Surveillance and reporting of disease outbreaks: private incentives and WHO policy levers

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Abstract

In spite of the obvious global public goods nature of warnings about infectious disease outbreaks, international legal requirements for reporting outbreaks remain weak and disclosure of outbreaks depends on the self-interest of nations. Using a simple game-theoretic model, we explore the incentives of countries to invest in disease surveillance and to report outbreaks to international health authorities. We evaluate existing and potential policy instruments available to the WHO to encourage countries to detect and report disease outbreaks, including medical assistance to control outbreaks, trade sanctions for non-reporting and assistance in disease surveillance. These ideas are relevant to policy design, not just in the context of singular events such as avian influenza, but also for more routine problems such as hospital-acquired infections.

1 Introduction

In November 2002, health authorities in Guangdong Province reported a cluster of atypical pneumonia cases to China's National Ministry of Health in Beijing. In late February 2003, an infected medical doctor from Guangdong spent a single night on the ninth floor of a Hong Kong hotel and infected at least 16 other persons visiting his floor. The others included a tourist from Toronto, a flight attendant from Singapore and a businessman who later travelled to Vietnam. From this single event, severe accute respiratory syndrome (SARS) spread internationally. By May 2003, there were 7,000

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infected in 30 countries. During the height of the global epidemic, more than 200 new cases were being reported each day. By the time the contagion was brought under control in June 2003, over 600 people died (WHO May 20, 2003).

Despite the early report from Guangdong, China did not report the outbreak of atypical pneumonia to the World Health Organization (WHO) until early February 2003. And though Chinese scientists had uncovered evidence linking SARS to a new coronavirus that same month (Enserink 2003), they did not allow WHO teams to visit Guangdong until early April. As a result, WHO scientists were not able to established the coronavirus link for themselves until mid-April (WHO July 4, 2003). Had the Chinese government reported the outbreak and its likely cause earlier, many hundreds of lives could have been saved. Had the disease been more virulent than it turned out to be, the effects of secrecy and delayed reporting by China could have been much more severe.

Although information on disease outbreaks is a global public good, international legal requirements for surveillance and disclosure of outbreaks remain weak. The first international convention ever to be globally adopted was a 1851 accord to contain cholera. But since then, there has been very slow progress in strengthening the accord or expanding its scope. Until May 2005, International Health Regulations only required countries to report outbreaks of cholera, plague and yellow fever. Current regulations cover a broader array of diseases and provide standards for surveillance systems and timely disclosure of outbreaks (WHO May 23, 2005). Unfortunately, because non-reporting carries no penalties, warnings continue to depend on the self-interest of nations .

This paper explores the incentives of countries to surveil their own populations for infectious diseases and report outbreaks to international health authorities such as WHO. At first blush, countries face conflicting incentives to disclose outbreaks. On the one hand, reporting may trigger trade sanctions that can impose large economic costs. 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).[1] On

[1] Ironically, before China itself became a serious source of avian flu outbreaks, it and Vietnam imposed trade sanctions on other counries that reported outbreaks. This

the other hand, countries may also report an outbreak in order to obtain international assistance for containing the outbreak before it develops into a full blown epidemic. This could be an important reason why Vietnam and Turkey have been quick to report incidents of avian flu. Incentives to report an outbreak, however, tell only half the story. A disease must be detected to be reported and countries control not only reporting but also investments in surveillance and detection. If a country does not want to report information about an outbreak, it may have an incentive to limit surveillance.

This paper presents a simple game-theoretic model to capture these basic dynamics. It also offers three significant contributions. First, we explore the various policy instruments available to WHO to encourage countries to detect and report disease outbreaks. These include not just medical assistance to control outbreaks, but trade sanctions for non-reporting and subsidies for surveillance. Because such punitive trade sanctions may be politically infeasible and ineffective against poor or plagued countries, surveillance subsidies are a better approach. These ought to be conditioned on the right of WHO to audit a country's surveillance network. The success of this instrument is limited by WHO's restricted financial resources.

Second, we question whether trade sanctions are unambiguously detrimental to reporting and disease control. It has already been recognized, though frequently forgotten, that sanctions – especially restrictions on travel – can limit the spread of a disease. The interesting finding of this paper, however, is that certain types of sanctions can actually encourage surveillance and reporting. Trade sanctions that follow reports of a human outbreak – or "*ex post*" sanctions – surely discourage reporting. But most trade sanctions are triggered not by outbreaks but by beliefs about a trade partner's probability of having a human contagion. These "preemptive" sanctions may be informal, as when international consumer demand for American beef fell after initial news reports that a U.S. cattle was infected with bovine spongiform encephalopathy (mad cow disease) (Blayney 2005), or formal, as when the U.S. banned poultry imports from all countries that had birds infected with avian flu (WSJ Nov. 21, 2005). In neither case were trade-restrictions limited to countries reporting human infections. Preemptive sanctions may encourage countries with a low risk of infection to submit to WHO audits of their surveillance network. Their goal is to avoid misguided preemptive sanctions. But this triggers a "reverse-lemons" effect.

prompted a visiting U.S. official to urge caution lest sanctions discourage nations from reporting outbreaks (WSJ Nov. 11, 2003)

Once some low-risk countries disclose, the rest of the world will revise upward its threat assessment for remaining non-disclosing countries. As a result, new countries will fall into the category of low-risk, non-disclosing countries. These countries may then find it cost-effective themselves to disclose. The process will repeat until only the most recalcitrant, high-risk countries refuse to disclose.

Third, conventional wisdom in the public health community is that investments in surveillance technology ought to focus on sensitivity, that is, on increasing the probability of a positive test result given the patient has an infection. The logic is that if one does not detect a disease, one cannot control its spread. We question the resulting near-exclusive attention given to lowering the number of false negatives. Because tests that lack specificity and incorrectly signal an outbreak trigger ex post trade sanctions and bring medical assistance that is of little value , they discourage reporting. Therefore, emphasizing a more balanced investment in sensitivity and specificity is likely to increase public information on disease outbreaks.

This paper relates to the economics literature on principal-agent problems. One contribution is to consider the case where there are multiple agents and each agent's cost of effort takes the form of sanctions from fellow agents. This is a combination of a moral hazard problem as between the principal and any given agent and an adverse selection problem as between agents. The generalizable insight of the paper is that if sanctions among agents are triggered by beliefs about types rather than by revelation of type, the inter-agent game can reduce the principal's agency costs. This result has many obvious applications, such as encouraging hospitals to report infection rates to national authorities, incentivizing cities to disclose their crime rates, inducing employees to "blow-the-whistle" on other employees and encouraging citizens to report local crimes to police.[2] A second contribution

[2] One application that has been the subject of prior work is inducing firms to disclose criminal violations by their employees. Articles by Arlen (1994) and Kaplow and Shavell (1994) have considered the problem of holding firms liable for the illegal behavior of their employees. Arlen argues that holding firms liable may have the perverse effect of discouraging reporting because it is reporting that triggers criminal punishment for the firm. This is identical to the notion that ex post trade sanction discourage the reporting of diseases. Kaplow and Shavell note that one can negate the perverse effect if criminal sanctions are lower for firms that turn their employees in to the authorities. In other words, Kaplow and Shavel argue that if inter-agent sanctions separately penalize a bad-type agent and a non-reporting agent, agents can be induced to report. This is similar to the role that punitive sanctions for non-reporting play in our model. Neither model considers the value of preemptive sanctions, that is, inter-agent sanctions triggered by beliefs rather than disclosures about type. This is particularly valuable when the principal cannot coordinate its strategy towards one agent with other agents.

of the paper is to examine the value of different types of audit technologies. In particular, it examines how false positives versus false negatives affect an agent's willingness to accept an audit in the case where the principal does not have the right to audit at-will.

The remainder of the paper is organized as follows. Section 2 presents the basic model and demonstrates the conventional wisdom regarding incentives to report outbreaks. Section 3 explores the various instruments available to WHO to encourage surveillance and reporting. Section 4 demonstrates how preemptive sanctions can encourage reporting. Section 5 examines the value of surveillance technology that targets false negatives versus false positives. Finally, the appendix offers derivations of the results in the main text.

2 Basic model

Consider a country with non-zero probability of experiencing an outbreak of infectious disease. It must decide how much money to invest in surveillance and, if it discovers an outbreak, whether to report this information to WHO. These decisions are made over time; that process can be described in a five stage game that is depicted in Figure 1. In stage one, the country must decide how much θ to invest in surveillance or disease testing. In stage two the country experiences an outbreak with probability p_0. If there is an outbreak, y_0 residents will die. The country values this loss at $(1-\alpha)\,y_0$, where $\alpha \in [0,1]$ measures how *in*sensitive the country's government is to its population's welfare. In stage three, the country observes the results of its surveillance program. If the country experienced an outbreak, its surveillance system will identify the outbreak with probability $q(\theta)$. A larger investment in surveillance increases the probability of detection, though at a diminishing rate: $q'(\theta) > 0$, $q''(\theta) < 0$. If there was no outbreak in stage two, the surveillance system would not report an outbreak. In other words, for now, it is assumed there are no false positives.

In stage four, if its surveillance network detected an outbreak, the country must decide whether to report the outbreak to WHO. If it reports, it may receive medical assistance c from WHO, but will also suffer *ex post* trade sanctions from other countries – we'll call them the "rest of the world" or ROW – with cost S. In stage five, the outbreak, becomes an epidemic with probability $p_1(c)$. Because medical assistance from WHO may help control the outbreak, the probability of an epidemic falls (though at a diminishing rate) with assistance: $p_1'(c) < 0$, $p_1''(c) > 0$. An epidemic will

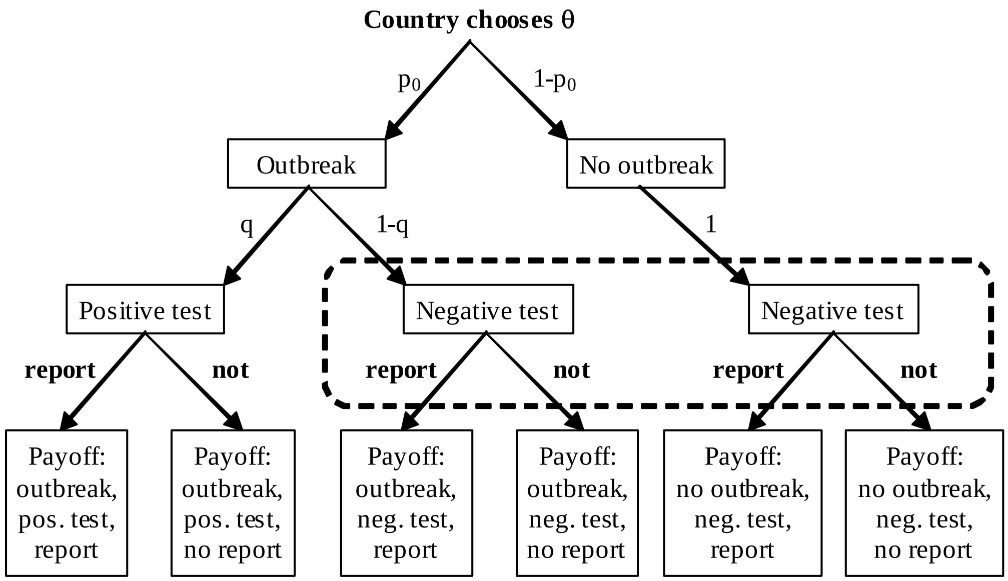

Figure 1: Extensive form game.

kill y_1 residents. The country values this at $\beta (1 - \alpha) y_1$, where β is the country's discount factor. Because the country cannot hide an epidemic, it will trigger sanctions S from the ROW, with cost βS.[3]

There are four objective states of the world in the model: the existence of an outbreak crossed with a positive or negative test result. However, the country only observes whether there is a positive test result, not whether it suffered an outbreak. Therefore, payoffs depend on two states – positive or negative test results – and a country's decision whether to report. Table 1 describes the payoffs. (To simplify the exposition, we define $Y_t = (1 - \alpha) y_t$.) If the country observes a positive test result but does not report, it faces a higher risk of an outbreak becoming an epidemic. It if does report, it will face immediate sanctions, but a smaller risk of an epidemic due to emergency

[3] This model ignores the risk of de facto reporting, that is, a positive test result that is discovered by the ROW even without reporting. The source could be government leaks, local media reports or indirect evidence such as the importation of body bags or large quantities of medication. The WHO calls this phenomenon rumour surveillance (Samaan et al. 2005). It can easily be incorporated into the model as a cost associated with a positive test result regardless of whether it is reported. Because the impact on reporting and surveillance will be similar to that of an epidemic or preemptive sanctions in Section 4, there is no need for a separate treatment of this form of reporting.

Test result	Report positive result?	Payoff
Positive	No	$-\theta - Y_0 - p_1(0)\,\beta\,[Y_1 + S]$
$[p_0 q]$	Yes	$-\theta - Y_0 - S - p_1(c)\,\beta\,[Y_1 + S]$
Negative	No	$-\theta - \frac{p_0(1-q)}{1-p_0 q}\left(Y_0 + p_1(0)\,\beta\,[Y_1 + S]\right)$
$[1 - p_0 q]$	Yes	$-\theta - \frac{(1-p_0)}{1-p_0 q} S - \frac{p_0(1-q)}{1-p_0 q}\left\{Y_0 + S + p_1(0)\,\beta\,[Y_1 + S]\right\}$

Table 1: Payoffs in basic model

medical assistance from WHO. If the country observes a negative test result and does not report, it again faces a higher risk of an epidemic. That risk is smaller, however, than with a positive test result because the test does shed light on whether there is an outbreak and there can be no epidemic without an outbreak. The last possibility is that the country observes a negative test result but reports an outbreak. This option will never be chosen because the country will suffer certain trade sanctions but get little benefit from medical assistance since it is unlikely that there was even an outbreak. Indeed, to simplify matters we will assume, quite reasonably, that WHO will not bother to provide medical assistance without an externally validated, positive test result.

Reporting. Because backward induction is employed to solve the game, let us consider the reporting decision before the surveillance decision. A country will report a positive test result if the payoff from doing so exceeds the payoff from non-reporting, or

$$S \leq \frac{\beta \Delta p_1(c)}{1 - \beta \Delta p_1(c)} Y_1 = \delta(\beta, c, 0)\, Y_1 \tag{1}$$

where $\Delta p_1(c) = p_1(0) - p_1(c)$ is the benefit of medical assistance in terms of reducing the risk of an epidemic. It may be verified that this benefit rises in the level of medical assistance: $\Delta p_1'(c) > 0$. A country is more likely to report the smaller is the cost in terms of *ex post* sanctions and the greater is the benefit in terms of the amount of medical assistance, how rapidly an outbreak is likely to explode into an epidemic, the number of lives that would be lost in an epidemic, and how much the government values those lives.

There are two, more subtle conclusions that follow from (1). First, if a country has its own medical resources, WHO medical assistance does not provide as strong an incentive to report an outbreak. Conversely, if the country does not rely on foreign trade or tourism for its economic wellbeing, the sanctions-related costs of reporting are likely to be negligible; therefore, WHO medical assistance is more effective in inducing reporting. Second, the probability with which a country's surveillance network detects an outbreak does not affect the reporting decision. This probability does not differ whether the country does or does not report because we are conditioning on a positive test result. (And there is no question that a country will not report an outbreak if tests reveal no outbreak.)

Surveillance. Suppose that a country has decided it will report a positive test result. The country will choose the amount to invest in surveillance so as to maximize the benefit of surveillance given reporting of positive test results:

$$\begin{aligned} \max_{\theta} & -\theta - p_0 q(\theta) \{Y_0 + S + p_1(c) \beta [y_1 + S\} \\ & -p_0 (1 - q(\theta)) \{Y_0 + p_1(0) \beta [Y_1 + S]\} \end{aligned}$$

It is easily verified that the optimality condition[4] is

$$q'(\theta^*) = \frac{1}{p_0 \{\beta \Delta p_1(c) Y_1 - [1 - \beta \Delta p_1(c)] S\}} \tag{2}$$

It follows (from the denominator) that the same conditions that encourage reporting also encourage investment in surveillance. Because surveillance magnifies the probability of detecting an outbreak, it is a complement to the benefits of reporting an outbreak. Anything which increases those benefits also increases the benefits of surveillance.

3 WHO's policy levers

WHO's central objective is to lower the probability of full blown epidemic because of the impact on both the originating country and the rest of the world. WHO along with partners such as the U.S. Centers for Disease Control and Prevention (CDC) provide a strong incentive for countries to report by promising medical and epidemiological expertise in the event of a reported outbreak. They also help and encourage countries to invest in their own surveillance program, as well as coordinate global surveillance networks such as the Global Outbreak Alert and Response Network (GOARN). GOARN has 120 member institutions around the world that track and help

[4] The second order condition is satisfied by the condition that the country chooses to report and the assumption that $q''(\theta) < 0$.

WHO mobilize to contain disease outbreaks. Although during the SARS crisis China did not report atypical pneumonia cases from mid-November 2002 until early-February 2003, GOARN members in the U.S. and Canada began to pick up local media reports of influenza cases in rural China as early as the end of November (Heymann and Rodier 2004). Perhaps if China had been a fully participating member of GOARN, WHO might have learned of the atypical pneumonia earlier and determined the true nature of the pathogen well before April 2003, when China first allowed WHO doctors into the country. Finally, an instrument that is not presently in WHO's toolkit, but perhaps should be is punitive sanctions against countries that suffer an outbreak but delay reporting it.

We will consider all three policy levers in the context of our model. The first is medical assistance c after a report of an outbreak. The second is a punitive sanction S_p imposed when a country does not report an outbreak but experiences an epidemic. The third is a surveillance subsidy θ_w. This may be given without strings or conditioned on allowing WHO access to information generated by a country's surveillance network. The key to valuing these levers is to understand WHO's information set before their use. No one observes whether there is an outbreak. Although the country observes a positive test result, WHO does not. WHO only observes positive test results that a country chooses to disclose and full-blown epidemics, which are difficult to conceal, even under authoritarian governments.

Medical assistance. We have already demonstrated that medical assistance, by reducing the risk of an epidemic, increases the incentive to report a positive test result. Here we explore the interaction between that incentive and a country's own medical resources m. At one extreme, WHO medical assistance completely displaces a country's own resources. In that case, the benefit of WHO assistance in lowering the probability of an epidemic is $\Delta p_1(c, m) = p_1(m) - p_1(c)$. A country's own resources simply lower the level of benefits that any level of WHO assistance provides. They do not affect the productivity of additional WHO assistance. At the other extreme, WHO's assistance is incremental to the country's own medical resources and this changes the marginal benefit of the external assistance to $\Delta p_1(c + m, m) = p_1(m) - p_1(m + c)$. Now the country's resources change both the level and slope of benefits from any given amount of WHO assistance. In either case, the country's medical resources reduce the incentive that WHO assistance provides for a country to report outbreaks, which reduces the returns to investment in surveillance.

Punitive sanctions. WHO has less information than a country and it can only observe a country's report of an outbreak or an epidemic. The threat of punitive sanctions for experiencing an epidemic without first reporting an outbreak can only encourage countries to report by altering the positive-test/no-report payoff as follows:

$$-\theta - Y_0 - p_1(0)\,\beta[Y_1 + S + S_p]$$

This expands the range of *ex post* trade sanctions over which a country will report:

$$S \leq \delta(\beta, c)\,Y_1 + \frac{\beta p_1(0)}{1 - \beta \Delta p_1(c)} S_p \tag{3}$$

which is another way of saying the country is more likely to report.

In a reporting equilibrium, punitive sanctions are costly when there is an outbreak but no positive test result. Therefore, these sanctions will encourage countries to obtain positive test results following an outbreak, that is, invest in surveillance. This is evident from the optimality condition for θ in the case of punitive sanctions:

$$q'(\theta^*) = \frac{1}{p_0\left\{\beta \Delta p_1(c)\,Y_1 - [1 - \beta \Delta p_1(c)]\,S + p_1(0)\,\beta S_p\right\}} \tag{4}$$

and the assumption that $q(\theta)$ is increasing and concave.

Punitive sanctions can take two forms. One is a trade restriction. Specifically, WHO convinces the ROW to limit trade with the offending country. Unfortunately, trade sanction may not be very effective following an epidemic. The ROW is already likely to have adopted *ex post* trade sanctions to limit the spread of the epidemic. Further sanctions will likely have little marginal impact on the country's exports. In technical terms, a country suffering an epidemic is already rubbing up against its participation constraint. At this point further incentives will simply cause the country to end even discussions with WHO.

A solution to the binding participation constraint is to offer the country some developmental assistance. The punitive sanction can then take the form of withdrawing the offer of assistance. Since external support is particularly valuable after a country has suffered an epidemic, the possible loss of support would be a strong inducement to participation. Assuming the participation constraint is a non-negative level of wealth, the amount of assistance required is $A = \beta(S + S_p) - W$, where W is the country's initial level of wealth. Poorer countries, which are less likely to meet the participation constraint but are also likely to have poor surveillance systems, will have to be offered a relatively greater amount of developmental assistance.

One difficulty with the assistance strategy is that it may not be politically and morally feasible to penalize a country by withdrawing assistance when a country has suffered an epidemic.[5] In short, WHO may not be able to commit to this strategy. Another difficulty with the assistance strategy is that it is very expensive. Because WHO does not know whether the country is in the outbreak or no outbreak state, it must offer assistance in both states. Although it may be counterintuitive, WHO cannot not offer lower levels of assistance, ceteris paribus, to countries with lower *ex ante* probabilities of an outbreak p_0. The reason is that the sanction can only be avoided by reporting a positive test result, which occurs after an outbreak has occurred. If countries with a lower *ex ante* probability of an outbreak lost less assistance, they would simply have less incentive to report the positive test result at this stage. Yet the updated probability of the outbreak is the same (one), and thus the value to WHO of a report is the same, regardless of the *ex ante* probability of outbreak.

Surveillance aid. There are two types of surveillance subsidies to consider. One is unconditional and the other is conditioned on WHO audits. Each dollar of unconditional subsidy θ_w increases total surveillance by less than a dollar. The reason is that WHO subsidies will permit a country to reduce its own investment in surveillance. Conversely each dollar of subsidy will displace a dollar of local spending on surveillance because the marginal value of each dollar a country invests in surveillance is greater than the cost of that investment for some level of own-investment greater than zero: $q'(\theta_w + \theta)\, p_0 \{\Delta p_1(c)[Y_1 + S] - S\} > 1$ for some $\theta > 0$. It is true that the higher the amount of WHO subsidy, the lower the country's investment in surveillance. But the rate of substitution of WHO dollars for country dollars approaches zero because $|q''|$ falls as θ_w rises.[6]

The other type of surveillance subsidy is one conditioned on WHO audits. A convenient way to implement this is to require that the country allow WHO to send its doctors to do the testing or the lab work on patient samples. The consequence is that WHO will always learn of positive test results. Conditional surveillance aid will only encourage reporting if two

[5] A related concern is that the country may suffer an outbreak and thus an epidemic even without a positive test result. Because the punitive sanction is triggered even in this case, the sanction may appear unfair. This too may make it hard to follow through on the punitive sanction.

[6] An interesting twist is possible when there are punitive sanctions. In that case, a country's participation contstraint may diminish the incentive effects of such sanctions. Surveillance subsidies, because they can relax the participation constraint, can renew the productivity of punitive sanctions.

requirements are met. First, a country must not already be in a reporting equilibrium, otherwise the condition is trivially met. If the country were already going to report, the conditional subsidy has the same effect as an unconditional subsidy. The second condition is that the country already has a positive level of medical resources to prevent an outbreak from becoming an epidemic. Because the country was not otherwise planning to report, the country would not invest in surveillance unless detection of an outbreak was privately useful. This would be the case only if the country had its own resources to prevent an outbreak from becoming an epidemic.

A perverse implication of the first requirement is that a conditional subsidy will discourage a country from investing any of its own money in surveillance. To see this, note that this subsidy will have two effects. On the one hand, the country will face a lower cost of surveillance in every state of the world. On the other hand, the country will face a higher cost in the state with a positive test result. The higher cost is because the country is forced to report even though reporting condition (1) is not satisfied. Countries could lower this cost by lowering the possibility of a positive test result and this is accomplished by cutting back on their own investments in surveillance.[7] An obvious corollary of this finding is that a conditional subsidy will only raise the level of investment in surveillance if the subsidy is greater than the private level of investment without the conditional subsidy. In either case, however, a conditional subsidy will increase the amount of public information on outbreaks available to the ROW.

How much will a conditional subsidy increase reporting? A country will accept aid if the benefits of the subsidy and reporting are greater than the benefits of private investment and not reporting:

$$\theta^* + p_0 \left\{ q\left(\theta_w\right) \Delta p_1 \left(c+m\right) - q\left(\theta^*\right) \Delta p_1 \left(m\right) \right\} \beta \left[Y_1 + S\right] \geq p_0 q\left(\theta_w\right) S \quad (5)$$

where θ^* is the optimal level of private investment without the subsidy and mandatory reporting. The first benefit (left-hand side) is that the country avoids spending any of its own money on surveillance. The second is that, if it is large enough, the subsidy may reduce the possibility that there is an epidemic. The extent of the benefit will depend on the medical resources

[7] More formally, observe that the optimality condition for private investment in surveillance is

$$q\left(\theta^* + \theta_w\right) = \frac{1}{p_0 \left\{ \Delta p_1 \left(c+m\right) \beta \left[Y_1 + S\right] - S \right\}}$$

When reporting condition (1) is not satisfied, the denominator is negative. It is easy to verify that the second order condition is not satisfied, suggesting a corner solution of $\theta^* = 0$.

of WHO relative to that of the country. The main cost (right-hand side) of accepting the subsidy is the cost of reporting, that is, sanctions if there is a positive test result.[8]

For analytic purposes, assume that the level of surveillance aid is the same as the amount of private investment without reporting, that is, $\theta_w = \theta^*$. In this case, equation (5) collapses to

$$S \leq \delta\left(\beta, c+m, m\right) Y_1 + \frac{\theta_w}{p_0 q\left(\theta_w\right)\left[1 - \beta \Delta p_1\left(m, c+m\right)\right]} \tag{6}$$

A useful comparison is the reporting condition for the case where the country has its own medical resources and does not reduce its own medical resources in response to medical assistance from WHO: $S \leq \delta\left(\beta, c+m, m\right) Y_1$. The appropriate conclusion is that a conditional subsidy expands the range of *ex post* sanctions that will induce reporting by the the second term in (6).

Equation (6) also illustrates a hidden cost of conditional subsidies to WHO. If WHO knew each country's medical resources, discount rate, and sensitivity to its population, then it can determine whether any given country would report even without conditional subsidies. These variables would identify $\delta\left(\beta, c+m, m\right) Y_1$ and thus the countries that would meet the reporting condition even with $\theta_w = 0$. WHO can save money by not offering such countries any subsidies. If, however, WHO does not have these data, it would have to offer conditional subsidies to all countries. These expenditure would, in some sense, be wasted on countries that would have reported even without subsidies.

Comparing levers. WHO has a choice of policy levers. It would be useful to know which lever is the most productive at inducing reporting and surveillance. The second and third columns of Table 2, respectively, summarize the answers. In general, one cannot endorse one lever as better than the rest. The appropriate lever to push at any given moment will depend on other factors, such expected mortality from an epidemic and the expected trade sanctions for reporting, as well the pressure currently applied on other levers. Nevertheless, there are four lessons to keep in mind.

First, from the perspective of WHO, the productivity of punitive sanctions will depend on the cost $(1/\lambda)$ that WHO bears from sanctions. The

[8]It is evident that the same factors that tend to induce reporting without conditional aid tend to induce countries to accept the conditional aid. These include greater medical assistance following an outbreak, a higher human cost of an epidemic, and lower ex post trade sanctions.

Lever	Reporting	Total Surveillance
c	$\frac{[1+\delta(\beta,c)]\beta p_1'(c)}{1-\beta\Delta p_1(c)}Y_1 > 0$	$\frac{(q'(\theta^*)/q''(\theta^*))\beta p_1'(c)[Y_1+S]}{p_0\{\beta\Delta p_1(c)[Y_1+S]-S\}} > 0$
S_p	$\frac{\beta p_1(0)}{1-\beta\Delta p_1(c)}\lambda$ if participation constraint not binding	$\frac{-(q'(\theta^*)/q''(\theta^*))\beta p_1(0)}{p_0\{\beta\Delta p_1(c)[Y_1+S]-S+p_1(0)\beta S_p\}}\lambda > 0$ if participation constraint not binding
Cond. θ_w	$\frac{1-\frac{\partial q}{\partial\theta_w}\frac{\partial\theta_w}{q}}{p_0 q(\theta_w)[1-\beta\Delta p_1(m,c+m)]} \gtreqless 0$	$-\theta^*$ if $\theta_w \leq \theta_w$, 1 otherwise

Table 2: Productivity of different policy levers

productivity may be high if the ROW primarily bears these costs.[9] Second, a punitive sanction is only productive if the target country is wealthy enough to suffer under the sanction. Where the participation constraint binds, WHO will have to promise developmental aid that it can withdraw as punishment. The cost of this aid is greater than one because WHO must provide it even in cases where there is no outbreak.

Third, additional conditional surveillance subsidies may reduce reporting if additional investment in surveillance is very productive (specifically, elasticity greater than one) at detecting outbreaks. In that case, the cost in terms of increasing the frequency of positive test results and thus *ex post* sanctions is greater than the benefit in terms of lowering own-investment costs and WHO medical assistance. Finally, conditional surveillance subsidies only increase the total level of surveillance if the subsidy is greater than the amount of private investment that the country would otherwise make. That said, conditional subsidies always increases the level of publicly-available surveillance. The reason is that surveillance conducted by the country in the absence of conditional subsidies is not reported to WHO.

4 Preemptive sanctions

Economic partners certainly impose trade and travel restrictions on a country that reports an outbreak. But this is not the only condition under which trade and travel are curtailed. Partners frequently impose what we call "preemptive" sanctions on countries based on suspicions of an outbreak

[9] From the perspective of the ROW, punitive trade sanctions will have a negative efficiency cost, but a positive distributive effect. According to the conventional economic theory of international trade, the net cost including the country targeted by the sanctions is negative. But excluding costs imposed on the target country, the sign is ambiguous.

that has not been confirmed. These sanctions are not always formal, or even under the control of partner governments. For example, concerns about avian flu discouraged tourism to Southeast Asia even before any governments imposed legal restrictions on travel to that region (TTG Asia Jan. 27 - Feb. 6, 2006). After all, it is only natural that demand for a country's products and services responds to perceived as well as actual risks to consumer health.[10] In this section we examine how sanctions triggered by the *probability* of an outbreak rather than a *report* of an outbreak affect the incentive to surveil and report outbreaks. Our primary finding is that, unlike ordinary *ex post* sanctions, preemptive sanctions actually encourage investigation and disclosure. Moreover, these sanctions complement the various policy levers available to WHO.[11]

We begin with the model as set forth in Section 2. There the rest of the world (ROW) imposed sanctions on a country only if it reported a positive test result. Now we assume that the ROW also imposes sanctions based on its belief that a country has an outbreak. This preemptive sanction takes the form of a probabilistic sanction λS where the probability λ of the sanction is the ROW's assessment of the probability of an outbreak given that the country does not report an outbreak:

$$\lambda\left(E\left[q\right],p_0\right)=\frac{\left\{1-q\left(E\left[q\right]\right)\right\}p_0}{1-q\left(E\left[q\right]\right)p_0} \tag{7}$$

The probability of a sanction depends on the ROW's belief about the probability of an outbreak p_0. We assume that this probability is public knowledge, even though an actual outbreak or a positive report may not be. The probability of a preemptive sanction also depends on the country's probability of detecting and reporting a sanction. Because a country's investment in surveillance is not public information, the probability of detection is simply based on the ROW's beliefs, that is, on $E\left[q\right]$. (We will relax our assumptions about p_0 and $E\left[q\right]$ later in this section.) Finally, the preemptive sanction is only imposed in the states of the world without a report of an outbreak. The reason is that, when there is a report, there will be certain *ex post* trade sanctions. The latter make preemptive sanctions redundant.[12]

[10] There is also the risk that unconfirmed concerns about disease outbreaks may cause foreign direct investment to decline.

[11] Indeed, WHO may have some direct but imprecise influence on preemptive sanctions because they are a primary source of information on the likelihood of outbreaks in each country.

[12] In any case, it is easy to verify that the probability of an outbreak given a report is $1/E\left[q\right]>1$.

Test result	Report positive result?	Payoff
Positive	No	$-\theta - Y_0 - \lambda S - p_1(m)\beta[Y_1 + S]$
$[p_0 q]$	Yes	$-\theta - Y_0 - S - p_1(m+c)\beta[Y_1 + S]$
Negative	No	$-\theta - \lambda S - \frac{p_0(1-q)}{1-p_0 q}(Y_0 + p_1(0)\beta[Y_1 + S])$
$[1 - p_0 q]$	Yes	$-\theta - \frac{(1-p_0)}{1-p_0 q}S - \frac{p_0(1-q)}{1-p_0 q}\{Y_0 + S + p_1(0)\beta[Y_1 + S]\}$

Table 3: Payoffs with preemptive sanctions

Table 3 describes how preemptive sanctions modify the country's payoffs in each privately observed state of the world.

Reporting and surveillance. It is immediately apparent that preemptive sanctions increase reporting. Because a country might now be sanctioned even if it does not report an outbreak, the incremental cost of reporting falls. The same logic also encourages more surveillance. The cost of surveillance is that it increases the probability of reporting an outbreak. If the relative cost of reporting declines, the cost of surveillance also falls, hence more surveillance. More formally, the reporting condition is now

$$S \leq \frac{\beta \Delta p_1}{1 - \lambda - \beta \Delta p_1} Y_1 \tag{8}$$

The right-hand side is clearly larger than in the reporting condition (1) for the basic model. The new surveillance condition is

$$q'(\theta^*) = \frac{1}{p_0 \{\beta \Delta p_1(c) Y_1 - [1 - \lambda - \beta \Delta p_1(c)] S\}}$$

Again, the right-hand side is larger the analogous condition (2) for the basic model. The lesson is that, whereas *ex post* sanctions discourage reporting and surveillance, preemptive sanctions increase both activities.

Static policy levers. Preemptive sanctions also affect the productivity of WHO's various policy levers. These sanctions add to the power of medical assistance, punitive sanctions and conditional surveillance to encourage reporting in the sense that smaller amounts of these incentives are now required to induce any given level of reporting. These levers continue to encourage more surveillance, though at a slightly lower rate because preemptive sanctions are now doing some of the heavy lifting.[13]

[13] The only caveat to these findings is that, although preemptive sanctions increase the

4.1 Dynamic policy lever: WHO-as-auditor

WHO plays the surveil-and-report game against many different countries. These countries likely differ in the probability that they will suffer an outbreak. If countries have private information on these probabilities, WHO can piggy-back on preemptive sanctions to get all but the most recalcitrant countries to surveil and report outbreaks. The critical policy instrument is that WHO offers to audit a country's surveillance system. Specifically, WHO would review a country's surveillance system and verify a country's negative and positive test results.

The driving force behind this fortuitous result is that the ROW imposes preemptive sanctions on what they believe is the average probability of an outbreak across countries (or classes of countries). It is difficult for lower-than-average-risk countries to prove they are relatively less dangerous and reduce their risk of suffering preemptive sanctions. If they report only negative test results, the ROW may remain skeptical because negative results are easy to fabricate: have only known uninfected persons take the test. If they report positive test results, the ROW will impose full sanctions immediately.

Suppose, however, that WHO can audit and confirm any country's own test results. Then lower-than-average-risk countries will give WHO access to its surveillance networks in order to convince the ROW that they are less threatening, reducing the risk of the ROW's preemptive sanctions. But as lower-risk countries submit to WHO audits, the ROW will revise upward its estimate of the average risk of outbreaks on non-audited countries. This in turn will increase the risk of preemptive sanctions against the non-audited countries. Among them, some previously higher-than-average-risk countries will now become lower-than-average-risk countries. They will request WHO audits to prove themselves safer than average and reduce the risk of preemptive sanctions. The process will repeat until only the most recalcitrant countries – or perhaps none at all – refuse to report. These last countries will be those that are least likely to report in the first place – those with little dependence on trade or tourism, those with a great deal of medical resources, or those that are highly insensitive to the health of their own citizens.

To formally demonstrate what we call the "reverse-lemons" result, let

productivity of punitive sanctions, they also increase their cost to the WHO. The reason is that, for countries whose participation constraint is not very slack, preemptive sanctions may lower wealth levels and make the participation constraint bind. This will increase the foreign aid that the WHO must promise to ensure punitive sanctions are productive.

countries be indexed by i and let p_{0i} be country i's probability of an outbreak. We assume that there is heterogeneity in this probability across countries and that p_{0i} is private information to country i, but that the ROW knows the average probability of an outbreak: $\bar{p}_0 = \sum_i p_{0i}/N$ among the N non-audited countries. To simplify, assume that probability of detection is one (so we can ignore the investment decision) and that WHO employs no other policy levers – not even medical assistance – to encourage reporting (so that no country is in a report equilibrium).[14]

Because a non-audited country never reports, the ROW estimates the probability of an outbreak without a report as simply the probability of an outbreak: $\lambda = \bar{p}_0$. Also because it does not report, the non-audited country suffers preemptive sanctions of λS whether or not it suffers an outbreak. If a country submits to an audit, it will suffer no preemptive sanctions when there is no outbreak because WHO vouches for negative test results and the probability of detection is assumed to be one. If there is a positive test result, however, the audit will disclose this to the ROW, triggering an *ex post* sanction of S.

A country prefers an audit only if the probability of *ex post* sanctions with an audit is lower than the incidence of preemptive sanctions without an audit: $p_{0i}S \leq \lambda S$. But this condition is identical to

$$p_{0i} < \bar{p}_{0i}$$

In other words, all countries with a lower-than-average probability of outbreak will submit to an audit.

This has important dynamic effects. The ROW will revise upward its estimate of the probability of an outbreak among non-audited countries to be

$$\bar{p}_0' = \sum_{p_{0i} < \bar{p}_0} p_{0i}/N' > \bar{p}_0$$

where N' is the number of countries with probabilities of outbreak above $\bar{p}_{0i}$. Of the countries that did not submit to an audit in the first round, which will now submit to an audit? Those for whom the probability of *ex post* sanctions with an audit is less than the incidence of preemptive sanctions without an audit, or countries with $p_{0i} < \bar{p}_0'$. This second round of exit from the ranks of the non-audited will cause ROW to again revise its estimate of

[14] The appendix demonstrates that the results are similar if we incorporate imperfect detection. Because countries that want to voluntarily report will also submit to an audit, they do not alter our result.

outbreak among non-audited countries to

$$\bar{p}_0'' = \sum_{p_{0i} < \bar{p}_0'} p_{0i}/N'' > \bar{p}_0' > \bar{p}_0$$

It should be apparent that this process will continue until countries with the maximum p_{0i} remain. At that point an audit provides the ROW no new information because the ROW knows the precise probability of outbreak among non-auditors: $p_{0,\max}$.

Introducing medical assistance only hastens this dynamic because it relaxes the auditing condition. Even some higher-than-average risk countries will now audit. The relevant condition is that the higher rate of sanctions with disclosure of positive test results does not offset the benefits of WHO medical assistance:

$$(p_{0i} - \lambda) S \leq p_{0i} \Delta p_1 (m, m+c) \beta [Y_1 + S]$$

This is equivalent to the condition $p_{0i} \leq \gamma(S, c) p_{0i}$ where

$$\gamma(S, c) = \frac{S}{S - \Delta p_1 (m, m+c) \beta [Y_1 + S]} > 1$$

At each iteration, a greater proportion of non-audited countries decide to be audited. This will make unravelling to disclosure all the quicker.

Introducing imperfect detection has the opposite effect: it slows down the unravelling. One reason is that the country now faces preemptives sanctions – though at a lower frequency – even if it submits to an audit. With imperfect detection, there is a risk of an outbreak even if the country does not obtain a positive test result. The ROW will use preemptive sanctions to address this risk. Ignoring a country's own medical resources, this changes the auditing condition to

$$p_0 \leq \frac{[\lambda(\bar{p}_0) - \lambda(\theta^*, \bar{p}_0)] S - \theta^*}{q(\theta^*) \{[1 - \lambda(\theta^*, \bar{p}_0)] S - \Delta p_1 (c) \beta [Y_1 + S]\}} \tag{9}$$

where $\lambda(\theta^*, \bar{p}_0)$ and $\lambda(\bar{p}_0)$ are preemptive sanctions against audited and non-audited countries and θ^* is surveillance by audited countries. The denominator is positive because the relevant countries are those who would not otherwise report. Non-audited countries do not surveil because they have no medical resources and audited countries surveil in order to reduce preemptive sanctions. Therefore, the numerator, and thereby the cutoff, is also positive.

Another reason that imperfect detection may slow down unravelling is a moral hazard with respect to surveillance when countries have their own medical resources and therefore surveil even in the absence of an audit. Countries that submit to an audit may actually surveil less in order to reduce the risk of *ex post* sanctions. This comes at a cost: preemptive sanctions against audited countries will rise. As such the gap between the rate of sanctions with and without auditing falls, narrowing the range of countries for whom auditing is cost effective. WHO can reverse this trend – in fact, control the rate of unravelling – by employing conditional surveillance aid, which is just a bundle of auditing and subsidies for investments in detection. The subsidies offset the moral hazard with private surveillance efforts. So long as the are sufficient to do so, the auditing condition becomes

$$p_{0i} \leq \frac{\left[\bar{\lambda} - \lambda_w\right] S + \left(\theta^{**} - \theta^{*}\right)}{q_w \left\{\left[1 - \bar{\lambda}\right] S - \Delta p_1 \left(m, m + c\right)\right\}} \tag{10}$$

where λ_w and $\bar{\lambda}$ are the rates of preemptive sanctions and θ^* and θ^{**} are private investments in surveillance with and without auditing, and q_w is the total level of surveillance, including subsidies, with auditing. The denominator is positive because we are only concerned with countries that do not voluntarily report. The first term in the numerator is positive for lower-risk countries so long as subsidies offset the moral hazard with private surveillance efforts and the second term is positive because of the cost savings from that moral hazard.

5 Sensitivity versus specificity

The public health community places a great deal of emphasis on the sensitivity of diagnostic testing for disease, that is, on the probability of detecting disease in an infected patient. For example, both WHO Manual on Animal Influenza Detection and Surveillance (2002) and the Bush Administration's National Strategy for a Pandemic Influenza (2005) repeatedly stress sensitivity but never once mention specificity, or the probability of not detecting disease in an unifected person, as an objective of surveillance. This focus on sensitivity makes a great deal of sense. One cannot stop an epidemic if one does not detect an outbreak. Increasing sensitivity and its corollary – reducing false negatives – ensure that the infected do no go without treatment and spread a contagion.

False negatives, however, have two sources. The obvious one is technological – the inability of a diagnostic test to identify an infected person.

	Positive test	Negative test
Outbreak	$p_0\tilde{r}$	$p_0(1-\tilde{r})$
No outbreak	$(1-p_0)(1-\hat{r})$	$(1-p_0)\hat{r}$

Table 4: Effect of sensitivity and specificity on conditional probability of an outbreak

The less obvious source is behavioral – the failure of countries to surveil their populations and report infections to authorities with the capacity to contain their spread. Ironically, an important cause of behavioral false negatives are diagnostic tests that lack specificity. Low specificity and its corollary – false positives – discourage surveillance and reporting because they increase the cost of these activities. False positives are all pain, no gain: they trigger sanctions but do not offer any benefits from medical assistance because there is no outbreak and thus epidemic to stop.[15] The lesson is that investments in diagnostic testing should not neglect the problem of technological specificity lest behavioral false negatives offset advances in technological sensitivity.

To illustrate our logic, let $\tilde{r}$ be sensitivity, or the probability of a positive test result given an outbreak, and $\hat{r}$ be specificity, or the probability of a negative test result given no outbreak or specificity. (This implies that $(1-\tilde{r})$ and $(1-\hat{r})$ are the probabilities of technological false negatives and false positives, respectively.) Ignoring hetergeneity in the risk of outbreaks, Table 4 describes how imperfect testing modifies the conditional probability of an outbreak. The main change from the basic model is that the lower left hand cell is no longer zero. Finally, let $\theta(\tilde{r}, \hat{r})$ be the monetary cost of investment in sensitive and specific surveillance. As is usual, we will assume this function is increasing and convex in its arguments.

Sensitivity and specificity alters the payoffs in the model with preemptive sanctions in two ways. First, the rest of the world (ROW) will reduce the

[15] A natural question is whether repeated testing can overcome false positives. That will not always be the case. First, early in their development, diagnostic tests might employ indicators for multiple ailments, including the disease being targeted. This will imply strong positive correlation across test results for a patient who has one of those ailments, but not the disease. Second, early on in an outbreak, there may be a great deal of confusion. This confusion can lead to false positives that are not reversed for some time (Zamiska Oct. 18, 2005). Third, false positives may trigger sanctions before a second test is conducted (Canadien Press Sept. 9, 2003). Indeed, it may even trigger preemptive sanctions afterwards as the ROW might rationally believe there is a greater chance of an outbreak despite a second negative test result because there is a risk of a false negative.

Test result?	Report?	Payoff
Positive	No	$-\theta(\tilde{r},\hat{r}) - \bar{\lambda}S$ $-(1-\gamma(\tilde{r},\hat{r}))(Y_0 + p_1(m)\beta[Y_1+S])$
$[p_0\tilde{r} + (1-p_0)(1-\hat{r})]$	Yes	$-\theta(\tilde{r},\hat{r}) - (1-\bar{\gamma})S$ $-(1-\gamma(\tilde{r},\hat{r}))(Y_0 + p_1(m+c)\beta[Y_1+S])$
Negative	No	$-\theta(\tilde{r},\hat{r}) - \bar{\lambda}S$ $-\lambda(\tilde{r},\hat{r})(Y_0 + p_1(0)\beta[Y_1+S])$
$[p_0(1-\tilde{r}) + (1-p_0)\hat{r}]$	Yes	$-\theta(\tilde{r},\hat{r}) - (1-\bar{\gamma})S$ $-\lambda(\tilde{r},\hat{r})(Y_0 + p_1(0)\beta[Y_1+S])$

Table 5: Payoffs with imperfect detection technology

frequency with which it imposes *ex post* sanctions because not all positive test results indicate an outbreak and trade and tourism sanctions hurt both the target and the sanctioning country. Specifically the probability of an *ex post* sanction falls to $(1-\bar{\gamma})$ where $\bar{\gamma}$ is the probability of no outbreak even though the country reports an outbreak. Note that this probability is based on the ROW's prior because the ROW does not observe $(\tilde{r},\hat{r})$. Second, the country alters its own assessment of the probability $(1-\gamma(\tilde{r},\hat{r}))$ that it suffered an outbreak given a positive test result and the probability $\lambda(\tilde{r},\hat{r})$ given a negative test result as follows:

$$1-\gamma(\tilde{r},\hat{r}) = \frac{p_0\tilde{r}}{p_0\tilde{r} + (1-p_0)(1-\hat{r})}$$

$$\lambda(\tilde{r},\hat{r}) = \frac{p_0(1-\tilde{r})}{p_0(1-\tilde{r}) + (1-p_0)\hat{r}}$$

The resulting payoffs are summarized in Table 5.

Reporting. Imperfect detection will have conflicting effects on reporting. On the one hand, because positive test results may be false, the value of medical assistance a country receives for reporting them falls. If there is no outbreak, there is no epidemic to prevent. On the other hand, false positives also cause the ROW not to sanction every report of a positive test result. This effect will reduce the cost of reporting. Formally, the reporting condition will be

$$S \leq \frac{(1-\gamma(\tilde{r},\hat{r}))\beta\Delta p_1(m, m+c)}{\left(1-\bar{\gamma}-\bar{\lambda}\right) - (1-\gamma(\tilde{r},\hat{r}))\beta\Delta p_1(m, m+c)}$$

Ignoring preemptive and less-than-automatic *ex post* santions, only the first effect matters and reporting will fall relative to the basic case (see equation

(1)). Relative to reporting under preemptives alone (see equation (8)), however, one cannot say whether reporting will rise or fall because it is unclear which effect is greater.

The more interesting finding is that sensitivity and – importantly – specificity increase the incentive to report. Sensitivity reduces the possibility that there is an outbreak that is not detected and therefore not controlled. Specificity rules out cases where there are sanctions because there is a positive test result but no benefits from medical assisance because there is no actual outbreak.

Surveillance. Before turning to surveillance, we should clarify who controls the rate of testing error. In reality, private firms and research institutions develop diagnositic tests. Their objectives, in turn, are set by a combination of WHO priorities and actual demand by target countries. If WHO highlights sensitivity, some countries will follow and tests that reduce false negatives will be supplied. Other countries may prefer specificity and tests that target false positives will be supplied. Early in the process the price of sensitivity and specificity will be high because research and development will still be required to develop tests and set up mass-production facilities. So when we assume countries must choose investments in sensitivity and specificity, we are really speaking of investments to generate demand for development and production of tests by organizations that may not even reside in those countries.

It is unclear whether imperfect detection raises or lowers the level of private investment in surveillance. The direction of the effect will depend on whether there are trade-offs between enhanced sensitivity and specificity. To see this formally, observe that the optimality conditions for sensitivity and specificity in the present model are

$$\theta_1(\tilde{r},\hat{r}) = p_0\left(\Delta p_1(c)\,\beta\,[Y_1+S] - \left[1-\bar{\gamma}-\bar{\lambda}\right]S\right) \quad (11)$$

$$\theta_2(\tilde{r},\hat{r}) = (1-p_0)\left(1-\bar{\gamma}-\bar{\lambda}\right)S \quad (12)$$

In order to compare these to prior models, we must change the control variable from the level of investment to the quality q of testing and interpret $\theta(q)$ as the cost of testing quality. The optimality condition under the preemptive sanctions model, for example, is

$$\theta'(q) = p_0\left(\Delta p_1(c)\,\beta\,[Y_1+S] - [1-\lambda]\,S\right)$$

Because the basic model, on which the model with preemptive sanctions is based, permitted false negatives, it is not surprising that the optimality condition under preemptive sanctions resembles that for sensitivity in the present model. What we are observing is actually the change in investment once we introduce specificity. The question is: does total investment rise or fall? The answer will depend on the form of $\theta(\tilde{r}, \hat{r})$. If there are no trade-offs between sensitivity and specificity, such as when $\theta(\tilde{r}, \hat{r}) = \theta(\tilde{r}) + \theta(\hat{r})$, then total investment will rise. Condition (11) ensures that investment in sensitivity is the same as before and (12) implies positive investment in specificity. If there are trade-offs such that sensitivity comes at the expense of specificity or vice verse, that is, $\theta_{12}(\tilde{r}, \hat{r}) > 0$, then it is possible that there will be less investment overall. The investment in specificity may cause the same level of expenditure on sensitivity to yield less sensitivity than before, and the improvement in specificity may not overcome that loss.

6 Conclusion

The goal of this paper was to explore some complexities concerning the incentives countries have to disclose disease outbreaks. With respect to WHO policy levers, we find that punitive sanctions may have limited effects against countries that are too poor to suffer any further and that subsidies for surveillance may create the moral hazard that recipients reduce private investment in surveillance. With respect to sanctions, we see that the incentive effects depend critically on the trigger for sanctions: unlike sanctions for reporting, sanctions for risk of disease may actually encourage disclosure. Finally, with respect to the quality of diagnotic testing, we observe an interesting relationship between sensitivity and specificity: namely, technological specificity may actually enhance behavioral and thus aggregate sensitivity.

The analysis in this paper, however, is still relatively simplistic. It introduces some twists because of imperfect information and gaming, but it does not account for other turns that may be found in real life. One example is that there may be serious constraints on the ability of WHO to audit countries' surveillance systems. Wide-ranging verification of test results requires a great deal of human resources and funding. The supply of these resources, like those for other international organizations, is limited by collective action problems among member states. Another example is that the rest of the world may be quick to impose sanctions on a target because it benefits politically-powerful domestic industries. This may increase the power of preemptive sanctions by reducing the relative cost of reporting. But it may also cause the rest of the world to increase the frequency of *ex post* sanctions despite false positives and those sanctions would increase the cost of reporting. Future work must explore these and other considerations to ensure that the public good value of disease surveillance and reporting is fully realized.

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8 Appendix

Derivation of (1). This follows from the second payoff being greater than the first payoff in Table 1.

Derivation of (2). The objective function of a country that will report a positive test result is

$$\max_{\theta} -\theta - p_0 q(\theta) S - p_0 q(\theta) \{Y_0 + \beta [Y_1 + S]\} - (1 - p_0 q(\theta)) \{Y_0 + \beta [Y_1 + S]\}$$

Equation (**2**) can be derived by solving the the first-order condition for $q'(\theta)$.

Derivation of Table 2. Medical assistance results are obtained by taking derivatives of (1) and (2) with respect to c and solving for $\partial S/\partial c$ and $\partial\theta/\partial c$, respectively. Punitive sanctions results are obtained by taking derivatives of (3) and (4) with respect to S_p and solving for $\partial S/\partial S_p$ and $\partial\theta/\partial S_p$, respectively. The first conditional surveillance aid result is obtained by taking the derivative of (6) with respect to θ_w and solving for $\partial S/\partial\theta_w$. The second result follows from the moral hazard with surveillance aid.

Derivation of (7). This is just a simplification of:

$$\begin{aligned} \lambda(E[q], p_0) &= \frac{\Pr(no\ report|outbreak)\Pr(outbreak)}{\Pr(no\ report)} \\ &= \frac{\{1 - E[q]\} p_0}{(1 - E[q]) p_0 + (1 - p_0)} \end{aligned}$$

Derivation of (9). For simplicity, ignore i subscripts. The non-audited country conducts no surveillance. Recall countries are in a no-report equilibrium; thus, without their own medical resources, there is no private benefit to surveillance in terms of preventing an epidemic. The ROW estimates the probability of an outbreak in a non-audited country as $\lambda(\bar{p}_0) = \bar{p}_0 = \int p_0 f(p_0)\, dp_0$.

If a country submits to an audit, it can credibly signal it spends θ on surveillance. The ROW estimates the probability of an outbreak without a report as

$$\lambda\left(\theta,\bar{p}_0\right)=\frac{\left(1-q\left(\theta\right)\right)\bar{p}_0}{1-q\left(\theta\right)\bar{p}_0}$$

Note that the derivative with respect to θ is

$$\frac{\partial\lambda}{\partial\theta}=\frac{\left(\lambda-1\right)\bar{p}_0 q'\left(\theta\right)}{1-q\left(\theta\right)\bar{p}_0}<0 \tag{13}$$

According to Table 3, the country chooses investment to maximize

$$\begin{aligned}&-\theta-p_0Y_0-p_0q\left(\theta\right)S-\left(1-p_0q_0\left(\theta\right)\right)\lambda\left(\theta,\bar{p}_0\right)S\\&-p_0q\left(\theta\right)p_1\left(c\right)\beta\left[Y_1+S\right]-p_0\left(1-q\left(\theta\right)\right)p_1\left(0\right)\beta\left[Y_1+S\right]\end{aligned}$$

There are preemptive sanctions even without a positive test result because of the posibility of false negatives.) The optimality condition is

$$q'\left(\theta^*\right)=\frac{1}{p_0\left\{\begin{array}{c}\Delta p_1\left(c\right)\beta\left[Y_1+S\right]+\\\left\{\frac{1-p_0q\left(\theta^*\right)}{1-\bar{p}_0q\left(\theta^*\right)}\bar{p}_0-1\right\}\left(1-\lambda\left(\theta^*,\bar{p}_0\right)\right)S\end{array}\right\}} \tag{14}$$

The last equation was derived using (13). So long as

$$\frac{1-p_0q\left(\theta^*\right)}{1-\bar{p}_0q\left(\theta^*\right)}>0>\frac{\overbrace{\Delta p_1\left(m+c\right)\beta\left[Y_1+S\right]-\left(1-\lambda\left(\theta^*,\bar{p}_0\right)\right)S}^{(-)}}{\bar{p}_0\left(1-\lambda\left(\theta^*,\bar{p}_0\right)\right)S} \tag{15}$$

the denominator of the right-hand side of (14) will be positive, implying $\theta^*>0$. Because the right-hand side of (15) is negative, there exists some $\tilde{p}_0>\bar{p}_0$ such that $p_0<\tilde{p}_0$ is a sufficient condition for $\theta^*>0$.

A country will submit to an audit if

$$\begin{aligned}&-\theta^*-p_0Y_0-p_0q\left(\theta^*\right)S-\left(1-p_0q_0\left(\theta^*\right)\right)\lambda\left(\theta^*,\bar{p}_0\right)S\\&-p_0q\left(\theta^*\right)p_1\left(c\right)\beta\left[Y_1+S\right]-p_0\left(1-q\left(\theta^*\right)\right)p_1\left(0\right)\beta\left[Y_1+S\right]\\&\qquad\geq-p_0Y_0-\lambda\left(\bar{p}_0\right)S-p_0p_1\left(0\right)\beta\left[Y_1+S\right]\end{aligned}$$

This simplifies to

$$\begin{aligned}&\left(1-p_0q_0\left(\theta^*\right)\right)\left[\lambda\left(\bar{p}_0\right)-\lambda\left(\theta^*,\bar{p}_0\right)\right]S+p_0q\left(\theta^*\right)\Delta p_1\left(c\right)\beta\left[Y_1+S\right]\\&\qquad\geq\theta^*+p_0q\left(\theta^*\right)\left[1-\lambda\left(\bar{p}_0\right)\right]S\end{aligned}$$

The benefits of auditing are lower preemptive sanctions and external medical assistance. The costs are the investment in surveillance and greater ex post sanctions. Solving for p_0 yields

$$p_0 \leq \frac{[\bar{p}_0 - \lambda(\theta^*, \bar{p}_0)] S - \theta^*}{q(\theta^*)\{[1-\lambda(\theta^*, \bar{p}_0)] S - \Delta p_1(c) \beta [Y_1 + S]\}} = \hat{p}(p_0, \bar{p}_0, S, c, Y_1) \tag{16}$$

Because the denominator is positive, countries will report if $[\bar{p}_0 - \lambda(\theta, \bar{p}_0)] S = |\lambda_1(\theta, \bar{p}_0)| S > \theta^*$. So long as ex post sanctions are sufficiently high or the marginal product of surveillance is greater than θ^*/S, the cutoff will be positive.

Once countries report, the ROW revises its estimate of an outbreak among countries that do not audit to

$$\int p_0 f(p_0 | p_0 \leq \hat{p}(p_0, \bar{p}_0, S, c, Y_1)) dp_0 > \bar{p}_0$$

This increase the cutoff for submitting to an audit by

$$\frac{[1-\lambda_2(\theta^*, \bar{p}_0)] S + \hat{p}(p_0, \bar{p}_0, S, c, Y_1) q(\theta^*) \lambda_2(\theta^*, \bar{p}_0) S}{q(\theta^*)\{[1-\lambda(\theta^*, \bar{p}_0)] S - \Delta p_1(c) \beta [Y_1 + S]\}} > 0 \tag{17}$$

So more countries will submit to an audited. So long as (16) is positive, the process repeats until all countries are audited because (17).

Derivation of (10). The ROW estimates the probability of an outbreak for a non-audited country as

$$\lambda(\bar{p}_0) = \frac{\{1 - q(\theta(\bar{p}_0))\} \bar{p}_0}{1 - q(\theta(\bar{p}_0)) \bar{p}_0} \tag{18}$$

where $\theta(\bar{p}_0) > 0$[16] is the implicit function defined by the equation for a country's optimal surveillance level

$$q'(\theta(\bar{p}_0)) = \frac{1}{\bar{p}_0 \{\Delta p_1(m) \beta [Y_1 + S]\}} \tag{19}$$

This is just the optimality condition (22) as applied to the average country.

The ROW estimates the probability of an outbreak without a report for an audited country, that is, $\bar{\lambda} = \lambda(\theta(\bar{p}_0, \theta_w) + \theta_w)$, as the implicit solution to the following pair of equations

$$\lambda(\bar{p}_0, \theta_w) = \frac{\{1 - q(\bar{p}_0, \theta_w)\} \bar{p}_0}{1 - q(\bar{p}_0, \theta_w) \bar{p}_0} \tag{20}$$

[16] No reporting implies no investment only if the country has no medical resources. In that case, $\Delta p_1(0) = 0$.

$$q'(\theta^* + \theta_w) = \frac{1}{\bar{p}_0 \left\{ \Delta p_1 (m+c) \beta [Y_1 + S] + (\bar{p}_0 - 1) \left(1 - \bar{\lambda}\right) S \right\}} \tag{21}$$

where $q(\bar{p}_0, \theta_w) = q(\theta(\bar{p}_0, \theta_w) + \theta_w)$. The second equation is simply the optimality condition (23) as applied to the average country.

Unlike the ROW, each country has private information on its own probability of an outbreak. If a country does not submit to an audit, surveillance is given by

$$q'(\theta^{**}) = \frac{1}{p_0 \{ \Delta p_1 (m) \beta [Y_1 + S] \}} \tag{22}$$

Note that θ^{**} rises with p_0. Therefore, if $p_0 < \bar{p}_0$, then $\theta^{**}(p_{0i}) < \theta^{**}(\bar{p}_0)$ which is $\theta(\bar{p}_0)$ in (19).

If a country accepts conditional surveillance subsidies, it can credibly reveal that it spends at least θ_w on surveillance. Payoffs in Table 3 suggests that the country chooses investment to maximize

$$\begin{array}{l} -\theta - p_0 Y_0 - p_0 q(\theta + \theta_w) S - (1 - p_0 q_0 (\theta + \theta_w)) \lambda (\theta(\bar{p}_0, \theta_w) + \theta_w) S \\ -p_0 q(\theta + \theta_w) p_1 (m+c) \beta [Y_1 + S] - p_0 (1 - q(\theta + \theta_w)) p_1 (0) \beta [Y_1 + S] \end{array}$$

The first order condition yields

$$q'(\theta^* + \theta_w) = \frac{1}{p_0 \left\{ \begin{array}{c} \Delta p_1 (m+c) \beta [Y_1 + S] + \\ \{\gamma(\bar{p}_0, \theta_w) \bar{p}_0 - 1\} (1 - \lambda(\theta(\bar{p}_0, \theta_w) + \theta_w)) S \end{array} \right\}} \tag{23}$$

where

$$\gamma(\bar{p}_0, \theta_w) \equiv \frac{1 - p_0 q(\bar{p}_0, \theta_w)}{1 - \bar{p}_0 q(\bar{p}_0, \theta_w)}$$

The last equation was derived using the result

$$\lambda'(\theta(\bar{p}_0, \theta_w) + \theta_w) = \frac{(\lambda(\theta(\bar{p}_0, \theta_w) + \theta_w) - 1) q'(\theta^* + \theta_w) \bar{p}_0}{1 - q(\theta^* + \theta_w) \bar{p}_0} \leq 0$$

So long as the country has

$$\frac{1 - p_0 q(\theta^* + \theta_w)}{1 - \bar{p}_0 q(\theta^* + \theta_w)} > 0 > \frac{\overbrace{\Delta p_1 (m+c) \beta [Y_1 + S] - (1 - \lambda(\theta(\bar{p}_0, \theta_w) + \theta_w)) S}^{(-)}}{\bar{p}_0 (1 - \lambda(\theta(\bar{p}_0, \theta_w) + \theta_w)) S}$$

the denominator of the right-hand side of (23) will be positive, implying $\theta^* > 0$. Because the right-hand side of the previous equation is negative, $p_0 < \bar{p}_0$ is a sufficient condition for $\theta^* > 0$. It is easy to verify that except in the case of an extremely safe country, it will not be the case that $\theta^* > \theta^{**}$. This is partly why WHO needs to provide surveillance aid.

A country will only accept conditional surveillance aid if the benefits outweigh the costs:

$$\begin{aligned}&-\theta^* - p_0 q\left(\theta^* + \theta_w\right) S - \left(1 - p_0 q_0\left(\theta^* + \theta_w\right)\right) \lambda\left(\bar{p}_0, \theta_w\right) S \\ &\quad + p_0 q\left(\theta^* + \theta_w\right) \Delta p_1\left(0, m + c\right) \beta\left[Y_1 + S\right] \\ &\quad > -\theta^{**} - \lambda\left(\bar{p}_0\right) S + p_0 q\left(\theta^{**}\right) \Delta p_1\left(m\right) \beta\left[Y_1 + S\right]\end{aligned}$$

Using the result

$$\begin{aligned}&p_0 q_w \Delta p_1\left(0, m + c\right) \beta\left[Y_1 + S\right] - \left(p_0 q^{**} - p_0 q_w + p_0 q_w\right) \Delta p_1\left(0, m\right) \beta\left[Y_1 + S\right] \\ &\quad = p_0 q_w \Delta p_1\left(m, m + c\right) - p_0\left(q^{**} - q_w\right) \Delta p_1\left(0, m\right) \beta\left[Y_1 + S\right]\end{aligned}$$

the condition simplifies to

$$\begin{aligned}&\left[\bar{\lambda} - \lambda_w\right] S + \left[\theta^{**}\left(p_{0i}\right) - \theta^*\left(p_{0i}\right)\right] + p_{0i} q_w \Delta p_1\left(m, m + c\right) \\ &\quad \geq p_{0i} q_w\left[1 - \lambda_w\right] S + p_{0i}\left(q^{**} - q_w\right) \Delta p_1\left(0, m\right) \beta\left[Y_1 + S\right]\end{aligned} \tag{24}$$

where λ_w and $\bar{\lambda}$ are the probabilities of a preemptive sanction and q_w and q^{**} are the probability of detection given surveillance levels with and without conditional surveillance aid, respectively.

There are two conditions under which a country will accept conditional surveillance aid. First, the amount of aid must be sufficient that $q_w \approx \bar{q} = q\left(\theta\left(\bar{p}_0\right)\right)$. This ensures

$$\bar{\lambda} - \lambda_w = \frac{\left(1 - \bar{p}_0\right)\left\{q_w - \bar{q}\right\}}{\left\{1 - \bar{q}\bar{p}_0\right\}\left\{1 - q_w \bar{p}_0\right\}}$$

is small or zero. Second, the country's probability of an outbreak must not be too high. To illustrate, rewrite (24) as

$$p_{0i} \leq \frac{\left[\bar{\lambda} - \lambda_w\right] S + \left(\theta^{**} - \theta^*\right)}{\begin{array}{c} q_w\left\{\left[1 - \bar{\lambda}\right] S - \Delta p_1\left(m, m + c\right)\right\} \\ + p_{0i}\left(q^{**} - q_w\right) \Delta p_1\left(0, m\right) \beta\left[Y_1 + S\right]\end{array}} \tag{25}$$

The first condition ensures first term in the numerator is close to zero. The question is: are the second term in the numerator and the second term in the denominator positive or negative. As it turns out, they move together. If p_{0i} is very small, it will be the case that $\theta^* > \theta^{**}$ and $q^{**} < q_w$. If p_{0i} is not too small, $\theta^{**} > \theta^*$ but $q^{**} > q_w$. [Complete.]