Smallpox, Risks of Terrorist Attacks, and the Nash Equilibrium: An Introduction to Game Theory and an Examination of the Smallpox Vaccination Program

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Abstract

Introduction: The smallpox vaccination emergency preparedness program has been unsuccessful in enrolling sufficient numbers of healthcare workers.

Objective: The objective of this study was to use game theory to analyze a pre-event vaccination versus post-event vaccination program using the example of a terrorist considering an attack with smallpox or a hoax.

Methods: A three-person game (normal and extensive form), and an in-person game are played for pre-event and post-event vaccinations of healthcare workers facing the possibility of a smallpox attack or hoax.

Results: Full pre-event vaccinations of all targeted healthcare workers are not necessary to deter a terrorist attack. In addition, coordinating vaccinations among healthcare workers, individual healthcare worker risk aversion, and the degree to which terrorists make the last move based on specific information on the status of pre-event vaccination all greatly impact strategy selection for both sides. A Nash Equilibrium of pre- and post-event vaccination strategies among a large number of healthcare professionals will tend to eliminate the advantage (of the terrorists) of a smallpox attack over a hoax, but may not eliminate some probability of a smallpox attack.

Conclusions: Emergency preparedness would benefit from game theory analysis of the costs and payoffs of specific terrorism/counter-terrorism strategies.

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Introduction

Terrorism certainly is not a game. Terrorism is coercion using threats or violence. However, games and game theory can help to anticipate terrorist actions and prepare, prevent, and mitigate the damage that terrorists would inflict. As Robert Aumann, the inaugural president of the Game Theory Society, observed in his presidential address, "game theory" is an unfortunate term for a study that might be better understood as "interactive decision theory."[1] Terrorists are developing and implementing plans for their next act while healthcare providers are preparing to prevent or mitigate the effectiveness of that attack. Terrorists and targets of terrorism carefully watch each others' activities and make decisions based on the actions and expected responses of the other group. This interactive decision process is precisely the material of game theory.

The nature of the next coercive act, whether a threat, violence, or both, only is known to the terrorists themselves. Actual violence (such as kidnapping, hijacking an airplane, detonating a "dirty" bomb, or sending anthrax through the mail) carries great risks for the terrorists and their cause, and potentially or intentionally ends in their own demise. Threats without actual violence, specifically hoaxes, (such as sending a Petri dish marked anthrax to an organization, leaving suspicious powders in public places, or depositing a fake bomb) carry a much lesser risk, but still have a damaging impact. The terrorists measure these risks and their payoffs by the perceived effect on the target

Payoffs Represented as Prisoners 1,2		Prisoner 2	
		Confess	**Don't**
Prisoner 1	Confess	5,5	0,20
	Don't	20,0	1,1

Table 1—The Prisoner's Dilemma

and the ultimate benefit to their cause. Although the terrorists often have an ideologically driven approach to coercion (e.g., an inclination to be more or less violent), they still act rationally in that they measure the cost to themselves relative to the damage to the target; they proceed in a manner that benefits that cause no matter the strategy. *Targets of terrorism* are defined as the group or individual that is subjected to terrorism. The targets also behave ideologically (e.g., refuse to bargain) and act rationally in that they measure the damage inflicted by terrorists and the cost of their efforts to prevent terrorism. Ultimately, targets and terrorists select a strategy in a non-cooperative manner, each with incomplete information of the other's preparations.

Studying terrorism and counter-terrorism strategy with game theory analysis may advance the understanding of the problem and help guide policy decisions.[2] Terrorism is a non-cooperative game—it also is a non-constant sum game. In a non-constant sum game, the outcomes do not add up to a strict winner or loser, and the outcome in payoff varies according to the strategies.

The classic example of a non-cooperative game in which each side cannot (or will not) share information on their strategies, is the Prisoner's Dilemma.[3] In this widely applied example, two prisoners each must choose whether to confess or not to confess to a recent crime. In this dilemma, two men are arrested as suspects for a robbery. Realizing they have no evidence, the police put them in separate rooms and offer a bargain—confess to the crime for a reduced sentence. Each prisoner is unsure of the other prisoner's strategy for responding to this questioning, but they both can reason out the problem. "If we both refuse to confess, we would both go to jail—but only for a year since they have no evidence. If the other guy confesses and I don't, then I will get 20 years in jail and they will let him go with a light sentence. If we both confess, then we will be judged leniently and each serves five years. If I confess and he doesn't, then they would let me go and he gets 20 years. Not confessing exposes me to the worst outcome (although I might get off completely) and confessing means that I will get off or get five years, but not 20."

One form of representing these strategies and payoffs is a matrix (Table 1). Prisoner 1's and 2's best strategy is to confess since one prisoner does not know what the other prisoner will do. Regardless of the other prisoner's actions, a confessing prisoner either will end up with 0 or 5 years of jail time. A prisoner that does not confess might get 20 years or one year. Although the best outcome for the prisoners as a group would be to remain silent, confessing is the strategy that is the best response to the dilemma no matter what the other prisoner's strategy. The "confess, confess" outcome in the Prisoner's Dilemma forms a unique equilibrium solution for this game. In this particular payoff matrix, the "confess" strategy is so superior to the other choices that it is "dominant" to "do not confess"—a "dominated" strategy. Dominant strategies equilibrium solutions such as these can create a "social dilemma" in which the solution that benefits both parties never is achieved. These terms are used in game theory to describe the characteristics of equilibrium solutions. Like the prisoner in the Prisoner's Dilemma, in this game, a player easily can consider the number of years in jail and identify the equilibrium solution by intuitive means. However, the game is influenced greatly by the characteristics of the payoffs in the matrix.

To fully elaborate a game model for terrorism, it is necessary to develop some concept of what the payoffs are. The commonality of the experience can provide fundamental guidance. For targets, terrorism is a "losing" game because stopping terrorism always has a cost and terrorism that is not stopped inflicts damage. Thus, the payoffs for the targets always are negative. For terrorists, the outcome of their actions—even death—always is self-perceived as a payoff (e.g., martyrdom, furthering the cause, political leverage, forcing the target into a defensive posture, etc.). Immediately, the game's inherent perpetual antagonism becomes apparent. In every case, the outcomes determine the value of a particular strategy—the targets try to minimize and the terrorists try to maximize. Interestingly, the one thing of value to both the terrorists and the targets is economy—each would like to achieve their goals with minimal cost and effort.

Two Further Simple Examples

The Prisoner's Dilemma is the best-known example in game theory because it packs important insights into a form that can be presented on a page and easily understood. However, for a discussion of terrorism and medical preparedness, two other examples will be of more help. The first is the coordination game. This can be illustrated by the familiar experience of meeting traffic on a narrow road. Each motorist chooses between two strategies: (1) drive to the left; or (2) drive to the right. If both choose the same strategy, then all is well; if not there is the risk of a crash (Table 2). The table is read as follows: the Chevy chooses the column, the Ford chooses the row, and the payoffs are in the cell at the intersection of row and column, with the first payoff to the Ford and the second to the Chevy.

However, while the Prisoner's Dilemma has a unique solution, the Meeting Traffic Game does not. The most commonly used concept of solution for games like these is the Nash Equilibrium. Each "player" chooses a strategy that is the best response to the strategy chosen by the other.[4] In this case, equilibrium exists whenever both players choose the same strategy. The problem is, if each one is ignorant as to what the other will do, they may not coordinate their strategies, and may crash. They must have enough information to coordinate their choices. In this case, a custom or law can be the source of the information they need. For example, the custom is to drive on the left in some countries, and on the right in other countries, a fact that is con-

Payoffs read as Ford, Chevy		Chevy	
		Left	Right
Ford	Left	1, 1	-10, -10
	Right	-10, -10	1, 1

Table 2—The Meeting Traffic Game

Payoffs read as Moriarty		Chevy	
		Canterbury	Dover
Holmes	Canterbury	10, -10	-10, 10
	Dover	-10, 10	10, -10

Table 3—The Escape-Evasion Game

sistent with the existence of two equilibria in this game—"left, left" (Great Britain's custom) or "right, right" (the US custom).

The second simple example is the escape-evasion game. In its classic form, this game pits Sherlock Holmes against Professor Moriarty.[5] Moriarty is fleeing from Holmes by train; his objective is to reach Dover and then ferry to France. Holmes is pursuing Moriarty's train in a second train that is closing on Moriarty! Moriarty has two options: (1) stay on the train all the way to Dover; or (2) leave the train at a station prior to reaching Dover (Canterbury), hope that Holmes bypasses him, and try to reach France by other means. Holmes can catch Moriarty either at Dover or Canterbury, but only if he correctly anticipates Moriarty's decision. If both make the same stop, Moriarty loses, while if they make different stops, Holmes loses (Table 3).

Once again, the first payoff is the payoff to Holmes. In this case, no combination of the strategies "Canterbury" and "Dover" is an equilibrium. Whenever Holmes chooses Dover, Moriarty's best response is to choose Canterbury, and conversely. In fact, this game does have an equilibrium—John Nash received the Nobel Prize for proving that every two-person game has an equilibrium when mixed and pure strategies are considered. In this case, the equilibrium is that Holmes and Moriarty each choose between Canterbury and Dover with 50-50 (0.5) probabilities. It is possible to appreciate that this equilibrium will occur if the game is played and replayed over time, with each player making the 50-50 guess—sometimes to their advantage, sometimes not. This is called a "mixed strategy", albeit apparently random. Conversely, equilibrium like the two equilibria in the Meeting Traffic game, is called an equilibrium in "pure strategies". The Escape-Evasion game that Holmes played has no equilibrium in pure strategies—there is not one best strategy such as "confess" in the Prisoner's Dilemma, or obeying the customs in the Meeting Traffic game. However, all of these simple games have equilibria—either mixed or pure strategies.[4] In order to capture both of these refinements it is necessary to create at least a three-person game, or more realistically, a game of n persons with n being a large number.

Preparing for the Smallpox Threat and Pre-Event Vaccination

Game theory is specifically applicable to bioterrorism emergency preparedness. Although it always has been presumed that stockpiles of smallpox are confined to the US and Russia, the fear of the possibility of a smallpox attack prompted the Department of Health to espouse the pre-emptive position of pre-event vaccination for dedicated teams of healthcare workers. (This action may have been prompted by some classified information, or may be further demonstration that a weapon of mass destruction (WMD) does not have to be employed to function as an effective bluff and extract a damaging cost from the target). During natural smallpox outbreaks, healthcare policy always has supported "ring" vaccination—a form of post-event vaccination that immunizes a ring of individuals around the outbreak to prevent its spread. In the case of a smallpox WMD, healthcare policy makers developed the pre-emptive strategy of pre-event vaccination. The goal was to develop a cadre of workers who would be able to respond to an epidemic and prevent the healthcare system from collapsing. A few healthcare workers and institutions complied voluntarily, but by 2004, most had refused or deferred their decision, waiting for evidence that the risks of the vaccination were worthwhile.[6–8] Is smallpox going to be the form of the next attack? What would the response be if a terrorist organization informed health officials that it had exposed a number of victims to smallpox? What if victims were purposefully infected with monkeypox to perpetrate a hoax? What if the terrorists merely perpetrate further powder hoaxes and scares and lead us to believe that a smallpox attack might have occurred?[9] The strategies are as numerous as the terrorist mind can conjure.

Consider a group of terrorists who have two choices: (1) develop and deploy a smallpox attack; or (2) perpetrate a hoax attack. Smallpox should be nearly impossible to obtain, however, release could be as easy as gradually infecting a few dozen people. Assume that a hoax could be perpetrated by any number of methods and could sustain itself for a short time before being discovered as a hoax. The use of vaccinia is a guaranteed defense, but carries a definite cost in morbidity and mortality. In this case, two strategy choices are considered: (1) develop a post-event vaccination program after a smallpox outbreak has been identified; or (2) employ a pre-event vaccination program of key healthcare workers. As the two strategies are considered, the best response of the terrorists also is considered. If the Health Department would develop a pre-vaccination program of healthcare workers and the terrorists do not actually have smallpox, a huge pre-event response would have been performed to what amounts to be a hoax. The cost or damage from pre-employing the vaccine would be significant compared to a small effort and investment in a hoax by the terrorists. If smallpox actually was released after a pre-event vaccination program, the terrorists might feel empowered by their boldness and ability to deliver a bioweapon, but would have accomplished little against an immunized community other than the cost of immunization. Alternatively,

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Payoffs read as T, H1, H2		H2			
		pre-vaccinate		No	
		H1		H1	
		pre-vaccinate	No	pre-vaccinate	No
Terrorist	Smallpox attack	2, -1, -1	4, -3, -1	4, -1, -3	10, -4, -4
	Hoax attack	5, -2, -2	5, -1, -2	5, -2, -1	5, -1, -1

Table 4—A Three-Person Preparedness Game

if the preparedness strategy only focuses on post-event vaccination and the terrorists do release smallpox, the losses would be great until the epidemic could be curtailed. Finally, if the post-event vaccination strategy is used in errant response to a successful hoax, the degree of panic and alarm as well as the morbidity and mortality of post-event vaccinia distribution would be a success for the terrorists.[10–12] The choices are difficult for the targets given the best response of the terrorists, and this is where a game theory application can be illustrative.

Bioterrorism and Emergency Preparedness: A Three-Person Game Example

Terrorism preparedness draws upon principles in the Coordination Game and Escape-Evasion game examples. On one hand, medical and other personnel in a target country must coordinate their preparations for a terrorist attack. On the other hand, terrorists will attempt to evade the preparations and attack by means for which the target country is least prepared—but the requirements of equilibrium in the two cases conflict. The medical personnel in the target country need information to coordinate their strategies of preparation. However, if this information is equally available to the terrorists, it will help them evade the preparations. In the escape-evasion game, suppose that Holmes and Watson both were pursuing Moriarty, and needed to be at the same stop in order to outnumber and capture him—but Moriarty could intercept their messages and so know where they intended to stop! The simplest game that would capture this complication is a three-person game. With a three-person game, comprehensible tabular examples still are valuable, though they are more complex. Suppose there are two healthcare professionals, H1 and H2, and a terrorist group T (Table 4). Each person, H1 and H2, either can or cannot be pre-vaccinated against smallpox and the terrorist can choose to attack with smallpox or perpetrate a hoax. Assume that the effectiveness of a smallpox attack declines as there are more vaccinated healthcare workers. If a critical mass of healthcare workers in an area under attack is vaccinated, they are likely to be able to maintain the healthcare system effectively, thus limiting the impact of the attack. Conversely, a small percentage of immunized workers would cause the healthcare system to fail, and the attack would have a great impact. In Table 4, suppose that agent H2 chooses the panel, left or right; H1 chooses the column in a panel, and the terrorist chooses the row. The payoffs are arbitrary and chosen to illustrate the arguments. The payoffs are ordered as terrorist, H1, H2. The payoffs are based on the ideas that the smallpox attack is more effective than a smallpox hoax strategy only if neither of the victims is vaccinated, and that vaccination is a risk or sacrifice. In the case of a hoax, extra effort and resources are required of all healthcare workers, but those who have been vaccinated bear the cost and risk of vaccination, without offsetting benefit.

Like the Escape-Evasion game, this game has no Nash Equilibrium in pure strategies. If the terrorist chooses a hoax, the best response is not to take precautions, but that means that the terrorists' most effective strategy is to use smallpox, and so on. There is a mixed strategy solution, though. Suppose that each health professional chooses either vaccination or no vaccination with 50/50 (0.5) probability, the terrorist band chooses "smallpox" with a probability of 0.2857, and chooses a hoax with higher probability of 0.7143. The average damaging payoff to each of the healthcare professionals is –1.714, and the terrorists' average payoff is 5—just what it would be if they always chose a hoax. Neither side can do better than this by deviating to another probability, unless the others also change.

A simple method to comprehend the arithmetic solution to this problem is to look at the terrorists' four different payoffs for each type of attack. The sum of these payoffs is 20 across the matrix. Since the probability of one healthcare worker being vaccinated is 50% (0.5), the probability of any particular combination of vaccinated and not vaccinated healthcare workers (when there are only two workers) is 0.25. Therefore, with a vaccination probability of 50% (0.5), the sum of the terrorists' payoff across all healthcare worker strategies is 20/4 = 5. Although more arithmetically complicated, the same solution can be achieved for healthcare workers average damaging payoff by applying the probability p of a small pox attack at 2,857 and probability of hoax q = 1-p across the payoffs for H1 and H2. The sum of these payoffs is -1.714.

Precommitment and Information

The mixed-strategy analysis is problematic. In applying a mixed-strategy approach, it is assumed that the preparations taken by the potential victims can be kept secret from the terrorists. However, it is quite plausible that this cannot be done—the extent of vaccinations against a smallpox attack would have to be public knowledge, and thus, would be known to potential terrorists. The terrorists may have the advantage of moving second, and that possibility must be considered.

Consider the game Escape-Evasion, assuming that the healthcare agents simultaneously choose whether or not to be vaccinated, and the terrorist choose their mode of attack knowing what the healthcare agents have done. This game

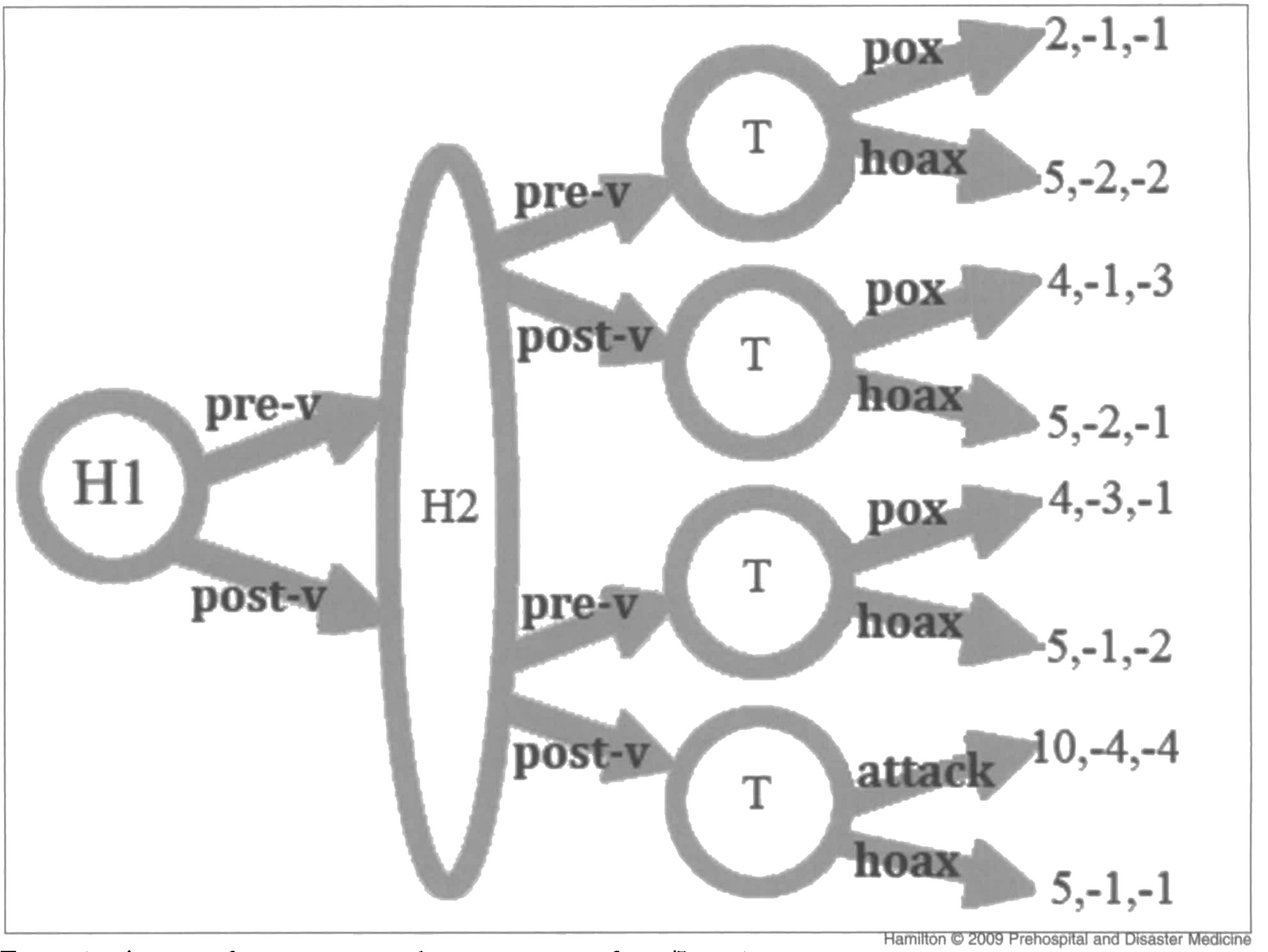

Figure 1—A game of terrorist preparedness in extensive form (H1 = healthcare worker #1; H2 = healthcare worker #2; T = terrorist; pre-v = pre-event vaccination; post-v = post-event vaccination; pox = smallpox)

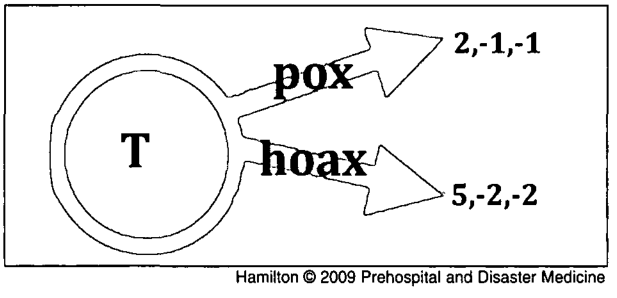

Figure 2—A Terrorist's sub-game (T = terrorist; pox = smallpox)

is shown as a tree diagram in Figure 1. The first decision is made by H1, who chooses to "pre-vaccinate" or "post-vaccinate." The second choice is made by H2, but H2 does not know what decisions H1 has made. In the conventional code of game theory, H2's lack of information about H1's decision is coded by the elongate lozenge for H2's decision—H2 does not know whether he is departing from the top or the bottom of the lozenge. The terrorists make the last decision. It is assumed that they know the decisions the healthcare agents have made, and have the second-mover advantage.

This game is solved by "backward induction." The healthcare agents must anticipate that the terrorists will use their knowledge of the preparations that have been made in order to choose the mode of attack that will yield them the best advantage. Thus, each of the "sub-games" is solved separately. The sub-game the terrorists solve if they know that both healthcare agents have been vaccinated, this is illustrated in Figure 2. In this case, the terrorist's clear choice is not to attack with smallpox, but instead choose a hoax. Every hoax perpetuates the fear of a true attack and reinforces the damaging costs of pre-event vaccination with relatively little effort on the part of the terrorists when compared to a true attack.

Each of the "basic" sub-games can be solved in the same way, and substitute the payoffs from that solution back into the larger game. This leaves us with a "reduced game" as illustrated in Figure 3. The "reduced game" is equivalent to the original game and will have the same solution.

In this game, the moves are made simultaneously—neither player knows what the other has done—so it is convenient to return to the normal form to analyze it. The normal form for this reduced game is shown in Table 5. This game is a coordination game. The escape-evasion aspect of the game has been eliminated by the second-mover advantage of the terrorists. The healthcare agents (by assumption) cannot act unpredictably, because their action is public knowledge; the terrorists have no need to do so because

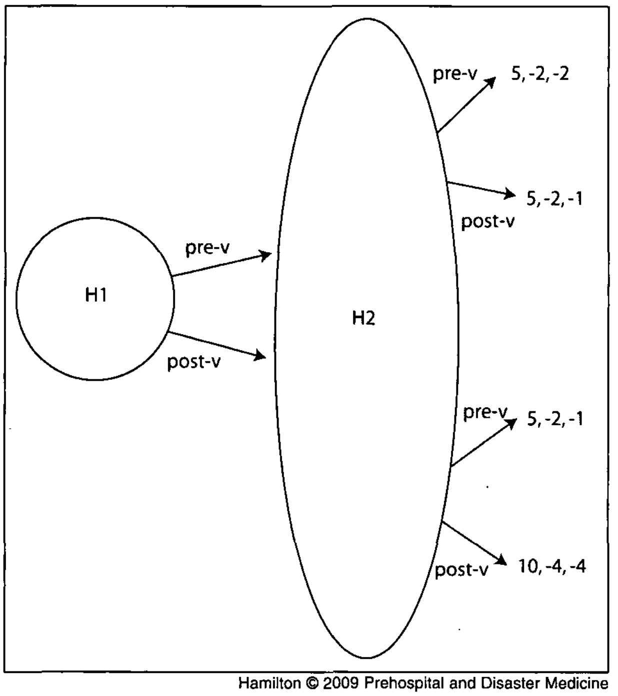

Figure 3—The Reduced Game

they can adjust their mode of attack to the preparations made by the healthcare agents. Thus, the game is reduced to relative advantages and disadvantages of the individual decisions healthcare workers. This game has two Nash equilibria in pure strategies—the two cases at which one is vaccinated and the other is not.

The coordination problem in this game is that—each not knowing what the other will do, and possibly guessing incorrectly—the two may choose (pre-vaccinate, pre-vaccinate) or, worse, (no, no) through miscalculation. Without any further information about the intentions of the others, this is a possibility. The game also has a mixed strategy equilibrium, in which each agent chooses to pre-vaccinate or not with a probability of 0.5, but this also is a poor alternative, since it assigns probabilities of 0.25 to (pre-vaccinate, pre-vaccinate) and (no, no). But this difficulty is partly a result of the simplifying assumption that there are only two healthcare professionals.

An n-Person Game Example

In the real world, there are >2 healthcare workers, and people may need some time and experience to arrive at a best-response strategy. Another game theorist, John Harsanyi, shared the Nobel Prize with John Nash. Harsanyi developed a Bayesian approach to game theory that stated that over time players will, maximize the expected value of their payoffs based on the probabilities of other players' strategies, and revise their strategies to achieve some satisfying strategy, after which they do not change.[11] Further along these lines, W. Brian Arthur suggested that in games involving multiple participants played out over time and each participant uses inductive reasoning to generate his/her own strategies (however unique or commonplace), and then, observes their effectiveness over time and makes changes to improve success.[12] The game he proposed as a model for this problem is known as the El Farol problem or the Bar Problem. The El Farol is a bar in Santa Fe, New Mexico that has popular music night. The size of the establishment was such that, on nights when there were too many patrons, the experience was much less enjoyable. On nights when it was not at capacity, the experience was worth repeating. In this game, one tries to develop a strategy for knowing when to go to music night at the bar.

		H2	
		Yes, Pre-Vaccinate	No
H1	Yes, Pre-Vaccinate	-2, -2	-2, -1
	No Pre-Vaccinate	-1, -2	-4, -4

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Table 5—The Reduced Game in normal form

To solve the problem, only the optimum number of patrons and the prior attendance for other music nights are given. Common approaches (it has not been crowded the last few weeks—go) start to fail (everyone does the same and goes). Arthur suggests that individuals will develop individual strategies for solving the problem, but that the population of these strategies forms the attendance pattern over time. The great variety of approaches that individuals would want to try—e.g., go when it was crowded the week before, go every other week, go when it was empty the week before, etc. Theory and practice say that over time, no matter what the approach, attendance fluctuates around the optimum number of patrons. In other words, strategies become "mutually co-adapted" and form an overall economy of strategies that keeps the El Farol close to its capacity on music night.[14,15]

Evidence suggests this is what is happening today in the realm of WMD terrorism. Although the anthrax letters and their victims were a discrete episode more than two years ago, municipalities continue to get frequent calls to analyze suspicious powders—some planted as hoaxes and some from panicking citizens. Even the targets are selecting separate approaches as businesses, municipalities, states, and the federal government develop their own strategies for coping with these problems. Indeed, Harsanyi's theories seem to be at work in the development of WMD counter-terrorism strategies. News reports from Japan suggest that as the Aum Shinrikyo threat has been removed, Japanese citizens have become less interested in gas masks and WMD preparation due to their own estimate of the probability of an attack. Indeed, it appears that the majority of healthcare workers in the US either consider the probability of a smallpox attack too remote and/or the effects of the vaccinia virus too devastating to participate in the pre-event vaccination program. It appears that the strategy is changing as information about probabilities change. Perhaps the value of the color-coded threat warning system for domestic preparedness is example of how the public might seek the information necessary to form a strategy that fits expected probabilities.

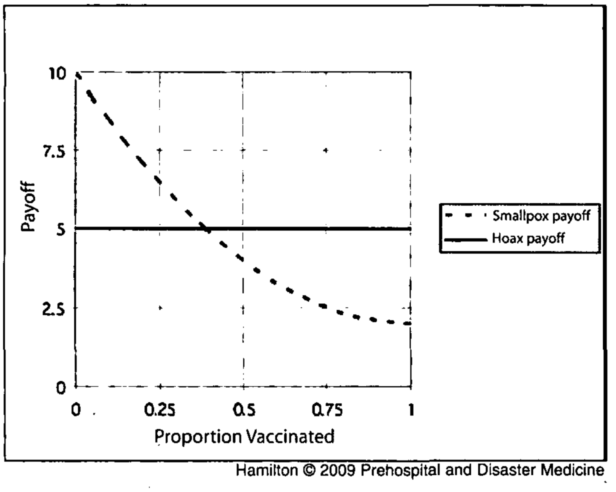

Figure 4—Payoff to terrorists

When preparedness for a smallpox attack as an n-person game is re-examined, it is clear that Nash Equilibrium reasoning can be extended to allow for many persons and learning by experience. The game still is reasonably simple if the average healthcare worker is substituted for each specific, concrete, real healthcare worker. Using this approach, the problem is reasoned in terms of a large mass of representative agent healthcare workers, and the terrorists are treated in the same representative way.[16,17] Equilibrium is reached when each representative agent chooses his or her best strategy, given the strategies chosen by all of the others. These equilibria sometimes correspond to the mixed strategy solutions of approximating two-person games.

To allow for large numbers of healthcare workers, assume that for each of their two strategies, the payoff to the terrorists depends only on the proportion of vaccinated healthcare workers. In Figure 4, the payoff to the terrorists, as it varies with the proportion vaccinated, is represented by the nonlinear curve. This curve yields 10 at zero, 4 at 0.5, and 2 at 1.0 as before. (It is the plot of a quadratic equation, namely $10 - 16x + 8x^2$, where x is the proportion vaccinated. However, because the curve is nonlinear, it will yield a somewhat different equilibrium than in the linear mixed strategy analysis.)

The terrorists' payoff from a hoax attack is constant at 5. Thus, the terrorists will choose a smallpox attack if <39% of healthcare workers are vaccinated. In this example, the "critical mass" is 39%. If >39% are vaccinated, a smallpox attack is less effective than the hoax. Hopefully, anti-terrorist policies eventually will reduce such payoffs to zero. This analysis is a "short run" analysis in that sense. Successful preparedness strategies against other forms of terrorist attacks could make a smallpox attack more attractive to the terrorists, calling for a balanced increase in the precautions against smallpox terrorism as well.

The assumed payoffs to healthcare workers also are adapted from the three-person game. If "hoaxed", the payoff is −1 if not vaccinated and −2 if vaccinated. If there is a smallpox attack (and no other attack) and the healthcare worker is protected by vaccination, the payoff again is −1. If

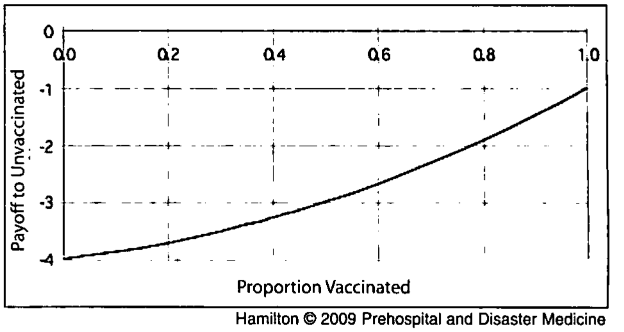

Figure 5—Payoff, if attacked, to unvaccinated health professionals depends on proportion of health professionals vaccinated

there is an attack and the healthcare worker is unvaccinated, the payoff is also nonlinear (Figure 5). This is the plot of a quadratic equation −4+x+2x2, and yields −4 if none are vaccinated, -3 if half are vaccinated, and −1 if all are vaccinated.

However, the payoffs to the healthcare workers not only depend on their own strategies, but also on those of the terrorists. As demonstrated, a 39% vaccination rate is the tipping point between a smallpox attack and the alternative strategy for the terrorists. Therefore, the plot of the payoffs for the healthcare workers against the vaccinated proportion indicates a discontinuity of payoffs at the tipping point (Figure 6).

In Figure 6, to the left of the 39% tipping point, the payoff to vaccination for a healthcare worker is −1, but the payoff to not being vaccinated is worse, -3 or less. However, to the right of the tipping point, the payoff to not being vaccinated is −1 while the payoff to being vaccinated is −2. Thus, the Nash Equilibrium for this game is that just 39% of the healthcare professionals are vaccinated, and the terrorists are indifferent between attacking by smallpox and the hoax. Thus, both choices yield the same payoff of 5 for the terrorists at equilibrium.

This calls for two realistic qualifications. First, the conclusion that the terrorists are undecided between attacking by smallpox and by hoax means that there is a positive probability that there will be a smallpox attack. To eliminate that probability in this model, a small increase in vaccinations beyond the tipping point would be required. This is not in the interest of the vaccinated persons, and is a move away from Nash Equilibrium. On the other side, this model and its conclusion require precise information about the payoffs and alternatives to the terrorists, information that probably will not be available. Allowing for the quality of the information that can be obtained, and if the assumptions behind the model are qualitatively correct, it can be concluded that: (1) if there are few enough vaccinated healthcare workers so that the healthcare system could be overcome by a smallpox attack, then, it is in the interests of the healthcare workers to be vaccinated; (2) if there are enough vaccinated so that the healthcare system can sustain an attack without collapsing, then probably little will be gained by more vaccinations, and further progress should be directed toward other attack strategies; and (3) if neither of the above is known to be true, it is not clearly against the interest of the healthcare worker to be vaccinated, and that

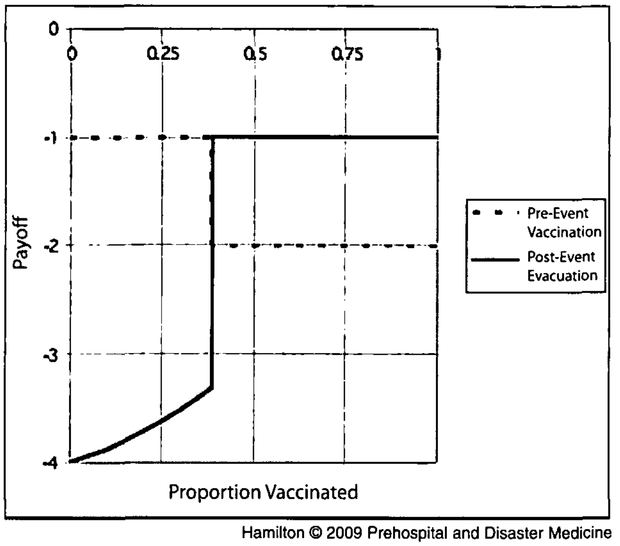

Figure 6—Payoff to health professionals

decision could depend on subjective estimates of risk and on the individual risk aversion.

Conclusions

These game examples are simplified. The conclusions depend on the payoffs assumed, and in some cases, small changes in these assumptions can precipitate large changes in the conclusions. Sensitivity analysis would be helpful, but is beyond the scope of this paper. Both sides may be able to choose between more than two alternatives, perhaps even some that might lead to peace. In addition, this exercise assumed a high degree of rationality, without any time or experience for learning. Nevertheless, the examples considered illustrate some of the principles that may be realized in a more complete, less simplified model:

1. It may be optimal for only a part of the target population to be vaccinated, as this may be enough to deter a smallpox attack;
2. Coordination problems can occur when healthcare agents make isolated decisions about whether to be vaccinated;
3. Randomization of strategies may be helpful or necessary. Deliberately unpredictable terrorist behavior is to be expected;
4. Whether the terrorists have information on the preparedness status and can make the last move makes a difference;
5. Thus:
   a. Solve by backward induction;
   b. The advantage of unpredictable behavior against the opponent is lost; and
   c. If there are only a few healthcare professionals, the coordination problem remains; and
6. A Nash equilibrium among a large number of healthcare professionals will tend to eliminate the advantage to the terrorists of utilizing a smallpox attack over other forms of attack, but may not eliminate the possibility of a smallpox attack.

Healthcare policy regarding WMD preparedness would benefit from using game theory to analyze strategies. Programmatic failure of counter-terrorism plans is possible if the interactive decision-making processes that guide individual healthcare workers, public health entities, and terrorists are ignored. Game theory provides a means to study those processes.

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