HIV/AIDS vaccine—Whittington, Pinheiro, & Cropper, 2003; Cropper et al., 2004; Suraratdecha et al., 2005).

In these stated preference studies, respondents are first asked a series of questions about their knowledge and perception of the disease and then informed about the properties of the vaccine, including the vaccine's effectiveness in protecting them from the disease. In contingent valuation (CV) surveys, respondents are asked how many vaccines they would purchase (for themselves and their household members) if the vaccine were available at a convenient location at a price of p. By varying p randomly across respondents, these data allow researchers and policymakers to map $D(p, \cdot)$. Conjoint, or choice experiment, studies map $D(p, \cdot)$ by asking respondents to make repeated choices between two or more different vaccine alternatives that differ in terms of their attributes (see Sur et al., 2006, and Cook et al., 2007, for two examples).

There are fewer tools for identifying the effect of incidence rates on demand in the demand function $D(p, I)$. Several studies have estimated this prevalence elasticity for flu and measles vaccines with panel data, observing the effect of lagged incidence on vaccine uptake (Li, Norton, & Dow, 2004; Mullahy, 1999; Philipson, 1996) and for condoms and HIV (Ahituv, Hotz, & Philipson, 1993, 1996). Longitudinal, rather than cross-sectional, travel cost or stated preference studies, could theoretically estimate $D(\cdot, I)$ if incidence changed over time, although we know of no such studies. Furthermore, no stated preference studies of private vaccine demand have varied baseline incidence levels as part of the information treatment. It would be difficult to convey this information in a household questionnaire, and unethical to mislead respondents about their baseline risk of infection. For the remainder of the paper, we will rely on demand functions estimated using data from stated preference studies where respondents were asked about a vaccine that was *Eff* percent effective in protecting them and were not told about the possibility of indirect protection. Because these studies provide no information on prevalence elasticity, we will restrict prevalence elasticity to zero and drop that argument from the coverage function and the demand function for notational simplicity.

Epidemiology and Herd Protection

In the absence of indirect (herd) protection, *Eff* represents the probability that a vaccinated individual will be immune to the disease. This "direct protection" is independent of coverage rates, and unvaccinated persons experience no reduction in their chances of contracting the disease, regardless of coverage. The duration of the vaccine's effectiveness (in years) is *Dur*.[5] Without indirect protection, the total number of cases avoided in the population is

$$\text{Cases avoided} = Dur \cdot Eff \cdot I \cdot D(p) \qquad (3)$$

Because *Dur*, *Eff*, and incidence (*I*) are constants, the number of cases avoided is proportional to the number of people vaccinated $D(p)$. Because this is a monotonically decreasing function of price, the number of cases avoided decreases as the user fee increases.

When a disease is transmitted primarily from person to person, vaccines will provide indirect protection by reducing the number of susceptible individuals who can spread the disease among both vaccinated and unvaccinated persons. For the illustrative purposes of this paper, we use a simple model of how disease incidence

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[5] Effectiveness may also wane over time, an extension we leave for future work.

changes as a function of coverage for both the vaccinated and unvaccinated individuals. We split the population into two groups (the vaccinated and the unvaccinated) and redefine the vaccine's "effectiveness" (probability of protection from infection) as a function of coverage rates. The function $U[P(p)]$ maps coverage rates into the probability that an unvaccinated person will be protected. Reducing the number of susceptibles in the population may also increase a vaccine recipient's effective protection (where the vaccine is not 100 percent effective); we call this protection to the vaccinated $V[P(p)]$. In the presence of herd protection, we replace the term *Eff* in equation (3) with the functions $V[\cdot]$ and $U[\cdot]$, to obtain the number of cases avoided per year:

Cases avoided per year $= [CA_{\text{vacc}} + CA_{\text{unvacc}}]$

$$= [V[P(p)] \cdot P(p) \cdot N \cdot I + U[P(p)] \cdot (1 - P(p)) \cdot N \cdot I] \quad (4)$$

Equation (4) implies that cases avoided per year are constant. It is possible, however, that cases avoided may change over time because (a) the vaccine's efficacy wanes and/or (b) the probability of disease transmission changes.

Economic Benefits

A policy analyst using an economic efficiency criterion to design a vaccination policy would seek to maximize the present value of total social economic benefits net of social costs. The demand function $D(p)$—estimated in a stated preference survey in our example—characterizes the marginal private benefits. That is, $D(p)$ evaluated at some price p_i is equivalent to the private value of the vaccine to those people who would just choose to acquire it at a price p_i or lower. The total private benefits (or willingness-to-pay) that accrue to people who chose to be vaccinated at a price of p_i are their expenditures on the vaccine (shown in brackets in equation (5)) plus their consumer surplus, which is the area under the demand curve between p_i and ∞ (or, alternatively, up to some maximum "choke" price p^c).[6]

$$\text{Private Benefits from Vaccination } (WTP_{\text{vacc}}) = [p_i \cdot D(p_i)] + \int_{p_i}^{\infty} D(p)dp \quad (5)$$

This WTP measure is comprehensive and includes respondents' expectations about reductions in mortality risk, privately borne treatment costs, pain and suffering, etc.[7] These benefits need not be discounted explicitly to obtain present values: We assume respondents discounted the benefits from the vaccine that would accrue over the years the vaccine is effective (*Dur*) in their WTP responses.

The total *social* benefits that accrue when $D(p_i)$ individuals are vaccinated have several additional components. If the public sector provides free or subsidized treatment for cases of the disease, society will benefit from reducing these public expenditures for

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[6] This is, of course, uncompensated demand; the correct welfare-theoretic measure of benefits would be the compensating variation, or the area under the Hicksian compensated demand function. Because expenditures on vaccines are likely to be a small part of the consumer's budget, we use the common assumption that income effects are small and Marshallian CS is a good approximation for Hicksian CV.

[7] Because the severity of the disease will usually depend on unobservable characteristics, neither respondents nor survey interviewers will know expected private treatment costs avoided with certainty.

each case avoided in both the vaccinated (CA_{vacc}) and unvaccinated (CA_{unvacc}). We refer to these social benefits as the public cost-of-illness avoided (*PubCOI*):

$$\text{Public COI Avoided} = \sum_{t=0}^{Dur-1} [PubCOI \cdot (CA_{vacc} + CA_{unvacc})/(1 + r)^t] \tag{6}$$

Because some of these social benefits accrue in the future, we discount them over the duration of the vaccine at a constant real rate of *r* to obtain present values.

We know that individuals who choose *not* to purchase the vaccine at p_i have marginal private benefits less than p_i. They may, however, still value the risk reduction that they receive through indirect protection, and these private benefits to the *unvaccinated* should be included in the total social benefits of the program. Because we cannot use their answers to the contingent valuation survey to estimate these benefits,[8] we add two categories of private benefits as constant values per case avoided in the unvaccinated: privately borne costs of illness and avoided mortality risk.

Private costs of illness might be both financial (that is, drugs, doctor visits, lost wages) as well as economic (opportunity cost of time spent waiting or caretakers' time). We assume this is an average (*PrivCOI*) per case avoided. We value reductions in mortality risk using a value-of-statistical-life calculation (*VSL*). We assume an average VSL for the entire population,[9] and multiply this by the case fatality rate (*CFR*), or the probability that a person who contracts the disease will die from it. The present value of the private benefits that accrue to the unvaccinated are therefore

$$\text{Private Benefits to Unvaccinated:} \sum_{t=0}^{Dur-1} [((PrivCOI + (VSL \cdot CFR)) \cdot (CA_{unvacc})]/(1 + r)^t \tag{7}$$

Thus far our approach has been to measure private benefits to the vaccinated (at p_i) using the private demand relationship and to measure social benefits by assuming constant values per case avoided through indirect protection. Recall, however, that stated preference surveys typically ask respondents about their WTP for a vaccine with one given efficacy (say, 50 percent). At high coverage levels, their effective protection—$V[P(p_i)]$—may actually exceed *Eff* (say, 80 percent), and the respondents' answers would not reflect the value of this higher level of protection unless respondents know about herd protection effects or are explicitly told about them in the contingent valuation scenario. Respondents may not have misunderstood the scenario; the stated preference survey simply did not measure WTP across

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[8] Why not simply use the area under the demand curve between 0 and p_i as the measure of private benefits to the unvaccinated? Suppose that respondents are told in a SP scenario that the vaccine will be 50 percent effective. Assume at p_i, 40 percent of the population choose to be vaccinated, conferring effective protection to the unvaccinated ($U(D(p_i))$) of 22 percent. To use this information, we would need to scale WTP to account for the difference between the 50 percent protection offered to respondents in the CV survey and the (say) 22 percent indirect protection the unvaccinated receive. One promising strategy for measuring the tradeoff between WTP and effectiveness is the use of conjoint/choice experiments where effectiveness is one attribute (see Cook et al., 2007; and Sur, Cook, et al., 2006).
[9] The average VSL may change, though, as one moves along the demand curve since those who place a higher value on reducing mortality risk will be more likely to purchase the vaccine (increasing the average VSL accruing to the unvaccinated as *p* increases). It may be that the unvaccinated have a lower VSL, on average, than the vaccinated.

a sufficiently wide array of effective protection levels.[10] We remedy this by applying the same private values per case avoided as described above (*PrivCOI + VSL * CFR*) to the additional cases avoided from effective protection levels larger than *Eff*:

$$\sum_{t=0}^{Dur-1} [(PrivCOI + VSL \cdot CFR) \cdot ((V[P(p_i)] - Eff) \cdot D(p_i) \cdot I)]/(1 + r)^t \quad (8)$$

Combining equations (5)–(8) gives the total social benefits of the cholera vaccination program. The first line of equation (9) describes private benefits to the vaccinated based on Marshallian demand (from responses to the stated preference survey) and the private benefits that accrue to the unvaccinated from indirect protection; the second line describes public sector cost-of-illness savings from avoiding all cases; and the third describes the private benefits that accrue to the vaccinated when the effective protection is larger than individuals beliefs about vaccine effectiveness.

$$\text{Total Social Benefits} = (p_i \cdot D(p_i) + [\int_{p_i}^{\infty} D(p)dp + \sum_{t=0}^{Dur-1} [(PrivCOI + VSL \cdot CFR) \cdot CA_{\text{unvacc}}$$

$$+ (PubCOI \cdot (CA_{\text{vacc}} + CA_{\text{unvacc}})$$

$$+ ((PrivCOI + VSL \cdot CFR) \cdot (V[P(p_i)] - Eff) \cdot D(p_i) \cdot I]/(1 + r)^t) \quad (9)$$

Finally, another potential source of social benefits that individuals do not account for in their private valuations may be macroeconomic-scale benefits from vaccination including higher educational achievement (Miguel & Kremer, 2004), increased labor productivity, or increased tourism. These effects are difficult to measure for any one additional vaccination program but may be quite large in aggregate (Bloom, Canning, & Weston, 2005). However, we omit them from our model.

Costs

For simplicity, we assume here that the vaccination program has constant marginal costs. We assume that there are no fixed set-up costs, resulting in constant average costs and no economies or diseconomies of scale in vaccination. The total economic cost of manufacturing, transporting, storing, and administering the full course of the vaccination (for multiple-dose vaccines) is a constant *C* per fully immunized person. These costs are present values: All costs are incurred in the first year.

$$\text{Social Costs} = C \cdot D(p_i) \quad (10)$$

Optimal Policies

The economic efficiency criterion is to maximize net economic benefits (total social benefits [equation (9)] less total social costs [equation (10)]). By taking the derivative

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[10] Note that this correction (equation [8]) would not be necessary if demand and WTP were measured over a range of vaccine efficacies that included all possible effective protection levels.

of this expression with respect to price and setting it equal to zero, we can find the optimality conditions that yields $p*$, or the socially optimal user fee. This will occur when marginal social benefits are set equal to marginal social costs (this expression is provided in the online appendix[11]). The next section demonstrates both well-known and less-well-known policy implications of these types of optimality conditions.

OPTIMAL VACCINE SUBSIDIES: A GRAPHICAL APPROACH

Figure 1 depicts a demand curve $D(p)$, which also represents the marginal private benefits (the change in total private benefits of vaccinating one more person). In Figure 1, some percentage of the target population $(N - Q^m)$ place no private value on the vaccine. They might be indifferent between taking and refusing a vaccine with zero price, or might in fact place negative value on the vaccine if they were concerned about side effects, time costs, or travel expenses to obtain the vaccine. In a competitive private market, vaccines would be sold at the price that equates the marginal cost (MC, assumed to be constant in Figure 1) with the marginal private benefits. This maximizes total private net benefits and occurs at point X; Q^o people choose to be vaccinated at this market price P^o.

Because of indirect protection, however, each additional vaccinated person reduces the risk for the remaining unvaccinated population. The shape and location of the marginal social benefits (MSB) curve depends on the epidemiology of the disease as well as the magnitude of the social benefits. The marginal social benefits curve shown in Figure 1 is illustrative only and is not based on empirical data.

The economically efficient solution from society's standpoint occurs at point Y where MC is equated with marginal social benefits. To reach the optimal number of vaccines $Q*$ in the private market, the government must offer a Pigouvian subsidy $s = P^0 - P*$. The gain in social surplus (net economic benefits) from lowering the fee to $P*$ is the shaded area C.
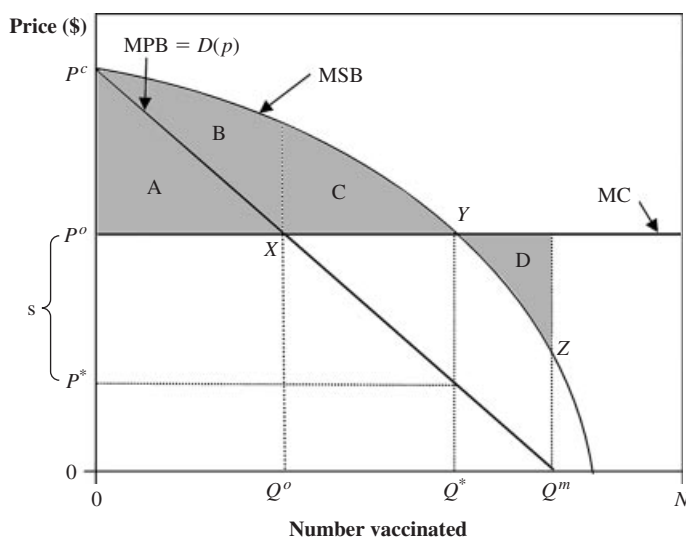

Figure 1. Subsidy $(P^o - P*)$ is optimal; vaccines at zero price may be a preferable second-best alternative.

Suppose, however, that policymakers cannot measure or identify the marginal social benefits. The government (or donor) might then decide that rather than guessing at the optimal subsidy, it will provide vaccines at zero price as a second-best solution. The number of people who would choose to be vaccinated will be Q^m. Because the MC of vaccination is larger than the MSB for every person vaccinated above Q^*, the welfare of individuals in society will be reduced (relative to the optimum) in the amount equal to the shaded area D. Providing vaccines for free is a better second-best solution than selling them at market price when area C is greater than area D (as depicted in Figure 1).

A related but different question is whether a program that provides vaccines at zero price will provide positive net economic benefits. This will be the case when the total social benefits (the entire area under MSB to the left of Q^m, or the area bounded by the origin -Q^m-Z-P^c) exceeds the total social costs of providing the vaccines (the rectangular area equal to $P^o * Q^m$). This is the case in Figure 1 (area A + B + C is greater than area D). If the MC curve were shifted upward, as in Figure 2, the total social benefits could be less than total social costs (area A + B + C is much smaller than area D). A zero-price vaccination program would then fail a cost-benefit test and would be a wasteful use of health resources.

If a second-best vaccination program with a zero vaccine price failed a benefit-cost test, a common reaction might then be to abandon the use of the vaccine, but such a conclusion misses an important point. Some fraction (Q^o people) place a high value on the vaccine and are willing to purchase it at the market price. Although it is easy to assume that this is simply a high-income subset of the population, these individuals may in fact be poor but have more experience with the disease, have a high perceived risk of being infected, or have other sound reasons for wanting to be vaccinated. If health decision makers were to prevent the vaccine from being sold at marginal cost (through either the public or private sector), Q^o people would not have the opportunity to purchase the vaccine, resulting in forgone private benefits equal to area A and additional forgone social benefits equal to area B (Figure 2). When marginal costs are constant, selling the vaccine at a price equal to marginal cost will always be preferable to not selling the vaccine at all.
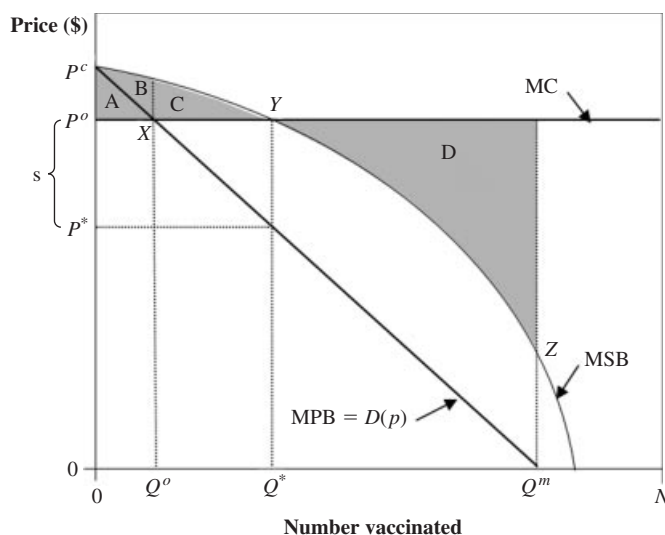

Figure 2. Vaccines at zero price do not provide positive social net benefits.

It is also possible that selling vaccines at marginal cost would be preferable to providing the vaccine for free. Suppose a large fraction of the population places a high value on the vaccine, but that private demand then drops off fairly quickly. In addition, suppose that the herd protection effect was large, at modest coverage rates: Once a relatively small number of people are vaccinated, the disease incidence drops quickly and the number of infected is very low (although the number of susceptibles may still be high). In this case, when vaccines are sold at marginal cost, there is sufficient private demand to reach some critical level of coverage that confers large indirect protection to the remainder of the population. This situation is represented in Figure 3, where the social loss from providing vaccines for free (area D) is much larger than the social gain (area C). In this case, if the correct subsidy (*s* in Figure 3) cannot be identified, selling vaccines at the market price would be a better second-best solution than providing them for free.

Figure 4 shows a different situation, where the marginal herd protection benefits are large even at high coverage rates. Here, only a subsidy larger than MC (that is, $P^* < 0$, or positive payments to the vaccinated) can induce the socially optimal number of people Q^* to be vaccinated, shown in Figure 4 by extending the vertical axis below zero (Hemenway, 1994). Selling vaccines at the market price is clearly not the preferable second-best solution because MSB are larger than MC even at Q^m (area C_1). An important question might be whether a program with free vaccines (with Q^m vaccinated) is a preferable second-best to a program that would provide additional monetary or nonmonetary incentives for people to be vaccinated (including compulsory programs or conditional cash transfer programs like Mexico's Progresa [Lagarde, Haines, & Palmer, 2007]). Inducing between Q^m and Q^* people to be vaccinated would result in social welfare gains equal to the area C_2, but inducing more than Q^* people to vaccinate would incur welfare losses equal to area D. This type of program would be the preferable second best when $C_2 > D$.

The common assumption that the provision of free vaccines is always socially optimal (or a preferable second-best solution) is unwarranted on economic efficiency grounds, and in some cases may lead to unwise use of scarce health resources. Knowing which of these situations apply for a given vaccine in a given location is
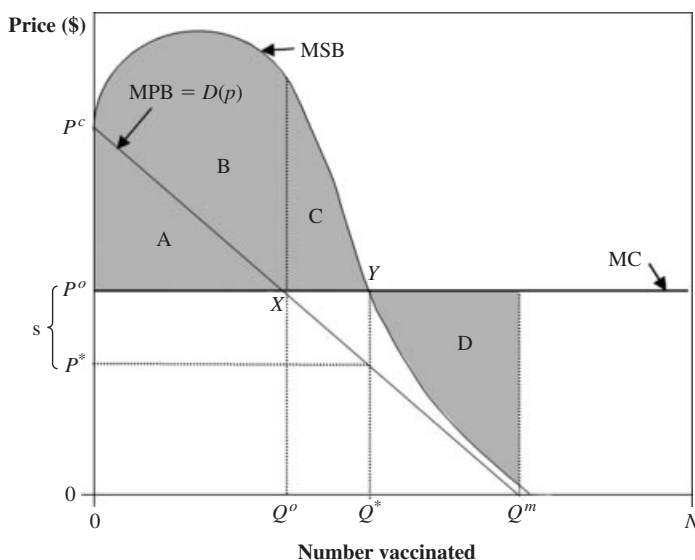

Figure 3. Selling vaccines at full m is the preferable second-best solution.
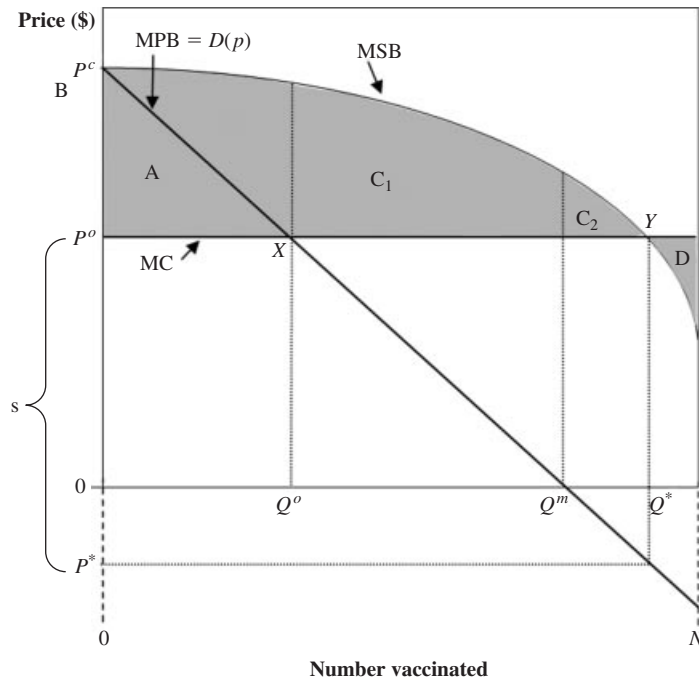
Figure 4. Inducing higher levels of vaccination with incentives or compulsion is the preferable second-best solution.

an empirical question. The remainder of the paper demonstrates an empirical framework for determining which "state of the world" exists in a specific policy context.

APPLICATION—CHOLERA VACCINATION IN TWO SLUMS IN KOLKATA, INDIA

Cholera

Cholera is a water-borne bacterial disease characterized by intense, watery diarrhea. It is easily treated by quickly rehydrating the patient with intravenous fluids; antibiotics are generally unnecessary and ineffective (Schaecter et al., 1998; Todar, 2006). Cholera can kill a patient within 24–48 hours, though in practice cases are rarely fatal as long as patients have access to IV rehydration (estimates of the case fatality rate are on the order of 1 percent with adequate access to treatment[12]). For the purposes of this paper, we will focus on endemic cholera, where cases occur nearly every year. One approach to controlling endemic cholera is the use of oral cholera vaccines. We model the use of a Vietnamese-produced version of the Dukoral (WC-rBS) vaccine that lacks the B-subunit (see online appendix[13] for more information on cholera and oral cholera vaccines).

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[12] According to the WHO's monitoring of cholera cases (World Health Organization [WHO], 2006), there were 131,943 cholera cases worldwide and 2272 deaths, for a gross worldwide case fatality rate of 1.7 percent. Worldwide CFR from same source is 2.3 percent. This average, however, reflects wide differences in access to treatment: Naficy et al. (1998) use a CFR of 1 percent for treated cases but 30 percent for untreated cases. CFRs may also differ by age: Murray, McFarland, & Waldman (1998) use 0.7 percent for children under five years old but a much lower CFR (0.14 percent) for children over age 5 and adults.
[13] This appendix is available at the end of this article as it appears in JPAM online. Go to the publisher's Web site and use the search engine to locate the article at http://www3.interscience.wiley.com/cgi-bin/jhome/34787.
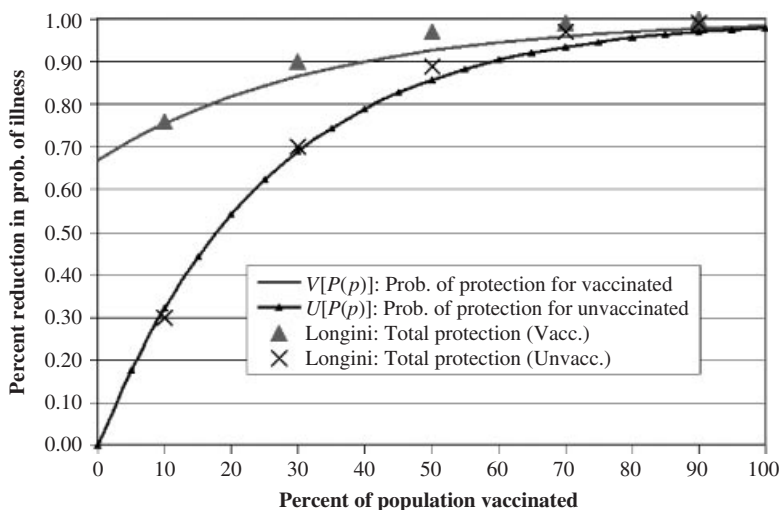
Figure 5. "Effective protection" for vaccinated and unvaccinated individuals based on data from Ali et al. (2005), plotted along with SIR predictions from Longini et al. (2007).

Evidence for Herd Protection from Oral Cholera Vaccines

We estimate the direct and indirect effects of vaccination using data from a recent re-examination of a large cholera vaccine trial in Matlab, Bangladesh, in the 1980s (Ali et al., 2005). Ali et al. found that as the percentage of vaccinated residents in a neighborhood increased, the incidence of cholera among the unvaccinated decreased. We model the Ali et al. results using a set of two differential equations to estimate $V[P(p_i)]$ and $U[P(p_i)]$, or the effective protection of the vaccinated and unvaccinated as a function of the percentage of the population vaccinated. This model is described in more detail in the online appendix, and the resulting predictions are shown in Figure 5. Our predictions are very similar to ones from a recent paper by Longini et al. (2007) in which the authors applied a state-of-the-art SIR epidemiological model to the same Matlab dataset (their predictions are also shown on Figure 5). We were unable to directly use Longini et al.'s results because the paper reported predictions at only five vaccination coverage levels and our model requires a continuous function between coverage and protection.

Private Demand, Economic Benefits, and Costs

We selected two urban slums in Kolkata, India, as the site for the illustration of our cost-benefit calculations because of the wealth of new economic data on cholera collected there. With a combined population of 185,000 people, the Tiljala and Narkeldanga slums are both impoverished, densely crowded cholera-endemic neighborhoods with some of the world's highest prevalence rates. We use data that have been recently collected in Kolkata on (1) the private economic benefits of cholera vaccines (Whittington et al., 2008), (2) baseline prevalence and vaccine cost data from a recent cholera vaccine trial that involved pre-vaccination surveillance (Deen et al., 2008; Sur et al., 2005; Lauria & Stewart, 2007), and (3) public and private cost-of-illness collected as part of the disease surveillance activities (Poulos et al., 2008).

Private Benefits

Our data on private demand and private economic benefits come from a contingent valuation survey that several of the authors carried out in 2004 in Tiljala and Beliaghata, a middle-class neighborhood (Whittington et al., 2008). We asked respondents about their willingness-to-pay for a cholera vaccine that was 50 percent effective and would protect them for three years. Specifically, we asked them how many cholera vaccines they would purchase for themselves and their household members if the price were one of four randomly assigned prices. We analyzed these count data as a function of price, income, and other socioeconomic characteristics, using a negative binomial regression model (see Whittington et al., 2008, for a more complete description of the econometric approach). We gave respondents in Beliaghata overnight to think about their answers to reduce any interviewer bias or yea saying.

We model private demand from Tiljala as an exponential function with two parameters, a constant ($a = 0.65$, or 65 percent) representing the fraction of the total population that would be covered if the vaccine were provided free, and a slope parameter ($b = -0.28$) representing the response to price. The constant incorporates the effect of other important covariates such as income, education, and experience with cholera on demand, independent of price (see Whittington et al., 2008, for more detail on the econometric analysis). As a point of reference, a cholera vaccine trial started in Narkeldanga in 2005 (and ongoing) achieved an overall population coverage rate of 62 percent (Lopez, 2007). Although coverage was boosted by significant publicity, it may have been suppressed by the fact that extensive consent forms were required and participants knew that they had a 50 percent chance of receiving a placebo.

$$\text{Coverage levels} = P(p) = a \cdot \exp(b \cdot p) \tag{11}$$

$$\text{Total number vaccinated} = D(p) = N \cdot a \cdot \exp(b \cdot p) \tag{12}$$

Vaccination Costs

The social cost of a cholera vaccination program is composed of three main components: (1) the cost of acquiring vaccines from the manufacturer, (2) the cost of delivering and administering the vaccine to the target population, and (3) the time and pecuniary costs incurred by household members to travel to the vaccination outpost and to wait to receive the vaccine. For acquisition cost, we assume vaccines can be purchased from manufacturers for US$0.50 per dose (DeRoeck, 2008). Preliminary estimates from Vietnam suggest that production costs could be as low as US$0.40 per dose (Thiem et al., 2006). We add 15 percent for customs, shipping, and insurance, and assume 10 percent wastage of vaccines, making the total vaccine acquisition cost about US$0.63 per dose.

We base our estimates of vaccine delivery costs on Lauria and Stewart's 2007 literature review of 22 vaccine cost studies in low- and middle-income countries. Their best estimate for delivery cost in a low-income country like India is US$0.5 per dose (see Lauria & Stewart, 2007; and Jeuland, Clemens, et al., 2008, for a detailed discussion of cholera vaccine delivery costs). There may be economies (or diseconomies) of scale in vaccination such that average delivery costs fall (rise) as the number of people vaccinated increase. Because there is little data available to reliably estimate this relationship, however, we prefer the simplicity of a constant marginal delivery cost measure.

To capture the time and pecuniary costs of traveling and waiting, we assume that every vaccine recipient walks 10 minutes each way to a nearby clinic (no financial transportation costs), where he or she spends 20 minutes waiting to be vaccinated.

We value this time equally for adults and children at one-half the median hourly wage among our respondents in Tiljala (US$0.18). The economic costs of traveling and waiting to be vaccinated is, therefore, US$0.06 *per dose* (0.67 hrs * US$0.09/hr).

The total social cost of providing the cholera vaccine is ~US$1.2 per dose ($0.63 acquisition + US$0.5 delivery + US$0.06 traveling/waiting). Because immunization against cholera requires two doses, the total cost per vaccinated person is about US$2.4. None of the three components of vaccine cost are known with a great degree of certainty; this estimate is our best approximation for the purposes of this paper.

Cost-of-Illness

Before the cholera vaccine trial began in Narkeldanga, NICED and IVI conducted an extensive passive surveillance study in the neighborhood. Patients who presented with cholera symptoms at program health clinics provided stool samples for laboratory confirmation (Deen et al., 2008, Sur et al., 2005). Lab-confirmed cases were then asked to participate in a study examining the privately borne costs of illness associated with their illness with cholera (Poulos et al., 2008). These household surveys covered direct financial costs (transportation, medicines, doctor fees, overnight stays, under-the-table payments, etc.) as well as direct and indirect economic costs (lost wages for patient and caretaker, value of time away from school for children). Poulos et al. (2008) found average private COI to be US$5.3 for cases in children and US$6.5 for adult cases. Because our model does not distinguish between adult and child cases, we use a weighted average of US$5.5 because incidence is six times higher in children (Deen et al., 2008).

The publicly borne cost-of-illness was estimated based on reported expenditures for treating 102 cholera cases at two Kolkata public hospitals, Kolkata's Infectious Diseases and Beliaghata General Hospital. Poulos et al. (2008) found average public COI to be approximately US$15 for child cases and US$16 for adult cases. We use US$15 for our analysis.

Value-of-Statistical Life

Estimates of the value of a statistical life (VSL) are now available for a number of less developed countries.[14] We extrapolate data primarily from two recent studies in Delhi, India (Bhattacharya, Alberini, & Cropper, 2007), and Matlab, Bangladesh (Maskery et al., 2008). Both studies estimated VSLs in the range of US$30,000 to US$100,000 using stated preference techniques. Two other studies in India used a labor hedonic approach (Shanmugam, 2001; Simon et al., 1999) and found much higher VSLs (US$370K–US$1.4M). We use an estimate of US$50,000 because incomes are low in these two slums.

Other Parameters

Table 1 summarizes the parameters used for the illustrative economic calculations. We use a (real) discount rate of 8 percent that reflects the high opportunity cost of capital to poor households. We assume that the information campaign would be sufficiently large that everyone in the two targeted slums would have heard about the availability of vaccines. We use an overall population incidence of 1.64 cases per 1000 per year based on the pre-trial surveillance study done in Narkeldanga (Deen et al., 2008).

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[14] It is theoretically possible to calculate a VSL from the Kolkata vaccine stated preference study. We have less confidence in this calculation, although it gives us values in the same range as Maskery et al. (2008) and Bhattacharya, Alberini, and Cropper (2007); for more information, see the appendix at the end of this article as it appears in JPAM online. Go to the publisher's Web site and use the search engine to locate the article at http://www3.interscience.wiley.com/cgi-bin/jhome/34787.

Table 1. Parameter values for two neighborhoods in Kolkata, India.

Parameter	Value
Population	185,000
a. Coverage (percent) at zero price	65 percent
b. Response to price	−0.28
Incidence (per 1000)	1.64
Case fatality rate	1 percent
VSL	US$50,000
Discount rate	8 percent
Marginal cost per person	US$2.4
Average private COI per case	US$5.5
Average public COI per case	US$15

RESULTS

Total private net benefits are maximized when the user fee is set to the full marginal cost of US$2.4 per person immunized. At this fee, a relatively small percent of the population (33 percent, or 61,000 people) would be covered. This can be seen in Figure 6 as the intersection of MC and MPB or in Figure 8 as the maximum of net private benefits (solid black lines in both graphs). Because of herd protection, however, we estimate that this level of vaccination would avoid 237 of the 303 annual cholera cases (78 percent) in the two slums. Of these 237 cases avoided per year, 149 are among the unvaccinated.

Total social net benefits of the vaccination program are maximized at a price of US$1.8 per fully immunized person. The implied subsidy of US$0.6 increases coverage to 39 percent, preventing an additional 16 cases per year. At this optimal fee, the total social benefits of the program are US$672,000. Most of the total social benefits come from private benefits to the vaccinated (WTP$_{vacc}$) and from reducing mortality risk in the unvaccinated (Table 2). Because both public and private costs-of-illness per case are low, these categories of benefits do not contribute much to the overall total benefits. The conclusions are not sensitive to different parameter estimates for costs-of-illness (for example, the optimal subsidy only changes from $0.58 to US$0.63 when public and private cost-of-illness per case are doubled). If we use a VSL estimate of $25,000 (half our base case estimate), however, the optimal subsidy falls to US$0.40 (coverage = 37 percent). With a VSL estimate of $100,000, the optimal subsidy would be US$0.75 (coverage = 41 percent).

What if the government or donors did not have access to these estimates of optimal p^* and coverage rates, and decided to provide the vaccine for free? First, such a program would probably produce net economic benefits. If vaccines are provided free of charge, we expect that 65 percent of the population would be vaccinated (the right-most point on the x-axis of Figures 6–8, which corresponds to Q^m in Figures 1–4) at a financial cost to the government of US$272,000. The program would prevent 286 cholera cases per year, or 94 percent of the cases expected to occur without vaccination.

How would the welfare loss associated with providing the vaccine for free compare to the social gain associated with increasing coverage above the market outcome of 33 percent (that is, can we compare the size of area D with area C in Figures 1–4 to determine whether selling at market price or providing vaccines for free is the preferable second best)? The total net social benefits at the market outcome (p = $2.4, coverage = 33 percent) are US$498,000 (area A + B). At the socially optimal price of p^* = 1.8 per person and coverage of 39 percent, total social net benefits are US$492,000 (area A + B + C). This makes area C equal to US$6,000, or the
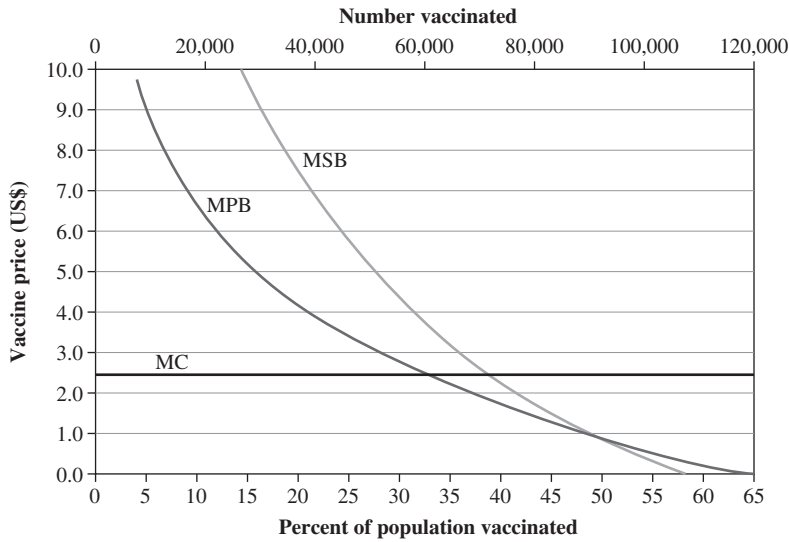
Figure 6. Marginal social benefits vs. marginal social costs of cholera vaccines in two slums in Kolkata, India.
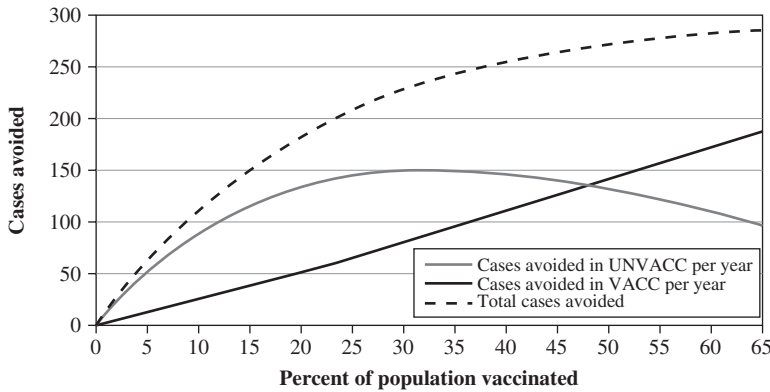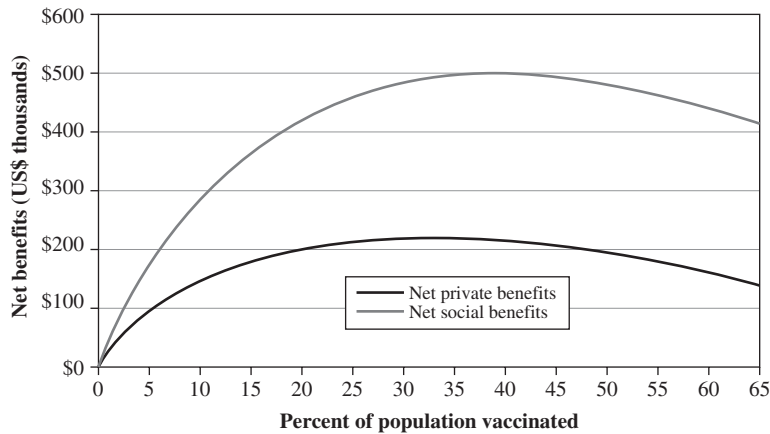

Figure 7. Cases avoided with increasing coverage.

Figure 8. Net private and social benefits.

Table 2. Decomposing total social benefits (at p^* = US$1.8).

Benefits	US$ (Thousands)
Private benefits for the vaccinated (WTP$_{vacc}$, equation [5])	$390
Public COI avoided (vaccinated and unvaccinated, equation [6])	$10
Private COI avoided among the unvaccinated (equation [7])	$2.2
Value of mortality risk reduction to the unvaccinated (unvaccinated, equation [7])	$203
Private COI + VSL (vaccinated for *Eff* > 50 percent, equation [8])	$67
Total Social Benefits	$672

additional private and social net benefits of increasing coverage from 33 percent to 39 percent. For each person over 39 percent vaccinated, however, social costs now exceed the social benefits. With no user fee, 65 percent of the population is vaccinated, and the total social net benefits are $416,000. Area D is therefore $76,000 (US$492,000 – US$416,000), much larger than area C. In this example, with this specific set of parameter values and with our assumed herd protection relationship, the preferable second best is to sell vaccines at market price rather than provide them free. This conclusion that a policy of selling vaccines at marginal cost is preferable to a policy of providing free vaccines is reinforced when one considers the financial feasibility of the two polices. Providing free vaccines requires finding the financing for a US$272,000 program in two neighborhoods when budgetary resources for health in India are very limited. On the other hand, a policy of selling vaccines at marginal cost is revenue neutral; it pays for itself.

DISCUSSION

We begin with the limitations of our approach. First, most of the parameters involved are not known with certainty, and a careful policy analysis would examine how sensitive our conclusions are to that uncertainty. Second, although we believe our epidemiological framework is a useful approximation, an agent-based SIR model would be preferable for policy analysis of indirect effects. Third, we have extrapolated the epidemiological effects observed in rural Bangladesh to urban Kolkata. On the one hand, one might think that indirect protection effects would be higher in a densely crowded urban area with more possibilities for interaction with infected patients. On the other hand, the control groups in Matlab lived in patrilineally related clusters (*baris*) where contact may actually be higher. Again, one would like to compare policy results using different specifications of the herd protection function to account for this uncertainty.

Finally, a dynamic model would have cholera vaccinations occur every three years or continuously through time where each member of the population would need to renew protection periodically. If we could identify prevalence elasticity, we could model how demand changes over time as direct and indirect protection lowers incidence. One might find a cyclical pattern where demand is high initially but falls as cases disappear. This might continue until a point where a sufficient number of people are neither vaccinated nor have acquired immunity from previous infection and an outbreak occurs. This would drive demand back up in subsequent periods and repeat the cycle. In this respect, future research might incorporate *perceptions*

of prevalence, rather than assuming that the population accurately knows actual prevalence in the community.

Some in the health sector may not find this approach compelling. Cholera affects the poor, they might argue, and we simply should not be charging people user fees for vaccines, regardless of what is the social optimum. We understand that society may view vaccines as a special class of merit goods, one that everyone should have a right to, regardless of ability or willingness to pay for them. Donors may well view vaccines against a disease that afflicts people living in unhygienic conditions beyond their control as a moral obligation—or simply as a good gift. Some donors, though, will still be concerned that their resources are used in the most economically beneficial manner for both health and non-health projects. They might also view their role as catalyzing health improvements in the short run while expecting that local governments will eventually take over financial responsibility for programs (Global Alliance for Vaccines and Immunization [GAVI], 2004).

From this perspective, our analysis of costs and benefits of cholera vaccination in these two slum neighborhoods in Kolkata illustrates some important points. These neighborhoods are both very impoverished and have some of the highest cholera incidence rates in the world. Using the private benefit estimates arising from our stated preference work, a free program would pass a social cost-benefit test. Stated preference estimates remain controversial, however, and many health policy analysts prefer to use either a cost-effectiveness approach or a cost-benefit approach that limits benefits to avoided treatment costs. Using standard techniques in cost-effectiveness analysis, Jeuland, Clemens, et al. (2008) estimate that a free cholera vaccination program in Kolkata would cost ~US$2820 per disability adjusted life-year (DALY) avoided without herd protection, or $830 per DALY avoided with herd protection. These are among the worst half (that is, least cost effective) interventions listed in the Disease Control Priorities Project (see Figure 1 in Laxminarayan et al., 2006). This conclusion is driven largely by the relatively high cost of vaccination, the incidence of cholera (1.64/1000) and the low case fatality rate and cost-of-illness (because cholera cases do not last long and are easily treatable). Using a measure of economic benefits that includes only avoided public and private treatment costs, the social costs ($289,000) would greatly exceed social benefits even with indirect protection [roughly $17,700 without discounting, or 864 cases avoided over three years * ($15 + $5.5)]. We believe that many donors and policymakers would find these economic indicators unattractive. A common reaction among health policy analysts might be to abandon cholera vaccination for Kolkata slums and focus on ensuring adequate treatment capacity when cases occur during the rainy season.

There is, however, middle ground between providing vaccines for free and not providing them at all. From an economic perspective, making vaccines available at full marginal cost (perhaps through government clinics or hospitals or during a mass campaign) would be preferable to not making them available at all. A policy of "market closure" would forgo several hundred thousand dollars of potential economic benefits in these neighborhoods in Kolkata; and it is a common policy response by governments in many developing countries. It is worth emphasizing again that these potential benefits need not accrue only to "rich" households. Our stated preference studies show that income is only one of several determinants of private vaccine demand. Many non-rich households value protection from cholera for themselves and their families highly and are prepared to pay for such protection.

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