Incentives for Reporting Infectious Disease Outbreaks

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ABSTRACT

The global spread of diseases such as swine flu and SARS highlights the difficult decision governments face when presented with evidence of a local outbreak. Reporting the outbreak may bring medical assistance but is also likely to trigger trade sanctions by countries hoping to contain the disease. Suppressing the information may avoid trade sanctions, but increases the likelihood of widespread epidemics. In this paper, we model the government's decision as a signaling game in which a country has private but imperfect evidence of an outbreak. First, we find that not all sanctions discourage reporting. Sanctions based on fears of an undetected outbreak (false negatives) encourage disclosure by reducing the relative cost of sanctions that follow a reported outbreak. Second, improving the quality of detection technology may not promote the disclosure of an outbreak because the forgone trade from reporting truthfully is that much greater. Third, informal surveillance is an important channel for publicizing outbreaks and functions as an exogenous yet imperfect signal that is less likely to discourage disclosure. In sum, obtaining accurate information about potential epidemics is as much about reporting incentives as it is about detection technology.

I. Introduction

What are the incentives for countries to disclose a domestic outbreak of an infectious disease to the rest of the world? On the one hand, countries that report an outbreak may obtain medical assistance from organizations such as the

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World Health Organization (WHO). Such medical assistance could prevent a small outbreak from developing into a full-blown epidemic. On the other hand, reporting may cause trading partners to impose trade sanctions to limit the spread of disease to their borders (Michaud 2003; Brownstein, Wolfe, and Mandl 2006). These sanctions impose large economic costs on the reporting country.[1]

The influence of these twin incentives on reporting should not be underestimated. Consider, for example, the reporting of meningococcal disease during the 1980s. As shown in Figure 1, the number of countries reporting epidemic meningitis (Neisseria meningitis) cases fell dramatically after 1988. Although this may have been due to a fortuitous retreat of the disease, a more likely cause is implicit economic sanctions by Saudi Arabia. Every year, millions of Muslims take a pilgrimage, called the Hajj, to Mecca, Saudi Arabia. In 1987 there was a large outbreak of bacterial meningitis among pilgrims at the Hajj. The next year Saudi Arabia began to bar pilgrims from countries with meningitis outbreaks (Moore et al. 1988; Khan 2003). This is believed to have led to a decrease in the willingness of countries with large Muslim populations to report meningitis outbreaks for fear that their citizens would be prevented from visiting Mecca. Figure 1 supports this belief.

Saudi Arabia also began requiring that all pilgrims be vaccinated, which could have lowered the rate of disease. However, the requirement was not enforced until the early 1990s. Moreover, the vaccine, which costs $55 per person, was unaffordable for countries in sub-Saharan Africa—the so-called "meningitis belt"—that have the highest rate of outbreaks. So the drop in cases is unlikely to be the result of vaccination. This conclusion is buttressed by the surge in meningitis after 1996. Since 1996–97, the International Coordinating Group on Vaccine Provision for Epidemic Meningitis Control (ICG)—an organization established by WHO—has provided subsidized meningococcal vaccines to countries at risk of epidemic meningitis (WHO 2009a). This policy resulted not in a decrease in reported cases—consistent with prevention—but rather in an increase in reported cases—consistent with reporting intended to obtain medical assistance.

In this paper we formalize the basic model of a country's incentive to report an outbreak by modeling the decision as a signaling game. We then extend the model by permitting the country's private information—its domestic surveillance—to be an imperfect indicator for whether there has been a domestic outbreak of disease. This extension yields two interesting insights about sanctions.

First, some trade sanctions encourage truthful disclosure of a country's private information. Trading partners certainly will sanction a country if it discloses evidence of an outbreak. But trading partners also will limit trade with a country that has not reported an outbreak if the country's surveillance is known to produce some false negatives. In that case the sanctions will reflect the risk that the country has

1. For example, when Peru reported an outbreak of cholera in 1991, its South American neighbors imposed an immediate ban on Peruvian food products. The subsequent loss of $790 million in food sales and tourism revenues far exceeded the domestic health and productivity costs of the epidemic. As the Peruvian Minister of Health noted, ". . . nothing compares to the loss of markets [other countries] took away from us in a difficult time" (Panisset 2000, p. 150).

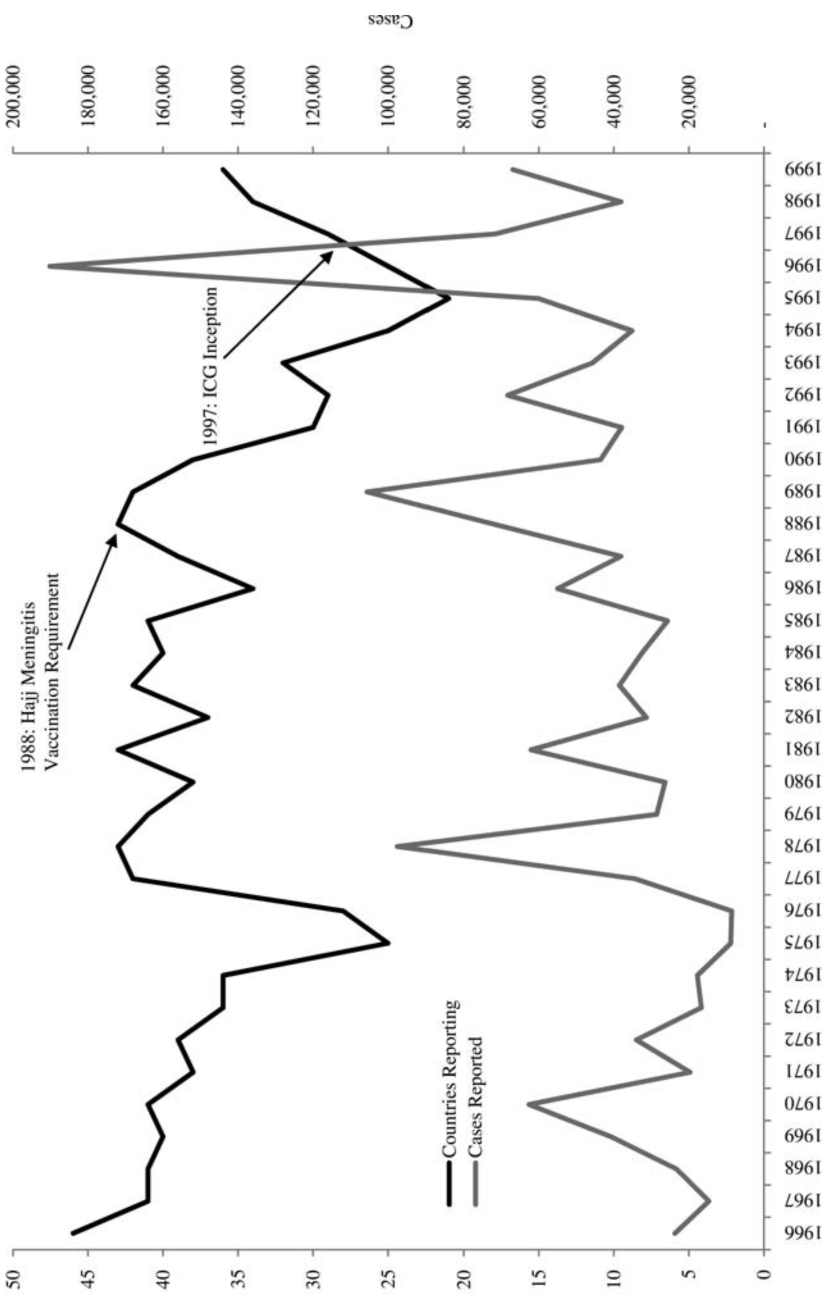

Figure 1
Epidemic meningitis cases between 1966 and 1999

suffered an undetected outbreak.[2] See Table 1 for examples.[3] A country's incentive to truthfully disclose positive evidence of an outbreak depends on the difference between these two sets of sanctions. The larger the risk of false negatives, the larger is the sanction imposed on a country that reports no outbreak. This, in turn, lowers the relative sanction on reporting positive evidence of an outbreak.

Second, improving the quality of a country's domestic surveillance may discourage a country from disclosing the results of that surveillance. This finding contradicts accepted wisdom at public health organizations such as WHO, the United Nation's Food and Agricultural Organization (FAO), and the U.S. Centers for Disease Control and Prevention (CDC).[4] Improving the predictive value of diagnostic testing lowers the likelihood of false positive results and thereby increases a country's confidence that medical assistance following disclosure will save lives. But improved testing also increases trading partners' confidence that a positive test result truly indicates the presence of an outbreak and therefore lowers trade following disclosure. If the trade response exceeds the expected gain from medical assistance, there will be less truthful disclosure.

Finally, we extend the model to incorporate informal surveillance, which may be defined as information from local citizens and doctors at the site of a potential outbreak that flows, through informal networks of scientists and public health professionals, out to the public domain. This information is different from the country's own diagnostic testing—or formal surveillance—and is not sanctioned by the government of the country experiencing a possible outbreak. However, it is carefully followed by the international community (Samaan et al. 2005) and serves as an exogenous public signal that provides independent information about whether a country has suffered an outbreak.[5]

The public health community has criticized informal surveillance—also called rumor surveillance—for being prone to error (Harris 2006). For the same reason that improvements in diagnostic testing may discourage a country from disclosing test results, improvements to informal surveillance also may discourage a country from disclosing its own test results. Nevertheless, improving the predictive value of in-

2. The baseline level of trade is assumed to be that which prevails when trading partners believe there is no outbreak. A sanction is the reduction in trade from this level.

3. It is difficult to show examples of sanctions that follow reports of no outbreaks because countries formally only announce outbreaks. So the table instead reports examples where countries were sanctioned before they formally announced any outbreak. The sanctions were described in the press as reflecting the fear of an as-yet undetected or unreported outbreak.

4. For example, WHO has stated that one of its central goals (and of the FAO) is to "facilitate . . . the rapid development of new methods for detecting the [avian influenza] virus in environmental samples" (WHO 2005). Similarly, the U.S. CDC has called for the transfer of diagnostic technologies as a central goal in promoting surveillance of avian influenza (Gerberding 2005).

The emphasis on quality of surveillance technology has been biased in favor of improving its sensitivity. Both the WHO Manual on Animal Influenza Detection and Surveillance (2002) and the U.S. National Strategy for a Pandemic Influenza (U.S. Homeland Security Council 2005) stress the importance of improving the sensitivity of tests but do not mention the specificity of tests.

5. Communication with Dr. David Nabarro, U.N. System Senior Coordinator for Avian and Human Influenza, September 9, 2008. If not for rumor surveillance (that is, information flowing through informal networks of scientists and public health professionals), the international community would not have learned of the SARS outbreak in China. Rumor surveillance is also used by WHO and the public health community for more routine tasks, such as acquiring information on malaria epidemics.

Table 1
Examples of trade sanctions before countries reported evidence of an outbreak

Date	Disease	Location	Sanction
		Sanctions imposed even before animal outbreaks	
2005	Highly pathogenic avian influenza	Not specific	Vietnam bans imports of poultry from 16 countries
2006	Highly pathogenic avian influenza	France	Poultry consumption falls 20 percent in France
2006	Highly pathogenic avian influenza	Bulgaria	Poultry sales falls 60 percent in Bulgaria
		Sanctions imposed before any human outbreak	
1997	Highly pathogenic avian influenza	Hong Kong	Hong Kong kills 1.5 million chickens
2001	Foot and mouth disease	United Kingdom	U.K. tourism and beef industries lose £ 3 billion
2003	Avian influenza	United States	U.S. poultry exports may have fallen 3 percent
2003	Mad cow disease	United States	U.S. beef exports fall 80 percent
2003–2005	Highly pathogenic avian influenza	Southeast Asia	Southeast Asian economies lose $12 billion in output (Thailand, $1 billion; Vietnam, 1.8 percent of GDP); outside the region poultry prices up 20 percent, volume down 8 percent
2005	Highly pathogenic avian influenza	Not specific	U.S. bans poultry imports from all countries reporting animal outbreaks
2006	Highly pathogenic avian influenza	Italy	Poultry consumption falls 70 percent in Italy

Sources: Blayney 2005; "Poultry from British Columbia" 2005 formal surveillance is usually less harmful to disclosure than improving the predictive value of formal surveillance. The main reason is that informal surveillance ameliorates the inferences made by trading partners after the disclosure of test results. By contradicting false positive diagnostic test results, it increases trade when those results are reported. So a country need not fear false positives when deciding whether to truthfully report test results. By contradicting false negative test results, it reduces trade when those results are reported. This reduces the relative sanction when a country reports any positive test result.

This paper addresses the problem of incentives for reporting of disease outbreaks, but the signaling model it employs fits a host of other problems. It applies to the case of a hospital deciding whether to report medical errors to public health authorities. Such reports may reduce patient demand or insurance reimbursements, but they also facilitate efforts by the medical staff to reduce errors. The model applies to individuals deciding whether to disclose a disability or mental illness. Disclosure may invite discrimination but it also facilitates accommodations. It applies to a school deciding whether to disclose information on the performance of its teachers. Poor teaching results may cause parents withdraw their children, but they also trigger financial assistance from the state government. It applies to the case of scholars admitting errors in their own research. Disclosure reduces the scholar's reputation, but invites ideas from colleagues about how to improve. In each case, we may be interested in improving the quality of the sender's private information or in having an independent public signal about the sender's type. But as this paper demonstrates, improving the technical quality of information may reduce the disclosure of private information.

This papers relates to two strands of research within the large literature on signaling. The first is papers on signaling to two audiences (see, for example, Gertner, Gibbons, and Scharfstein 1988; Dewatripont 1987; Austen-Smith and Fryer 2005). Gertner, Gibbons and Scharfstein (1988), for example, model a firm's common signal to capital markets and product markets. The signaling game to just one audience—the capital markets—could result in either a separating equilibrium (where high- and low-profit firms send different signals) or a pooling equilibrium. Adding a second audience—competitors in the product market—can either break the separating equilibrium (if the low-profit firm benefits by sending a high-profit signal) or induce separation from the pooling equilibrium (if the low-profit firm benefits by sending a low-profit signal). In our model, the two audiences are trading partners and organizations, such as WHO. Whichever is considered the first audience, we would obtain a pooling equilibrium (signaling no outbreak to trading partners to avoid sanctions, or signaling outbreak to WHO to obtain medical assistance). By adding the second audience, it is possible to obtain separation because the second audience rewards the opposite signal as the first. Thus our model is the special case of a two-audience model where the second audience can change some pooling equilibra into ones with separation.

Our model also relates—though mainly by departure—to papers that try to encourage disclosure of private information by punishing nondisclosure of negative information more harshly than disclosure of negative information (see, for example, Arlen 1994; Kaplow and Shavell 1994; Arlen and Kraakman 1997; Pfaff and Sanchirico 2000). This paper rules out such an incentive scheme because it is not sequentially rational in a one-shot game. Ex post, a trading partner does not want to insufficiently punish honest reporting of an outbreak or excessively punish failure to report an outbreak that happens to become an observable epidemic. Even if an individual trading partner might want to employ such an incentive in a repeated game, it is hard to coordinate such a strategy with multiple trading partners.

In Section II we present a signaling model with imperfect private information to capture both the basic incentives to report an outbreak and the role that quality of testing plays in incentives to disclose test results. In Section III, we introduce informal surveillance—in the form of an imperfect public signal—to the model. To highlight the effect of the public signal, we assume it is received before the country sends a signal to its trading partner. The public signal is correlated with whether there is an outbreak but otherwise uncorrelated with the country's diagnostic testing.

II. Signaling Game with Only Formal Surveillance

This section presents a signaling game in which a country that privately observes a positive result from a diagnostic test for an outbreak decides whether to truthfully disclose that result to its trading partner. Two key assumptions generate interesting results from the model. First, we assume that the trading partner cannot commit to a sanction policy that punishes the country more if the country reports a negative test result when there is an epidemic than if the country reports a positive test result. The reason is that it is not credible to sanction a country less after a positive report to encourage reporting, thus requiring the country to take on greater epidemic risk than is ex post rational (and thus sequentially rational). Second, we assume that the diagnostic test is an imperfect indicator of whether the country has suffered an outbreak. We believe this is a realistic assessment of the value of modern surveillance.

A. Before the Game: Outbreak

The country suffers a disease outbreak with probability p. Neither the country nor the trading partner observes the outbreak. However, the country performs and privately observes the results of a diagnostic test. The test imperfectly identifies whether there is an outbreak. If there is an outbreak, the test gives a positive result with probability q. If there is no outbreak, it gives a negative result with probability r. In the medical literature, the probabilities $q$and r are known as the sensitivity and the specificity, respectively, of the test. We assume (p,q,r) are known by all players.

To determine how results from the diagnostic test affect players' beliefs about the probability of an outbreak, it is useful to define some additional terms. For example, the unconditional probability that the country observes a positive test result is $f = pq + (1-p)(1-r)$. Moreover, define

$$\pi^P \equiv \Pr(\text{outbreak} \mid \text{positive test}) = \frac{pq}{f}$$

$$\pi^N \equiv \Pr(\text{outbreak} \mid \text{negative test}) = \frac{p(1-q)}{1-f}$$

In the medical literature, π^P is called the predictive value of a positive and $1-\pi^N$ is the predictive value of a negative test. If the test is informative, then $\pi^P > p > \pi^N$. If the test is uninformative, then $\pi^P = \pi^N = p$ and $f = 1/2$.

B. Timing of the Game

After the country privately observes the results of the diagnostic test, it learns that it is of either type positive ($t = P$) or type negative ($t = N$). Following this realization, it plays the following signaling game with the trading partner.

Signal

The positive-type country can send two possible signals. It can report that it observed a positive test result ($s = P$) or report that it observed a negative test result ($s = N$). We are concerned with countries that conceal information about positive results, not with countries that fabricate positive results. Therefore, we restrict the negative type to only reporting a negative result ($s = N$).

Action

Depending on the signal received, the trading country selects an observable trade amount $T \geq 0$.

C. After the Game: Medical Assistance and Epidemic

There are two dangers from an outbreak. The first is that it may become an epidemic and kill y people in the country. If the positive-type country does not report a positive result, we assume an outbreak becomes an epidemic with probability one. If it reports a positive result, however, it receives humanitarian medical assistance. The medical assistance typically helps contain a disease and, as a result, reduces the probability that an outbreak becomes an epidemic by w to $(1-w) < 1$. We assume that an organization, like WHO, exogenously provides the medical assistance upon the report of a positive test result. The trading partner observes the provision of the medical assistance.

The second danger from an outbreak is that if it becomes an epidemic, that epidemic may spread to its trading partner—becoming a pandemic—and kill z people there. Whether the epidemic spreads depends on trade flows T between the host country and the trading partner. To capture this in a simple way, we assume that the probability of spread is T/T_0 where T_0 is the level of trade if all players know for sure that there is no outbreak.

D. Payoffs

Each player's payoff depends on the expected loss of life within its borders and the gains from trade. Let $B(T)$ denote the economic benefit from trade. We assume $B(T)$ is monotonically increasing over the range $[0, T_0)$ and concave ($B''(T) < 0$).

The positive-type country's payoff depends on the signal it sends. If it sends a positive signal, it receives medical assistance, reducing the chance that any outbreak becomes an epidemic. But the positive signal comes at the cost of a possible trade sanction as the trading partner reacts by closing its borders. If the positive type sends a negative signal, it forfeits medical assistance but avoids a trade sanction. More formally, the positive type's expected payoff is

$$E[u(t=P,s=P)] = -\pi^P(1-w)y + B(T)$$

$$E[u(t=P,s=N)] = -\pi^P y + B(T)$$

Because the negative type can send only the no outbreak signal, its expected payoff is $E[u(N,N)] = -\pi^N y + B(T)$. Naturally, the level of trade T may depend on the signal that is sent, as we shall see when describing some equilibria of this game.

Turning to the trading partner, let the function $\mu[t|s]$ represent its belief about whether the country is type t after it observes signal s. The trading partner's expected payoff is

$$E[v(T,s=P)] = -\{\mu[P|P]\pi^P(1-w) + \mu[P|N]\pi^P + \mu[N|N]\pi^N\}\frac{T}{T_0}z + B(T)$$

The first term above is the expected loss of life, given the trading partner's beliefs following the signal. The second term represents the gains from trade.

E. Trading Partner's Strategy

To simplify our characterization of the trading partner's strategy, let T_E^s indicate a trading partner's choice of trade in equilibrium E when it observes signal s. In addition, let

$$(1) \quad T(x) = \arg\max_T - x(T/T_0)z - B(T)$$

indicate the trading partner's best response level of trade if it believes the probability of an epidemic in the country is x. Since $B(T)$ is concave, the optimal value $T(x)$ is a strictly decreasing function of x.[6] In other words, the greater the expected probability of an epidemic in the country, the less the trading partner wants to engage in trade.

We also can simplify our discussion of the country's reporting strategy by defining a function $\tilde{B}(x) = B(T(x))$, which describes the relationship between (i) a trading partner's beliefs about the probability of an epidemic in the country and (ii) the economic benefit from the level of trade the trading partner chooses. This function is illustrated in Figure 2. Because $B(T)$ is monotonically increasing (see Panel A), the best-response curve for trade (Panel B) implies that $\tilde{B}(x)$ is also strictly decreasing in the trading partner's beliefs (Panel C). Later, when we examine whether improved technology encourages truthful disclosure, the answer will depend on the slope of $\tilde{B}$—that is, the rate at which the economic value of trade contracts as the trading partner's posterior belief on the probability of an epidemic rises.

6. The first-order condition for Equation 1 is $B'(T) = xz/T_0$. The second-order condition is satisfied because $B''(T) < 0$ by assumption.

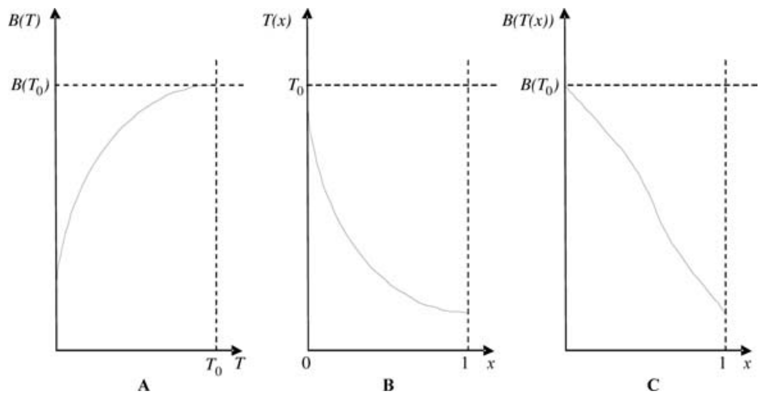

Figure 2
Relationship between beliefs x about the probability of an epidemic and the economic value B of trade

F. Equilibrium Concept

A perfect Bayesian equilibrium E of the signaling game we have described consists of a set of signals and trade flows $\{s(P), s(N), T_E^s\}$ and a set of beliefs $\{\mu[P|s]\}$ such that the following both hold:

1. Each country type and the trading partner maximize their expected payoffs given the beliefs and strategy choices of the other players.
2. The trading partner's beliefs are as follows: (a) when the information set is on the equilibrium path, the beliefs are derived from the equilibrium strategies via Bayes rule, and (b) when the information set is off the equilibrium path, the beliefs form a probability distribution over the country types.

G. Results

We explore three types of equilibrium of the signaling game between the country and its trading partner: separating, pooling, and semiseparating. The existence of each equilibrium depends on the accuracy of the diagnostic test and the efficacy of the medical assistance. Before turning to the comparative statics, we describe parameter ranges and beliefs for which the positive type truthfully reveals the outbreak and for which it hides the test result. Note that these parameter values and beliefs are merely sufficient conditions, so the equilibria we describe are not unique.

Proposition 1

There are values for lives lost in an epidemic

$$(2) \quad \bar{y} = \frac{\tilde{B}(\pi N) - \tilde{B}(\pi P(1-w))}{\pi^P w} \ \& \ \underline{y} = \frac{\tilde{B}(p) - \tilde{B}(\pi P(1-w))}{\pi^P w}$$

such that (i) if $y \geq \bar{y}$, there exists a separating equilibrium (SE), defined as

$$
\begin{array}{ll}
s(P) = P & s(N) = N \\
\mu[P|P] = 1 & \mu[P|N] = 0 \\
T^P_{SE} = T(\pi^P(1-w)) & T^N_{SE} = T(\pi^N)
\end{array}
$$

and (ii) if $y \leq \underline{y}$, there exists a pooling equilibrium (PE), defined as

$$
\begin{array}{ll}
s(P) = s(N) = N & \\
\mu[P|N] = f & \mu[P|P] = 1 \\
T^N_{PE} = T((1-f)\pi^N + f\pi^P) = T(p) & T^P_{PE} = T(\pi^P(1-w))
\end{array}
$$

Proof. (i) By Equation 1, T^P_{SE} and T^N_{SE} provide the trading partner its highest payoffs given the beliefs $\mu[P|P] = 1$ and $\mu[P|N] = 0$, respectively. Since the negative type has no choice, we need consider only deviations by the positive type. The positive type cannot profitably deviate if $-\pi^P(1-w)y + \tilde{B}(\pi^P(1-w))) \geq -\pi^P y + \tilde{B}(\pi^N)$, where, recall, $\tilde{B}(x) = B(T(x))$. Rearranging yields $y \geq \bar{y}$.

(ii) By Equation 1, T^P_{PE} and T^N_{PE} provide the trading partner its highest payoffs given the beliefs $\mu[P|P] = 1$ and $\mu[P|N] = f$, respectively.[7] The off-the-equilibrium-path belief $\mu[P|P] = 1$ is consistent with the strategies since only the positive type can declare an outbreak. The positive type cannot profitably deviate if $-\pi^P y + \tilde{B}(p) \geq -\pi^P(1-w)y + \tilde{B}(\pi^P(1-w))$. Solving for y yields $y \leq \underline{y}$.

The benefit of truthfully disclosing a positive test result is that the country receives medical assistance, which reduces the probability of an epidemic by w and thus saves $\pi^P wy$ lives. The cost is that the trading partner may reduce the level—and thus the economic value—of trade with the country. In a separating equilibrium, if the country reports a positive result, the trading partner expects that it actually observed a positive test and will receive medical assistance. Therefore, the trading partner expects the probability of an epidemic is $\pi^P(1-w)$. If the country reports a negative result, the trading partner believes there was a negative result, so the probability of an epidemic is expected to be π^N.

Recall that the level of trade falls in the trading partner's expectation of risk from an epidemic. Therefore, if $\pi^P(1-w) > \pi^N$,[8] the economic value of trade sanctions when the country truthfully reports is $\tilde{B}(\pi^N) - \tilde{B}(\pi^P(1-w)) > 0$. The country will still report a positive test result if the value of lives saved exceeds the value of trade sanctions: $\pi^P wy \geq \tilde{B}(\pi^N) - \tilde{B}(\pi^P(1-w))$. Solving for y reveals that a separating equilibrium exists when $y \geq \bar{y}$.

A pooling equilibrium requires that the positive type prefers not to report its positive result. The benefit of truthful reporting is, as before, $\pi^P wy$ lives are saved. The cost, however, is different. In a pooling equilibrium, a negative report is unin-

7. If $\tilde{B}(x)$ is concave, then the trading partner can do strictly better by randomizing between $T(\pi^P)$ with probability f and $T(\pi^N)$ with probability $1-f$. By Jensen's inequality $f\tilde{B}(\pi^P) + (1-f)\tilde{B}(\pi^N) \geq \tilde{B}(f\pi^P + (1-f)\pi^N) = \tilde{B}(p)$, Of course, this will change $\underline{y}$ to $\underline{y}' = [f\tilde{B}(\pi^P) + (1-f)\tilde{B}(\pi^N) - \tilde{B}(\pi^P(1-w))]/\pi^P w$.

8. If $\pi^P(1-w) < \pi^N$, there will be greater trade when the positive type discloses. With no cost at all to disclosing, the country will always do so.

formative. Therefore, the trading partner believes the probability of an epidemic is simply its prior belief about an epidemic, or p.

If the positive type ventures off the equilibrium path and discloses a positive result, the trading partner expects it is a positive type and, after accounting for medical assistance, believes that the risk of an epidemic is $\pi^P(1-w)$. So long as $\pi^P(1-w)>p$, there will be a trade sanction from reporting. The positive type will pool with the negative type if the cost of the sanction exceeds the benefit of medical assistance: $\tilde{B}(p)-\tilde{B}(\pi^P(1-w))\geq\pi^P wy$. Solving for y reveals a pooling equilibrium is possible only if $y<\underline{y}$. (If $\pi^P(1-w)<p$, there is no sanction to reporting. In that case, $\underline{y}<0$ and no pooling equilibrium exists.)

Since the risk the trading partner assigns to the negative type is lower in a separating equilibrium (π^N) than in a pooling equilibrium (p), the level of trade enjoyed by negative types is greater in the separating equilibrium than in the pooling equilibrium and there is actually more to lose by truthful reporting in the separating equilibrium. Therefore, $\bar{y}>\underline{y}$, and there is no overlap between the region permitting a separating equilibrium and that permitting a pooling equilibrium. In between these regions lies a semiseparating equilibrium:

Proposition 2

For every value of $m\in[0,1]$, there is a

$$y^*(m)=\frac{\tilde{B}\left(\dfrac{fm\pi^P+(1-f)\pi^N}{fm+(1-f)}\right)-\tilde{B}(\pi^P(1-w))}{\pi^P w}\in[\underline{y},\bar{y}]$$

such that there exists a semiseparating equilibrium (SSE), defined as

$$s(P)=\begin{Bmatrix}P \text{ with probability } 1-m\\ N \text{ with probability } m\end{Bmatrix}\qquad s(N)=N$$

$$\mu[P|P]=1\qquad \mu[P|N]=\frac{fm}{fm+(1-f)}$$

$$T^P_{SSE}=T(\pi^P(1-w))\qquad T^N_{SSE}=T\left(\frac{fm\pi^P+(1-f)\pi^N}{fm+(1-f)}\right)$$

Proof: By Equation 1, T^P_{SSE} and T^N_{SSE} are optimal for the trading partner given the beliefs, $\mu[P|P]=1$ and $\mu[P|N]=fm/[fm+(1-f)]$.[9] For the positive type to mix, it must be indifferent between signaling positive and signaling negative. For any given value T^N_{SSE} (which depends on m), this occurs when

9. As in the pooling equilibrium, if $\tilde{B}(x)$ is concave, then Jensen's inequality suggests the trading partner can do strictly better by randomizing between $T(\pi^P)$ with probability $\mu[P|N]$ and $T(\pi^N)$ with probability $1-\mu[P|N]$. Of course, this will change $y^*(m)$ to

$$\frac{\dfrac{fm}{fm+(1-f)}\tilde{B}(\pi^P)+\dfrac{(1-f)}{fm+(1-f)}\tilde{B}(\pi^N)-\tilde{B}(\pi^P(1-w))}{\pi^P w}\in[\underline{y}',\bar{y}]$$

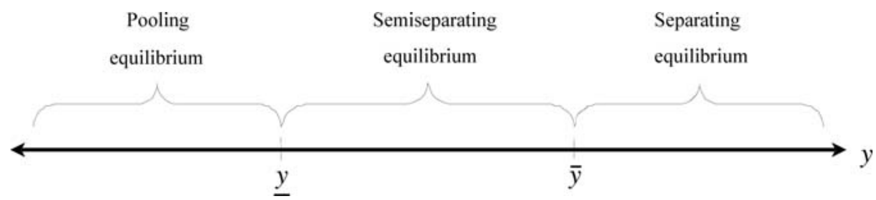

Figure 3
Relationship between y and the equilibrium of the signaling game

$$(3) \qquad -\pi^P(1-w)y+\tilde{B}(\pi^P(1-w))=-\pi^P y+\tilde{B}\left(\frac{fm\pi P+(1-f)\pi N}{fm+(1-f)}\right)$$

Solving Equation 3 defines the value of y that supports a given mixed strategy $(m,1-m)$. Finally, observe that

$$\frac{d}{dm}\frac{fm\pi^P+(1-f)\pi^N}{fm+(1-f)}=\frac{f(1-f)(\pi^P-\pi^N)}{[fm+(1-f)]^2}>0$$

and $\lim_{m\to 0} y^*(m)=\bar{y}$ and $\lim_{m\to 1} y^*(m)=\underline{y}$, so $y^*\in[\underline{y},\bar{y}]$.

Consider the trading partner's beliefs when it observes a negative signal. Believing that the positive type sends a negative signal with probability m, the trading partner thinks the country is a positive type with probability $\mu[P|N]=fm/[fm+(1-f)]$. Given that the risk from a nondisclosing positive type is π^N, the trading partner expects the probability of an epidemic to be $\mu[P|N]\pi^P+(1-\mu[P|N])\pi^N$. Contrast this with the probabilities π^N and p that it assigns to an epidemic following a negative signal in a separating and pooling equilibrium, respectively. It is evident that as the country's probability (m) of hiding its positive result goes to 0 and 1, the trading partner's beliefs about an epidemic converge to those in a separating and pooling equilibrium, respectively. This implies that $y^*(m)$ converges to the thresholds for a separating equilibrium $(\bar{y})$ and a pooling equilibrium $(\underline{y})$, respectively.

As a result, the equilibria described in Propositions 1 and 2 can be neatly mapped onto three intervals of y, as illustrated in Figure 3. It is important to note that this figure does not imply that the central parameter of the model is y or simply that countries with larger populations at risk are more likely to truthfully disclose test results. We use y as the parameter on which to index the ranges for different equilibria only for convenience. Other choices of index parameters, for example, w, π^P, π^N or z are as important as y for defining the ranges for different equilibria but are embedded in the function $\tilde{B}$. Defining ranges in terms of any of these parameters would involve the unintuitive use of implicit functions.

That said, it is true that as the domestic mortality (y) from an epidemic rises, the country is more likely to truthfully disclose because the expected medical benefits to disclosure rise. For the same reason, however, increasing the medical assistance (w) upon disclosure lowers the thresholds $\bar{y}$ and $\underline{y}$ and thereby promotes truthful disclosure. The effect of trading partner mortality $(\bar{z})$ is more complicated:

Proposition 3

In the context of the equilibria described in Propositions 1 and 2, increasing z encourages truthful disclosure if $\tilde{B}$ is concave and discourages disclosure if $\tilde{B}$ is convex. If $\tilde{B}$ is linear, z has no effect on disclosure.

$$(5) \quad \frac{d\bar{y}}{d\pi^P} = -\frac{\bar{y}}{\pi^P} - \frac{\tilde{B}'(\pi^P(1-w))(1-w)}{\pi^P w}$$

$$(6) \quad \frac{d\underline{y}}{d\pi^P} = -\frac{\underline{y}}{\pi^P} - \frac{\tilde{B}'(\pi^P(1-w))(1-w)}{\pi^P w}$$

These are positive if

$$(7) \quad -\tilde{B}'(\pi^P(1-w))\pi^P(1-w) > \pi^P w\bar{y}$$

$$(8) \quad -\tilde{B}'(\pi^P(1-w))\pi^P(1-w) > \pi^P w\underline{y}$$

respectively. Increasing the predictive value of a negative result, $1-\pi^N$, affects the thresholds as follows:

$$-\frac{d\bar{y}}{d\pi^N} = -\frac{\tilde{B}'(\pi^N)}{\pi^P w} > 0$$

$$-\frac{d\underline{y}}{d\pi^N} = 0$$

Better testing technology is captured by an increase in the positive predictive value of a positive test (π^P) or the negative predictive value of a negative test ($1-\pi^N$). From Equation 5 it is apparent that increasing π^P has two effects on the threshold for a separating equilibrium ($\bar{y}$). According to the first term, it increases the expected gain from medical assistance. Since a positive test is now more likely to indicate an outbreak, it is also true that any given level of assistance is more likely to save lives. However, according to the second term, a higher π^P also increases the trading partner's expectation that there is an epidemic. This will cause it to restrict trade. If the reduction in trade is greater than the additional expected lives saved, the range of y over which the country will truthfully report will shrink. A similar analysis explains how π^P also might increase the threshold for a pooling equilibrium ($\underline{y}$).

Whether tests with greater positive predictive value (π^P) encourage or discourage truthful disclosure depends on the curvature of the benefits from trade ($\tilde{B}$). Mechanically, Conditions 5 and 6 imply that better technology increases sanctions more than medical benefits if

$$-\tilde{B}'(\pi^P(1-w))\pi^P(1-w) > \pi^P w\bar{y} = \tilde{B}(\pi^N) - \tilde{B}(\pi^P(1-w))$$

$$-\tilde{B}'(\pi^P(1-w))\pi^P(1-w) > \pi^P w\underline{y} = \tilde{B}(p) - \tilde{B}(\pi^P(1-w))$$

respectively, where we have used Equation 2 to substitute for $\bar{y}$ and $\underline{y}$. The right-hand side now expresses the medical benefits of truthful disclosure in terms that allow apples-to-apples comparisons of sanctions and medical benefits. Obviously, if $\tilde{B}$ were linear or convex, the left-hand side would exceed the right-hand side. The effect of higher π^P on sanctions would dominate and truthful reporting would be discouraged. This is illustrated for the $\bar{y}$ threshold in Panel A of Figure 4. If, however, $\tilde{B}$ were sufficiently concave that additional risk of an epidemic had a smaller effect on the benefit of trade than on medical benefits, higher π^P technology would encourage truthful reporting, as in Panel B.

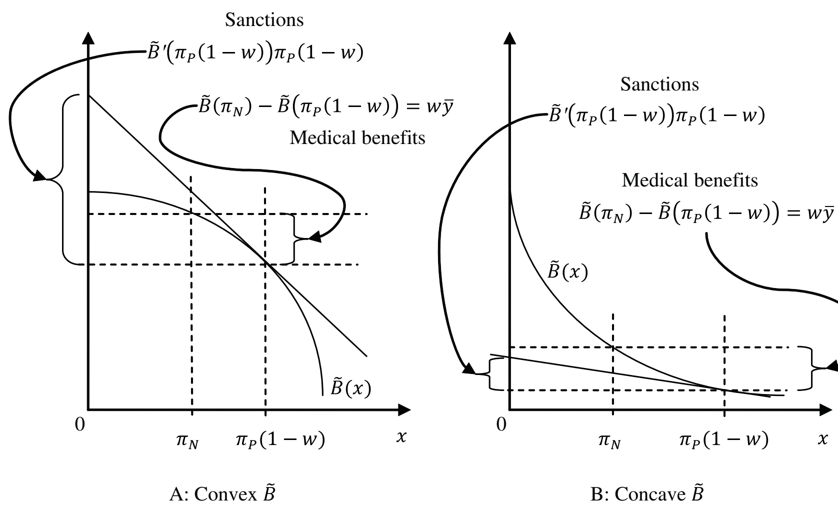

Figure 4
Better testing technology encourages truthful disclosure only if $\tilde{B}$ is sufficiently concave

The intuition is similar to that for the effect of mortality (z) in the trading partner. A greater positive predictive value of a test result increases the trading partner's fears of an epidemic. If the benefit from trade is convex in those fears, trade falls considerably as fear rises. So a higher positive predictive value causes a big reduction in trade, outweighing the linear benefits of positive predictive value on medical benefits ($\pi^P w\bar{y}$ or $\pi^P w\underline{y}$). If the benefits from trade are sufficiently concave in the fear of an epidemic, then trade falls much less as fear rises. So a higher positive predictive value may increase linear medical benefits more than it reduces concave concave trade benefits.

Unfortunately, there is no chance that improving the negative predictive value of tests $(1-\pi^N)$ promotes reporting. Since this improvement reduces the number of false positives, it has no effect on the value of medical assistance. However, increasing the predictive value of a negative result does reduce sanctions when the country signals a negative test in a separating equilibrium.[10] The result is to increase the relative sanctions against truthful disclosure.[11]

10. Because a negative signal is uninformative in a pooling equilibrium, the improvement has no impact on sanctions in such an equilibrium.
11. If one is interested in more precise changes in technology, such as changes in the sensitivity q and specificity r of a test, the effects are more convoluted. Improvements in sensitivity and specificity both increase π^P and lower π^N, though sensitivity has greater positive effects on and specificity has greater negative effects on π^N.

III. Signaling Game with Formal and Ex Ante Informal Surveillance

In this section we introduce informal surveillance to the model in the previous section. This surveillance takes the form of an exogenous public signal correlated with whether there was an outbreak in the country, but independent of the test result privately observed by the country.

A. Before the Game: Public Signal

The same public signal is sent to both players just after the country privately observes the result of the diagnostic test for whether it has experienced an outbreak, but before the country and the trading partner play the signaling game in Section IIB. The public signal, like the country's private diagnostic test, is imperfect. We employ the superscript i to indicate variables associated with informal surveillance. Let q^i and r^i be the sensitivity and specificity, respectively, of the public signal. We assume that (q^i, r^i) are known to all players.

To help show how results from the public signal affect players' beliefs about the probability of an outbreak, we define some additional terms. The unconditional probability of a positive public signal is $f^i = pq^i + (1-p)(1-r^i)$. To indicate cases where informal surveillance produces a positive and negative signal, we use the superscripts iP and iN, respectively. Let

$$\Pr(\text{outbreak} \mid i = P) = \frac{pq^i}{f^i} \equiv \pi^{iP}$$

$$\Pr(\text{outbreak} \mid i = N) = \frac{p(1-q^i)}{1-f^i} \equiv \pi^{iN}$$

We assume that the public signal and the country's private test are independent. So, upon observing a positive public signal and a positive signal from its test, the country updates its posterior on the probability of an outbreak as follows:

$$\pi^{P,iP} \equiv \Pr(\text{outbreak} \mid t = P, i = P)$$

$$= \frac{\Pr(t = P \mid \text{outbreak})\Pr(i = P \mid \text{outbreak})\Pr(\text{outbreak})}{\Pr(t = P)\Pr(i = P)}$$

$$= \frac{qq^i p}{ff^i} = \frac{\pi^P \pi^{iP}}{p}$$

Likewise,

$$\pi^{P,in} \equiv \Pr(\text{outbreak} \mid P, N = \frac{\pi^P \pi^{iN}}{p}$$

$$\pi^{N,iP} \equiv \Pr(\text{outbreak} \mid N, P) = \frac{\pi^N \pi^{iP}}{p}$$

$\pi^{N,iN} \equiv \Pr(\text{outbreak} \mid N,N) = \dfrac{\pi^N \pi^{iN}}{p}$

If the public signal is informative, then $\pi^{P,iP} > \pi^P > \pi^{P,iN}$ and $\pi^{N,iP} > \pi^N > \pi^{N,iN}$.

B. Signaling Game

After both players receive the public signal and the country observes the result of its private diagnostic test, the players play a signaling game similar to that in subsection 2B. The main difference is that, although there are still two types, $t = \{P,N\}$, there are also two information sets at which the country may act, $i = \{P,N\}$. Therefore, there are actually two signaling games that may be played. One is when the public signal is positive, and the other is when it is negative. Conditional on the public signal, the signaling game proceeds as before. Moreover, the nature of medical assistance and the probabilities of an epidemic following the game are unchanged.

C. Payoffs

The players' payoffs again depend on the expected loss of life in an epidemic and the gains from trade. However, the players' posterior beliefs about the probability of an epidemic and their choice of signal or trade reflect the public signal.

The positive-type country's payoffs are:

$$E[u(t=P,i=P,s=P)] = -\pi^{P,iP}(1-w)y + B(T)$$

$$E[u(P,N,P)] = -\pi^{P,iN}(1-w)y + B(T)$$

$$E[u(P,P,N)] = -\pi^{P,iP}y + B(T)$$

$$E[u(P,N,N)] = -\pi^{P,iN}y + B(T)$$

Because the negative-type country's signal set is restricted, its payoffs are simply $E[u(t=N,i=P,s=N)] = -\pi^{N,iP}y + B(T)$ and $E[u(N,N,N)] = -\pi^{N,iN}y + B(T)$.

Turning to the trading partner, let the function $\mu[t \mid i,s]$ represent the trading partner's belief about the country's type t after it observes the public signal i and the country's signal s. The trading partner's expected payoff is

$$E[v(T,i,s=P)] = -\{\mu[P \mid i=P,s=P]\pi^{P,iP}(1-w)$$

$$+\mu[P \mid N,P]\pi^{P,iN}(1-w)$$

$$+\mu[P \mid P,N]\pi P,iP + \mu[P \mid N,N]\pi^{P,iN}$$

$$+(\mu[N \mid P,N]\pi N,iP + \mu[N \mid N,N])\pi^{N,iN}\}\frac{T}{T_0}y + B(T)$$

D. Trading Partner's Strategy and Equilibrium Concept

The definitions of the functions $T(x)$ and $\tilde{B}(x)$ are unchanged. The equilibrium concept is also the same, except that the country's signal and the trading partner's beliefs about type and trade strategy will depend on the public signal. Specifically, let $TE_{i,s}$ indicate a trading partner's choice of trade in equilibrium E when it observes private signal s and public signal i.

E. Results

Although there are different signaling games being played when there are positive and negative public signals, the equilibria for the games are symmetric in the sense that, other than conditioning on a positive or negative public signal, all the other characteristics of a type of equilibrium are the same. Therefore, to economize on space, we shall describe three types of equilibrium for the signaling game after an arbitrary signal i. The specific equilibria for the game after a positive (negative) public signal may described by replacing each i condition with $i=P$ $(i=N)$ and each i superscript with $i=iP$ $(i=iN)$. We repeat that the conditions on parameters and beliefs are merely sufficient conditions, so the equilibria are not unique.

Proposition 5

There are values for lives lost in an epidemic

$$\bar{y}^i = \frac{\tilde{B}(\pi^{N,i}) - \tilde{B}(\pi^{P,i}(1-w))}{\pi^{P,i}w} \tag{9}$$

$$\underline{y}^i = \frac{\tilde{B}(\pi^i) - \tilde{B}(\pi^{P,i}(1-w))}{\pi^{P,i}w} \tag{10}$$

such that (i) if $y \geq \bar{y}^i$, there exists a separating equilibrium (SE), defined as

$$\begin{array}{ll} s(t=P,i)=P & s(N,i)=N \\ \mu[P \mid i,s=P]=1 & \mu[P \mid i,N]=0 \\ T_{SE}^{i,P}=T(\pi^{P,i}(1-w)) & T_{SE}^{i,N}=T(\pi^{N,i}) \end{array}$$

and (ii) if $y \leq \underline{y}^i$, there exists a pooling equilibrium (PE), defined as

$$\begin{array}{ll} s(t=P,i)=P & \\ \mu[P \mid i,N]=f^i & \mu[P \mid i,P]=1 \\ T_{PE}^{i,N}=T(f\pi^{P,i}+(1-f)\pi^{N,i})=T(\pi^i) & T_{PE}^{i,P}=T(\mu^{i,P}(1-w)) \end{array}$$

Proof. See proof for Proposition 1.

Proposition 6

For every value of $m \in [0,1]$, there is a

$$y^*(m,i) = \frac{\tilde{B}\left(\dfrac{fm\pi^{P,i}+(1-f)\pi^{N,i}}{fm+(1-f)}\right) - \tilde{B}(\pi^{P,i}(1-w))}{\pi^{P,i}w} \in [\underline{y}^i, \bar{y}^i]$$

such that there exists a semiseparating equilibrium (SSE), defined as

$$s(t=P,i)=\begin{Bmatrix} P \text{ with probability } 1-m \\ N \text{ with probability } m \end{Bmatrix} \qquad s(N,i)=N$$

$$\mu[P\,|\,i,s=P]=1 \qquad \mu[P\,|\,i,N]=\frac{fm}{fm+(1-f)}$$

$$T_{SSE}^{i,P}=T(\pi^{P,i}(1-w)) \qquad T_{SSE}^{i,N}=T\left(\frac{fm\pi^{P,i}+(1-f)\pi^{N,i}}{fm+(1-f)}\right)$$

Proof: See proof for Proposition 2.

Given the similarity between equilibria without a public signal and equilibria conditional on a public signal, the following proposition should come as no surprise:

Proposition 7

In the context of the equilibria described in Propositions 5 and 6, improving the predictive value of testing technology may discourage truthful reporting even in the presence of informal surveillance.

Proof: See proof for Proposition 4.

Indeed, the same point may be made about the presence of informal surveillance itself.

Proposition 8

In the context of the equilibria described in Propositions 5 and 6, the presence of informative informal surveillance may discourage truthful reporting.

Proof: See appendix.

Such surveillance may discourage disclosure because it increases trade sanctions along with the expected medical benefits of reporting. Comparing the effects of private testing and informal surveillance, however, reveals that in most cases improvements to private testing discourage reporting more than improvements to public surveillance:

Proposition 9

At the positive public signal node: (i) increasing the predictive value of a positive private test result raises both $\bar{y}$ and $\underline{y}$ more than increasing the predictive value of a positive public signal; (ii) increasing the predictive value of a negative test result raises $\bar{y}$ more than increasing the predictive value of a negative public signal; and (iii) there is no difference between the effect of increasing the predictive value of negative test result and increasing the predictive value of a negative public signal on $\underline{y}$.

At the negative public signal node: (i) increasing the predictive value of a positive private test result raises $\bar{y}$ and $\underline{y}$ more than increasing the predictive value of a positive public signal if increasing the predictive value of a positive test result increases $\bar{y}$ and $\underline{y}$, respectively; (ii) increasing the predictive value of a negative test result raises $\bar{y}$ more than increasing the predictive value of a negative public signal

Table 2
Would improvements to the private test or improvements to the public signal do more to discourage truthful reporting?

Node	Equilibrium threshold	Improvement in predictive value of	
		Positive result	Negative result
Positive	SE	Private test	Private test
Positive	PE	Private test	No difference
Negative	SE	Private test if it raises SE threshold	Private test if more predictive positive private test raises SE threshold
Negative	PE	Private test if it raises PE threshold	Public signal worse if it raises PE threshold

if increasing the predictive value a positive test result raises $\bar{y}$; and (iii) increasing the predictive value of a negative public signal raises $\bar{y}$ more than increasing the predictive value of a negative test result if increasing the predictive value of a negative public signal raises $\underline{y}$.

Proof: See appendix.

This proposition is summarized in Table 2. The main reason that improvements to informal surveillance may be less harmful is that they moderate inferences based on private testing. In cases where better private testing discourages truthful reporting, improvements to informal surveillance therefore encourage truthful reporting. For example, a positive public signal blunts the effect of any negative signal sent by the country. Since a more predictive negative test result always reduces trade, a more predictive positive public signal increases trade following a negative signal. This reduces the implicit trade sanction from sending a positive signal and thus the cost of truthful reporting.[12] Likewise, a negative public signal blunts the effect of any positive signal sent by the country. If a more predictive positive test result reduces trade, a more predictive negative public signal will encourage trade following a positive signal. This reduces the cost of a public signal and thus truthful reporting.

Improvements to informal surveillance have no impact in the off-diagonal cases—that is, increasing the predictive value of a positive public signal has no impact at

12. The only case where this does not hold is for the pooling equilibrium threshold at the negative node. Increasing the predictive value of a negative public signal does not blunt the predictive value of a negative test result because the two types of country pool. So the negative signal from the country does not reveal a negative test result.

the negative public signal node and vice versa. In these cases, whether improvements to private testing are better than improvements to informal testing hinges on whether better private testing encourages truthful reporting. For instance, because a more predictive negative test result always discourages truthful reporting, it is worse than a more predictive negative public signal at the positive public signal node.

IV. Conclusion

Recent history has witnessed both epidemics that spread quickly and epidemics that are lethal. The 2002–2003 outbreak of severe acute respiratory syndrome (SARS) infected more than 8,000 people in 27 countries within just nine months. The world was spared, however, because it had a low case fatality rate of 9.6 percent (WHO 2009b). Highly pathogenic avian influenza (HPAI), in contrast, has a high case fatality rate (~ 60 percent), but fortunately has not been able to achieve human-human transmission.[13] As of December 6, 2009, several million people in 208 countries have been infected with swine flu (H1N1), which has had a low case fatality rate (~ one percent) (WHO 2009d, 2009e). If our luck runs out and we experience an epidemic that both spreads quickly and has a high case fatality rate, the consequences would be devastating. By one estimate, a modern epidemic as severe as the 1918 flu could kill 62 million people (Murray et al. 2007) and reduce GDP by 4.7 percent in the United States alone (Congressional Budget Office 2005).

Because it is easier to limit the spread of a disease than to lower its case fatality rate, WHO's strategy for coping with outbreaks relies heavily on early detection and containment. But detection requires disclosure ("WHO Proposes Plan" 2006), so minimizing the loss of life demands an understanding of countries' incentives to disclose evidence of disease outbreaks.

This paper models disclosure as a signaling game. The main innovations are to allow the country's private information—its domestic surveillance—to be an imperfect indicator of an outbreak and to permit an exogenous public signal—informal, or rumor, surveillance—of whether there is an outbreak. The first innovation reveals that improvements in formal surveillance technology may, counterintuitively, discourage disclosure of outbreaks. Although better technology may increase the expected benefits from medical assistance, it also increases the economic sanctions because a more informative disclosure will give trading partners more reason to fear an epidemic. The second innovation reveals that informal surveillance is less harmful to disclosure than formal surveillance. The reason is that a negative public signal increases trade following a false positive disclosure and a positive public signal reduces trade after a false negative disclosure. Therefore, informal surveillance reduces the relative sanction from truthfully disclosing that evidence of an outbreak from formal surveillance.

Of course, incentives to disclosure are only half the story. To have information to disclose, a country must first invest in surveillance. If a country does not plan to

13. Between 2003 and August 11, 2009, it had infected 438 and killed 262 in 15 countries (WHO 2009c).

disclose any information, it has less reason to invest in surveillance. If the level of investment in surveillance affects the quality of information gathered, however, the relationship becomes more complicated. If better detection discourages disclosure, then reducing investment in surveillance may encourage disclosure.

Even before investing in surveillance, there is much a country can do to reduce the probability of an outbreak. It also could invest in preventive measures, such as sanitation or vaccination. To the extent that ex post medical assistance designed to promote disclosure functions as insurance against an outbreak, it may substitute for self-help through preventive measures (Ehrlich and Becker 1972). Thus, there may be a tradeoff between ex post reporting and ex ante infection control.

Our analysis is subject to a number of caveats. The most notable is that we have considered only a one-shot game that does not account for the role of repeat play and reputation. If countries develop a bad reputation for not truthfully disclosing epidemics, and this lowers levels of trade between epidemics, then countries have an additional incentive to disclose. This may be an explanation for China's relatively greater cooperation with international swine flu surveillance after its widely denounced initial decision initially to suppress news of SARS ("China's Missed Chance" 2003).

The paper offers some clear directions for policy. First, providing countries with the ability to control outbreaks is likely to encourage them to look for and report outbreaks because it increases the benefits of disclosure. Second, efforts to upgrade surveillance capacity in countries should pay attention to their effect on incentives for reporting outbreaks. Third, reducing the burden or pain of sanctions after disclosure of an outbreak could be helpful in encouraging reporting. Although it may be difficult to coordinate trading partners so as to prevent sanctions upon disclosure, it may be possible—through the International Monetary Fund or World Bank—to provide countries with financial insurance against economic consequences of sanctions.

References

Arlen, Jennifer, and Reinier Kraakman. 1997. "Controlling Corporate Misconduct: An Analysis of Corporate Liability Regimes." *NYU Law Review* 72(1):687–779.

Arlen, Jennifer. 1994. "The Potentially Perverse Effects of Corporate Criminal Liability." *Journal of Legal Studies* 23(2):833–67.

Austen-Smith, David, and Roland G. Fryer, Jr. 2005. "An Economic Analysis of 'Acting White'." *Quarterly Journal of Economics* 120(2):551–83.

Blayney, Don P. 2005. "Disease-Related Trade Restrictions Shaped Animal Product Markets in 2004 and Stamp Imprints on 2005 Forecasts." *Outlook Report LDP-M-133–01, Economic Research Service*. Washington, DC: U.S. Department of Agriculture.

Brownstein, John S., Cecily J. Wolfe, and Kenneth D. Mandl. 2006. "Empirical Evidence for the Effect of Airline Travel on Inter-Regional Influenza Spread in the United States." *PLoS Medicine* 3(10):e401.

"China's Missed Chance." 2003. *Science*, July 18, 301: 294–96.

Congressional Budget Office. 2005. "A Potential Influenza Pandemic: Possible Macroeconomic Effects and Policy Issues." Washington, D.C.: Congressional Budget Office.

Dewatripont, Mathias. 1987. "Entry Deterrence Under Trade Unions." *European Economic Review* 31(1–2):149–56.
Ehrlich, Isaac, and Gary S. Becker. 1972. "Market Insurance, Self-Insurance, and Self-Protection." *Journal of Political Economy* 80(4):623–48.
Gerberding, Julie L. 2005. "Statement by Julie L. Gerberding, M.D., M.P.H. Director Centers for Disease Control and Prevention U.S. Department of Health and Human Services on Influenza Preparedness before the Subcommittee on Labor/HHS/Education and Related Agencies Appropriations Subcommittee, United States House of Representatives, April 12, 2006." [available online at http://www.hhs.gov/asl/testify/t050412b.html].
Gertner, Robert, Robert Gibbons, and David Scharfstein. 1988. "Simultaneous Signalling to Capital and Product Markets." *RAND Journal of Economics* 19(2):173–90.
Harris, Shane. 2006. "The Bug Bloggers." *Bulletin of Atomic Scientists* 62(1):38–43.
Kaplow, Louis, and Steven Shavell. 1994. "Optimal Law Enforcement with Self-Reporting of Behavior." *Journal of Political Economy* 102(3):583–606.
Khan, M.A. 2003. "Outbreaks of Meningococcal Meningitis during Hajj: Changing Face of an Old Enemy." *Journal of Pakistan Medical Association* 53(1). [available online at http://jpma.org.pk/PdfDownload/67.pdf].
Michaud, Joshua. 2003. "The International Infectious Disease Outbreak Surveillance and Reporting Game." Working paper. Unpublished.
Murray, Christopher J.L., Alan D. Lopez, Brian Chin, Dennis Feehan, and Kenneth H. Hill. 2007. "Estimation of Potential Global Pandemic Influenza Mortality on the Basis of Vital Registry Data from the 1918–20 Pandemic: a Quantitative Analysis." *Lancet* 368:2211–18.
Moore, Patrick S., Lee H. Harrison, Edward E. Telzak, Gloria W. Ajello, and Claire V. Broome. 1988. "Group A Meningococcal Carriage in Travelers Returning from Saudi Arabia." *Journal of the American Medical Association* 260(18):2686–89.
Panisset, Ulysses B. 2000. *International Health Statecraft: Foreign Policy and Public Health in Peru's Cholera Epidemic*. Lanham: University Press of America.
Pfaff, Alexander, and Chris Sanchirico. 2000. "Environmental Self-Auditing: Setting the Proper Incentives for Discovering and Correcting Environmental Harm." *Journal of Law, Economics, and Organization* 16(1):189–208.
"Poultry From British Columbia Is Banned in U.S. Due to Bird Flu." 2005. *Wall Street Journal*, November 21, p. A5.
Samaan, Gina, Mahomed Patel, Babatunde Olowokure, Maria C. Roces, and Hitoshi Oshitani the World Health Organization Outbreak Response Team. 2005. "Rumor Surveillance and Avian Influenza H5N1." *Emerging Infectious Diseases* 11(3):436–66.
U.S. Homeland Security Council. 2005. "National Strategy for Pandemic Influenza." [available online at http://www.flu.gov/professional/federal/pandemic-influenza.pdf].
"WHO Proposes Plan to Stop Pandemic in Its Tracks." 2006. *Science*, Jan. 20, 311: 315–16.
WHO. 2002. "WHO Manual on Animal Influenza Diagnosis and Surveillance." [available online at http://www.wpro.who.int/internet/resources.ashx/CSR/Publications/manual+on+animal+ai+diagnosis+and+surveillance.pdf].
———. 2005. "Responding to the Avian Influenza Pandemic Threat: Recommended Strategic Actions." [available online at http://www.who.int/csr/resources/publications/influenza/WHO_CDS_CSR_GIP_05_8-EN.pdf].
———. 2009a. "International Coordinating Group (ICG) on Vaccine Provision for Epidemic Meningitis Control." [available online at http://www.who.int/csr/disease/meningococcal/icg/en/index.html].

———. 2009b. “Summary of Probable SARS Cases with Onset of Illness from 1 November 2002 to 31 July 2003.” [available online at http://www.who.int/csr/sars/country/table2004_04_21/en/index.html].
———. 2009c. “Cumulative Number of Confirmed Human Cases of Avian Influenza A/(H5N1) Reported to WHO.” [available online at http://www.who.int/csr/disease/avian_influenza/country/cases_table_2009_08_11/en/index.html].
———. 2009d. “Pandemic (H1N1) 2009 - update 63 - Weekly Update.” [available online at http://www.who.int/csr/don/2009_08_28/en/index.html].
———. 2009e. “Pandemic (H1N1) 2009 - update 78 - Weekly Update.” [available online at http://www.who.int/csr/don/2009_12_11a/en/index.html].

Appendix

Proof of Proposition 8: Observe that $\lim_{\pi^i \to 0} \bar{y}^i = \bar{y}$ and $\lim^i_{\pi^i \to 0} \underline{y} = \underline{y}$. So increasing π^i from 0 is akin to introducing informal surveillance. Furthermore,

$$\frac{d\bar{y}^i}{d\pi^i} = \frac{\tilde{B}'(\pi^{N,i})\pi^N - \tilde{B}'(\pi^{P,i}(1-w))(1-w)\pi^P}{p\pi^{P,i}w} - \frac{\bar{y}^i\pi^P}{p\pi^{P,i}}$$

$$\frac{d\underline{y}^i}{d\pi^i} = \frac{\tilde{B}'(\pi^i) - \tilde{B}'(\pi^{P,i}(1-w))(1-w)\pi^P}{p\pi^{P,i}w} - \frac{\underline{y}^i\pi^P}{p\pi^{P,i}}$$

Improving π^{iP} increases these cutoffs at the positive public signal node if

$$-\tilde{B}'(\pi^{P,iP}(1-w))\pi^P(1-w) > \pi^P w\bar{y}^P - \tilde{B}'(\pi^{N,iP})\pi^N$$

$$-\tilde{B}'(\pi^{P,iP}(1-w))\pi^P(1-w) > \pi^P w\underline{y}^P - \tilde{B}'(\pi^{iP})$$

respectively. Reducing π^{iN} increases these cutoffs at the negative public signal node if

$$-\tilde{B}'(\pi^{N,iN})\pi^N + \pi^P w\bar{y}^P > -\tilde{B}'(\pi^{P,iN}(1-w))\pi^P(1-w)$$

$$-\tilde{B}'(\pi^{iN}) + \pi^P w\underline{y}^P > -\tilde{B}'(\pi^{P,iN}(1-w))\pi^P(1-w)$$

respectively. Obviously, increasing the predictive value of a positive public signal has no effect on games played at the negative public signal node and vice versa.

Proof of Proposition 9: Consider the marginal effects of improving the predictive value of a positive signal at the positive node. The effects on the separating equilibrium threshold are:

$$\frac{d\bar{y}^{iP}}{d\pi^{iP}}\frac{\pi^{iP}}{\bar{y}^{iP}} = \frac{\tilde{B}'(\pi^{N,iP})}{w\bar{y}^{iP}}\frac{\pi^N}{\pi^P} - \frac{\tilde{B}'(\pi^{P,iP}(1-w))(1-w)}{w\bar{y}^{iP}} - 1$$

$$\frac{d\bar{y}^{iP}}{d\pi^P}\frac{\pi^P}{\bar{y}^{iP}} = \frac{-\tilde{B}'(\pi^{P,iP}(1-w))(1-w)}{w\bar{y}^{iP}} - 1 =$$

$$\frac{d\bar{y}^{iP}}{d\pi^{iP}}\frac{\pi^{iP}}{\bar{y}^{iP}} - \frac{\tilde{B}'(\pi^{N,iP})}{w\bar{y}^{iP}}\frac{\pi^N}{\pi^P} > \frac{d\bar{y}^{iP}}{d\pi^{iP}}\frac{\pi^{iP}}{\bar{y}^{iP}}$$

The effects on the pooling equilibrium threshold are

$$\frac{d\underline{y}^{iP}}{d\pi^{i,P}}\frac{\pi^{iP}}{\underline{y}^{iP}}=\frac{\tilde{B}'(\pi^{iP})}{\pi^{P}w\underline{y}^{iP}}-\frac{\tilde{B}'(\pi^{P,iP}(1-w))(1-w)}{w\underline{y}^{iP}}-1$$

$$\frac{d\underline{y}^{iP}}{d\pi^{P}}\frac{\pi^{P}}{\underline{y}^{iP}}=\frac{-\tilde{B}'(\pi^{P,iP}(1-w))(1-w)\pi^{iP}}{w\underline{y}^{iP}}-1$$

$$=\frac{d\underline{y}^{iP}}{d\pi^{iP}}\frac{\pi^{iP}}{\underline{y}^{iP}}-\frac{\tilde{B}'(\pi^{iP}}{\pi^{P}w\underline{y}^{iP}}>\frac{d\underline{y}^{iP}}{d\pi^{iP}}\frac{\pi^{iP}}{\underline{y}^{iP}}$$

A one percent improvement in the private signal increases these thresholds more than a one percent improvement in the public signal.

Consider the marginal effects of improving the predictive value of a positive signal at the negative node. The effects on the separating equilibrium threshold are $d\bar{y}^{iN}/d\pi^{iP}=0$ and

$$\frac{d\bar{y}^{iN}}{d\pi^{P}}=\frac{-\tilde{B}'(\pi^{P,iN}(1-w))(1-w)\pi^{iN}}{p\pi^{P,iN}w}-\frac{\bar{y}^{iN}\pi^{iN}}{p\pi^{P,iN}}$$

The effects on the pooling equilibrium threshold are $d\underline{y}^{iN}/d\pi^{iP}=0$ and

$$\frac{d\underline{y}^{iN}}{d\pi^{P}}=\frac{-\tilde{B}'(\pi^{P,iN}(1-w))(1-w)\pi^{iN}}{p\pi^{P,iN}w}-\frac{\underline{y}^{iN}\pi^{iN}}{p\pi^{P,iN}}$$

If a better private signal raises the separating or pooling equilibrium threshold, it is more harmful than a better public signal.

Consider the marginal effects of improving the predictive value of a negative signal at the positive node. A better private signal raises the separating equilibrium threshold more than a better public signal:

$$-\frac{d\bar{y}^{iP}}{d\pi^{iN}}=0<-\frac{\tilde{B}'(\pi^{N,iP})\pi^{iP}}{p\pi^{P,iP}w}=-\frac{d\bar{y}^{iP}}{d\pi^{N}}$$

Further, there is no difference in the effect of an improvement in the public signal and the private signal on the pooling equilibrium threshold.

Consider the marginal effects of improving the predictive value of a negative signal at the negative node. The effects on the separating equilibrium threshold are

$$-\frac{d\bar{y}^{iN}}{d\pi^{iN}}\frac{\pi^{iN}}{\bar{y}^{iN}}=-\frac{\tilde{B}'(\pi^{N,iN})}{w\bar{y}^{iN}}\frac{\pi^{N}}{\pi^{P}}+\frac{\tilde{B}'(\pi^{P,iN}(1-w))(1-w)}{w\bar{y}^{iN}}+1$$

$$-\frac{d\bar{y}^{iN}}{d\pi^{N}}\frac{\pi^{N}}{\bar{y}^{iN}}=-\frac{\tilde{B}'(\pi^{N,iN})}{w\bar{y}^{iN}}\frac{\pi^{N}}{\pi^{P}}=\frac{d\bar{y}^{iN}}{d\pi^{iN}}\frac{\pi^{iN}}{\bar{y}^{iN}}+\frac{d\bar{y}^{iN}}{d\pi^{P}}\frac{\pi^{P}}{\bar{y}^{iN}}$$

A one percent improvement in private signal raises the separating equilibrium threshold more than a one percent improvement in the public signal if a more predictive positive private signal would also increase that threshold. The effects on the pooling equilibrium threshold are:

$$-\frac{d\underline{y}^{iN}}{d\pi^{iN}}=-\frac{\tilde{B}'(\pi^{iN})-\tilde{B}'(\pi^{P,iN}(1-w))(1-w)\pi^{P}}{p\pi^{P,iN}w}+\frac{\underline{y}^{iN}\pi^{P}}{p\pi^{P,iN}}$$

and $-d\underline{y}^{iN}/d\pi^{N}=0$. If a better public signal raises the pooling equilibrium threshold, then it is more harmful than a better private signal.