Quantitation of Social Variables in Epidemics: A Computational Modeling Approach

John Kraemer

MPH Capstone Project in Infectious Diseases

Johns Hopkins Bloomberg School of Public Health

Completed under the guidance of Donald S. Burke, MD
Popular culture perceptions of disasters, including disease epidemics, often view the public as a terrified mass, engaging in mindless and antisocial flight from danger. It makes for good television, but, unfortunately, this perception sometimes has been carried over into academic journals\(^1\) and governmental planning exercises.\(^2\) As planning goes forward for a potential influenza pandemic or other large-scale disease outbreaks, it is important to understand psychosocial determinants of behavior during epidemics.

This paper seeks to develop a framework through which one could model compliance with health-promoting instructions during the emergence of an epidemic disease. It addresses only some of the constellation of public health interventions that could be utilized: facemask wearing, avoidance of crowded places, and quarantine and isolation. Though it was written with pandemic influenza in mind, most of the data comes from Severe Acute Respiratory Syndrome (SARS), so it has application beyond influenza. The control methods addressed were chosen mostly on the basis of the availability of quantitative research. Lack of research about social dynamics of compliance with treatment or prophylaxis during epidemics prevents consideration of these options. A similar lack of quantitative research on vaccine compliance during novel outbreaks (because there is generally no vaccine available for an emerging infection), coupled with the expectation that demand for any available vaccine would far outstrip supply in an influenza pandemic,\(^3,4\) resulted in inattention to that control method in this paper also.

Additionally, one should recognize that epidemics sometimes induce extreme behaviors,\(^5\) but these defy a simple model. In 1994, 500,000 people fled Surat, India after a small outbreak of plague.\(^6\) In 1665, the village of Eyam also acquired plague, but its residents chose to stay rather than spread the disease to nearby villages, and 80 percent died.\(^7\) Disease occasionally evokes intense fear or equally intense self-sacrifice, but it usually causes people to cope in
predictable, and thus modelable, ways. These “normal” responses are what this paper addresses.

Compartmental models are a relatively straightforward way to model infectious disease dynamics. In these models, populations are divided into epidemiologically relevant compartments. These, for example, might be susceptible, infectious, and recovered in a fairly simple model of a disease like measles, for which survival of the disease confers lasting immunity. Such a model is abbreviated as an SIR model. More complicated models might add an exposed (E) class – those people who are latently infected – and become an SEIR model. For diseases that have a stage during which one is asymptomatically infectious (A), the model could become SAIR. Other diseases do not confer only temporary immunity, so one eventually returns to the susceptible compartment; models for these diseases would take the form SIRS. One might also add other compartments, such as dead (from baseline deaths or from disease), depending on the disease, and one can combine the forms listed above (to create, for example, an SEAIRS model) or simplify the models (an SIS model), as appropriate.\(^8\)

Compartmental models also include parameters that define the rate of movement from one compartment to another. \(\beta\) represents the transmission parameter, a measure of the number of infectious contacts per time period, and it defines the rate of movement from the susceptible to the infectious compartment (or the exposed compartment if this intervenes between the susceptible and infectious blocks). This measure generally assumes random mixing in a population. The reciprocal of the average latent period (\(\epsilon\)) defines the rate of movement from the exposed to the infectious block. The reciprocal of the average infectious period (\(\gamma\)) defines the rate of movement from the infectious to the recovered compartment (or back to the susceptible compartment, if there is no immunity). Lastly, the reciprocal of the average time immune (\(\rho\))
defines the rate of movement from the recovered back to the susceptible block, if immunity is not lasting.\textsuperscript{8}

It is important to note that other forms of models also use these compartments and parameters, though not in exactly the same way. Agent-based models of disease, divide a population into individual agents in a relevant environment. There are often factors other than just disease status that govern their actions and mixing is generally not assumed to be random.\textsuperscript{9} However, as disease progresses through an agent community, the agents are usually classified in epidemiologically relevant ways, such as susceptible, exposed, infectious, and immune. Biological aspects of the disease usually determine how long agents stay in each state, as with compartmental models. Thus, while this paper specifically focuses on compartmental models, it has applicability to other types of models.

\textit{A Review of the Literature}

\textbf{Previous Epidemic Models with Behavior Change}

Behavior change during epidemics has often been left out of models of disease system dynamics. Models are made much simpler if one can assume constant parameters throughout the epidemic. However, it has become increasingly clear that realistic models, at least for certain diseases, must include behavioral responses to diseases. Social and behavioral factors may also contribute to disease propagation. Some modelers have begun taking this into account, drawing on disciplines ranging from economic theory to physics to more traditional disease modeling to incorporate behavior into their models.

In recent years, behavior has become a significant part of many models that seek to
explain sexually transmitted disease (STD) dynamics. Some such models are pretty straightforward, such as two SIS models Hyman and Li. In one model, a population is broken into multiple subpopulations. Sexual partnerships are formed both within and between the subpopulations. The model was formulated in two different ways. In one formulation, intergroup partnerships continue regardless of infection level in the groups, though members of high-infection subgroups stop forming intragroup partnerships once an infection threshold has been crossed. In the other formulation, members of subgroups with low infection levels stop forming intergroup partnerships with those in high-infection subgroups once a particular level of infection has been reached. The model determined that the first formulation does not have much effect on STD transmission; however, in the second formulation, self-imposed isolation can prevent an epidemic in the low-infection subgroups, though the epidemic continues in the high-infection subgroups. Because the model is an SIS model, the disease can persist without running out of susceptibles.\textsuperscript{10}

The same authors devised a similar model that looks at the effect of idealized behavior change as a function of infection level in a group. The model is another multigroup SIS model, in which group members make determinations about the desirability of partnerships with people in other groups on the basis of infection levels. The higher infection levels are in a different group, the lower the desirability (and thus level) of partnership with someone in that group is. The model indicated that the overall infection level is sensitive to the level of partnerships with those in highly infected groups. However, it also determined that, if people continue to have partnerships within their own groups and across groups (that is, if people or groups do not completely isolate themselves), and epidemic cannot be eradicated once it has begun.\textsuperscript{11}

A similar SIR model predicted the effect of change from high-risk to low-risk behavior in
a closed population. The model consists of two separate groups: one is high-risk and has more potentially infectious contacts, while the other is low-risk and has fewer such contacts. Members of the group can change from the high-risk group to the low-risk group (but not vice versa), and, in so doing, change the number of contacts that they make. The model is designed to simulate HIV transmission in populations where there is a core transmission group. In the model, given enough time, all members of the high-risk group will switch to the low-risk group. The model concluded that behavior change does, in fact, influence the size of an epidemic. Very low rates of change from the high to low-risk group actually increases the size of the epidemic; however, at higher rates of change, the size of the epidemic falls below what one would see with no group changes. The authors conclude that multiple groups inherently slow the spread of epidemics “because the number of susceptible-infective pairs are reduced.” At low rates of group change (and when the difference in contacts between high and low-risk groups is small), increased homogeneity may outweigh the overall decrease in contacts; at high rates of group change the decreased contacts trump homogeneity.12

Several models of behavior during STD epidemics are based on economic theory. A key idea that many of these models incorporates is prevalence elasticity. In economics, elasticity is a measure of responsiveness of a variable to changes in the level of another. For example, if demand on a market is price-elastic, then a small change in price will cause a relatively large decrease in the quantity of a good demanded. Conversely, if demand is inelastic, the quantity demanded will not respond much to changes in price. Similarly, economists argue that preventive behavior during an epidemic should be prevalence-elastic; as prevalence of a disease increases – and so does risk of contact with an infectious person – susceptible people should take more steps to avoid infection.13 Note that this is similar to the Health Belief Model assertion that
people should engage in more preventive behavior when they perceive greater susceptibility to disease.

Research has found evidence supporting prevalence elasticity of condom use. As levels of HIV infection increased, so did the levels of male condom use. However, condom use by married men was not responsive to HIV prevalence, which is consistent with the prevalence-elasticity model in that married men in monogamous relationships would not face increased risk from increased prevalence. Other research has found evidence of prevalence elasticity for influenza vaccination; the highest vaccination rates are found among those age groups who have the highest influenza attack rates. Similarly, measles vaccination falls when there is a lower prevalence of measles and increases with prevalence.13

Microeconomic models of STDs also predict that people’s beliefs about the future of epidemics create incentives to engage in more or less risky behavior in the present and that people rationally maximize utility. For HIV, the models assume that both sexual contacts and avoidance of disease are desirable but in tension – more sexual contacts result in increased risk of disease. Thus, in the model an optimal outcome balances the utility from increased sexual contacts with the risk of disutility from disease, but unless every potential sexual contact is infected, the optimal number of contacts is greater than zero. If prevalence rises, the costs of a contact increase while the benefits do not, so less contacts occur; the converse is also true. However, beliefs about the future are also relevant in this model. If one expects that prevalence will rise in the future, less benefit accrues from avoiding infection but the utility from each additional contract remains the same, so the number of contacts increases. (In essence, one might as well have fun today if everyone will die tomorrow anyways.) Thus, in this model, behavior responds both to the degree to which one feels presently susceptible to a disease and the
degree to which one expects to be susceptible in the future.\textsuperscript{14}

Several models have also been used to investigate the effect of behavior changes on the spread of a bioterrorist smallpox outbreak. In one such model, an integral equation SIR model is used to predict the effect of various interventions on an epidemic caused by the introduction of one smallpox case into a population of 50,000 completely susceptible people, assuming a fairly low estimate of smallpox’s transmissibility. The model tested the effects of several interventions, including home quarantine and “cautious contact” with others. In the quarantine intervention, it was assumed that contacts of infectious people would comply with quarantine at a 90 percent rate. In the cautious contact intervention, it was assumed that, once smallpox was reported, contact with infectious people outside of hospitals would decrease by 50 percent. The model predicted a reduction from about 46,000 cases when only strict vigilance of cases was used to about 45,000 cases when home quarantine only was added and about 41,000 cases when cautious contact only was added. Adding strict hospital isolation (a 95 percent reduction in hospital transmission) reduced the number of cases to about 20,000. Of especial importance, combining hospital isolation with either a 90 percent effective quarantine or cautious contact prevented a sizable epidemic from occurring (93 and 10 cases, respectively).\textsuperscript{15}

An SEIR model was used by Del Valle and colleagues to determine the effect of different changes in contact rates during a smallpox epidemic on the spread of disease and the effectiveness of quarantine, isolation, and ring vaccination in a simulated attack where one infectious individual is introduced into a population of one million people. When behavior change is considered, people are assumed to reduce their number of contacts during the epidemic by ten-fold. There are three levels of behavior change: high behavior change (2.3 percent of people change from high to low contacts per day, or 95 percent by day 60), medium behavior
change (2 percent per day or 82 percent by day 60), and low behavior change (1.6 percent per day or 65 percent by day 60). All three behavior change parameters substantially lower the magnitude of the epidemic, and result in its control. In the absence of any intervention, 181 cases are expected after 60 days and 967,000 after one year. Low behavior change is modeled to result in 120 cases after 60 days and 1647 cases after a year. Medium change results in 96 and 306 cases, respectively; high change in 69 and 108 cases. In fact, in the model high behavioral change is more effective as a single control method than isolation, quarantine, ring vaccination, or mass vaccination when used alone. Behavior change also marginally reduces the size of epidemic when used in combination with isolation, quarantine, and ring or mass vaccination.\textsuperscript{16}

One further study used an SEIR model to investigate the effect of interventions, which included behavior change, on the transmission of Ebola during epidemics in the Democratic Republic of Congo and Uganda. In the Congo outbreak, transmission was mostly nosocomial, and interventions consisted of barrier nursing and isolation, contact tracing, and education for both patients and contacts. In the Uganda outbreak, interventions included voluntary hospitalization, contact tracing, barrier nursing and isolation, and education of the community that included “avoiding crowd gatherings during burials.” In Congo, the model indicated that the interventions reduced the transmission rate of the virus by almost three-quarters; in Uganda, transmission was reduced by half.\textsuperscript{17}

The Health Belief Model

The Health Belief Model (HBM) is one of the most well-established models of behavior change. Originally devised by United States Public Health Services psychologists in the 1950s, it seeks to explain why people do or do not engage in health-promoting behaviors. It is part of a
field of behavior theory known as value-expectancy theories, which consist of two major components, the value one places on a health outcome and the expectancy one has that a behavior will result in that outcome being attained. The HMB has the advantage of being fairly well-validated and of consisting of fewer components than most other behavior change models, making it fairly easy to apply. The HBM consists of six specific constructs: perceived susceptibility, perceived severity, perceived benefits (or efficacy), perceived barriers, cues to action, and self-efficacy.18

Perceived susceptibility is a construct that measures the extent to which one feels he or she is susceptible to a disease or condition. Perceived severity measures to what degree one believes a condition would impact one’s overall health or other aspects of one’s life. Perceived benefits, sometimes referred to as perceived efficacy of acting, is the extent to which one believes a given behavior will reduce susceptibility to, or severity of, a disease. Perceived barriers measures the level of costs (physical or psychological) that one believes acting would entail. Cues to action measures the level to which one perceives outside cues that encourage one to behave in a particular manner; it is important to note that this construct has been poorly studied and is often left out research that utilizes the HBM. The last construct, self-efficacy, measures to what degree one believes that they can carry out the behavior that would promote a desirable outcome. Self-efficacy was not included in earlier formulations of the HBM. It is believed to be quite important for large-scale lifestyle changes; however, it is likely much less important for simple actions, for which most people possess sufficient self-efficacy.18, 19

The HBM has been validated when applied to a range of health behaviors designed to minimize adverse infectious disease outcomes. Behaviors to prevent HIV research are probably the most extensively studied of these.18 One study investigated the effect of the “core” HMB
constructs – perceived severity, susceptibility, benefits, and barriers – on several HIV-preventive behaviors among Asian-American college students. Perceived severity and barriers were found to be significant predictors of preventive behavior. In particular, severity was associated with increased care in the selection of sexual partners, reduced numbers of sexual partners, and “generally positive changes toward safer sexual behavior.” Barriers were negatively associated with more careful selection of partners, reduction of partners, and making sure that partners are HIV negative.20

Another study investigated the effect of the HBM constructs (except for cues to action) on a range of HIV-preventive behavior among Taiwanese immigrants to the United States. Self-efficacy was consistently significantly associated with all three risk behaviors: number of sexual partners, frequency of sexual intercourse, and consistency of condom use. Perceived barriers was also significantly associated with frequency of sexual intercourse, and perceived severity was significantly associated with frequency of condom use. For all behaviors, inclusion of the entire set of HBM constructs significantly improved the multiple regression analysis.19

A third study investigated the effect of HBM constructs on condom use when visiting a commercial sex worker in Thailand, and compared the predictive value of the HBM constructs with those of another behavior change model, the Theory of Reasoned Action (TRA). Though the TRA constructs predict preventive behavior slightly better than the HBM constructs, the HBM constructs were strongly predictive of condom use. All of the HBM constructs were significantly associated with condom use except for self-efficacy, which was associated at a marginally significant level. One unexpected result turned up: perceived susceptibility was negatively associated with condom use, instead of the expected positive association.21 This is a result that has been found several times with HIV-preventive behavior HBM research, and is
believed to be a result of people who do not take preventive behaviors believing themselves to be at increased risk.\textsuperscript{18,21} As a result, it is now recommended that perceived susceptibility be measured conditionally on behavior (e.g. “if you do not use a condom, would you feel susceptible to HIV?”).\textsuperscript{18}

Another study investigated the effect of the HBM constructs on intent to engage in tuberculosis-preventive behaviors among Mexican Americans. It was found that increased perceived susceptibility, benefits, and “attention to action cues” were significantly associated with intent of preventive behavior. Perceived barriers were not associated with intent, but this is not surprising; barriers are believed to affect the likelihood that one transfers intent to act into actual action and actual action was not used as a response variable in this study. Interestingly, it was also found that the degree to which study participants had acculturated to American society substantially affected the predictive value of the HBM constructs.\textsuperscript{22}

Another study looked at the effect of HBM constructs (except for cues to action) on vaccination against hepatitis B among men who have sex with men (MSM); it also compared the predictive value of the HBM constructs with those of the Theory of Planned Behavior. The HBM constructs were found to be better predictors of vaccination. Specifically, perceived susceptibility and perceived susceptibility were associated with higher vaccination. Certain barriers were associated with lower vaccination, especially a fear that one’s lifestyle would become known by taking a vaccine targeted to the MSM community. Self-efficacy and benefits were not significantly associated with vaccination.\textsuperscript{23}
Research on Behavior During Epidemics

Engaging in Protective Behaviors

In the event of a disease with a high attack rate in a population, such as pandemic influenza, coercive methods of control, such as quarantine or isolation, may be infeasible due to lack of personnel for enforcement.\textsuperscript{24} Thus, it is likely that much of the behavioral control of pandemic influenza would be done through personal protective behavior, such as facemask wearing or the avoidance of crowded places.\textsuperscript{25} These behaviors would likely be important control measures for those people who are susceptible to disease.

Facemasks

As was the case for SARS in Asia, during influenza in 1918, masks were greeted as a protective measure in much of the Western world.\textsuperscript{26} Studies have not been conducted to determine the effectiveness of mask wearing in limiting the transmission of influenza,\textsuperscript{25} but a protective association was found between wearing facemasks and SARS transmission.\textsuperscript{27} It is believed that a similar association may exist for influenza, as influenza is believed to be primarily transmitted via large-droplet produced by coughing or sneezing,\textsuperscript{28} and one study found a decrease in influenza-associated respiratory disease in Hong Kong during the span of time in which SARS precautions were in place, including facemask wearing, among others.\textsuperscript{29} Considering this, it is likely that at least some jurisdictions will require the public to wear masks in response to pandemic influenza.

Several studies have been conducted on factors associated with increased facemask wearing during the SARS epidemic in Asia and Canada. These studies generally have used the
constructs measured in the Health Belief Model (HBM), along with demographic variables, to explain facemask wearing. The HBM contends that health behavior is a function of several psychological constructs, including perceived severity of the disease, perceived susceptibility, perceived barriers to action, and perceived benefits from action or the efficacy of that action. In virtually all studies, the degree to which one felt susceptible to SARS was an independent predictor of mask wearing. Maximum likelihood estimates of the increased odds of facemask wearing associated with high perceived susceptibility were as high as 6.5-fold when compared to those who perceived low susceptibility, but most were in the 2.4 to 2.7 range. Another study measured a similar construct, the degree to which one believed SARS to be under control, and reported a similar association.

The degree to which one believed that wearing a mask was efficacious in preventing transmission also was independently associated with increased mask wearing. The majority of studies found increased odds of mask wearing among those with a high perception of efficacy compared to those with a low perception, with odds ratios usually ranging from 1.4 to 2.7, with one study finding an odds ratio of 7.2 fairly early in the SARS epidemic in Hong Kong. Another study tested the same construct under a different name, perceived benefits from the preventive behavior, and reported a significant odds ratio of 1.4. This finding is consistent with the historical record; American cities in 1918 had both a high level of mask wearing and, it seems, a great belief in the effectiveness against influenza.

Perceived severity of SARS also was often found to be associated with mask wearing, though a few studies found a non-significant relationship. Research that found a significant relationship reported an increase in odds ranging from 1.6 to 2.2-fold.

Perceived barriers to mask wearing were not associated with facemask wearing, probably
because of the low level of barriers to obtaining or wearing a mask.\textsuperscript{31} In the only study that measured it, cues to action was significantly associated with mask wearing, with an odds ratio of 2.4.\textsuperscript{31} A similar construct, awareness, was not significantly associated with a range of preventive behaviors in another study.\textsuperscript{33} Self-efficacy was only studied in one piece of research, at it was also found to be a significant predictor of a set of preventive behaviors, of which mask wearing was one.\textsuperscript{33} However, this study did not investigate the effect of barriers on preventive behavior. It is likely that there is considerable overlap in the perceived barriers and perceived self-efficacy constructs, so it is possible that self-efficacy would not have been significantly associated with preventive behavior had barriers also been included in the model.

\textit{Avoidance of Crowded Places}

Crowding is associated with increased transmission of influenza. In 1918, transmission was often associated with military bases,\textsuperscript{25,26} and annual epidemic transmission is strongly associated with schools.\textsuperscript{36,37} It is believed that dissuading crowding could slow the epidemic and lower its peak incidence,\textsuperscript{25} because it decreases the amount of contact between infected and susceptible people.\textsuperscript{38} This was a measure that was conducted in the United States in 1918,\textsuperscript{26} and it was also common in countries afflicted by SARS in 2003.\textsuperscript{39} Several models predict that it can be a tool for decreasing transmission of airborne pathogens, including smallpox\textsuperscript{16,38} and SARS.\textsuperscript{38} In an influenza pandemic, it is likely that the government would recommend that people avoid crowded places, and that people would do so even in the absence of an official instruction.

The determinants of avoidance of crowded places during the SARS epidemic were reported in a couple of studies. These studies did not measure perceived efficacy of avoiding crowding, though, oddly they did measure the effect of one’s belief in the efficacy of masks on
whether one visited crowded places.\textsuperscript{30,32} In one study, neither perceived susceptibility nor perceived severity of the disease predicted precautionary behavior.\textsuperscript{32} In the other, both were significant predictors, with high perceived susceptibility associated with 3.0 times the odds of avoidance of crowded places and high perceived severity of the disease associated with 2.0 times the odds.\textsuperscript{30} Though both studies were conducted on people who traveling to or from Hong Kong during SARS, the latter study is likely more representative of the general population. It consists of a sample that is more demographically representative of Hong Kong’s population, whereas the former study not conducted solely on travelers to mainland China during the epidemic, who are likely to have different risk perceptions than those who avoided the mainland.\textsuperscript{32}

In the 1918 influenza pandemic, people avoided places where they might come into contact with others. Consider the following from a man who lived through the pandemic: “The fear was so great people were actually afraid to leave their houses. People were actually afraid to talk to one another. It was almost like don’t breathe in my face, don’t look at me and breathe in my face.”\textsuperscript{26} People seemed to control their movements both out of a belief that to move freely would expose them to greater risk of infection and that staying home would protect them from illness.

Similar behavior was seen in epidemics from farther back in history. Accounts of London during the plague of 1665 tell of normally crowded markets being nearly abandoned. Places of public gathering would be vacated within a short time of plague being reported in the vicinity.\textsuperscript{40} Farther into antiquity, when Thucydides wrote of the plague of Athens in 430 BCE, he described people’s fear of one another and a belief that the plague was worst in the most crowded parts of the city.\textsuperscript{41}
Quarantine and Isolation

Quarantine is the segregation from the general public of people who are believed to have been exposed to a pathogen and may become infectious. It is differentiated from isolation, which is the segregation of people who are presently infectious, or at least believed to be so. In a compartmental model, quarantine would be applied to people in the exposed compartment, and isolation to people in the infectious compartment. Quarantine was used successfully during the SARS epidemic, decreasing infections through quicker identification of cases when they arose. With policymakers cognizant of this success, quarantine is a tool likely to be used in the event of pandemic influenza, though it may be very difficult logistically to conduct on a large scale, and this difficulty may be exacerbated by influenza’s short generation time and relatively high proportion of transmission by asymptomatic people, estimated at between 30 and 50 percent. One model, created to determine the effect of quarantine on the spread of the 1918 influenza in Canada, indicates that a quarantine will not have much effect unless it can decrease contacts’ mobility by at least 90 percent. However, the high proportion of asymptomatic transmission also means that isolation of cases alone will be effective in slowing transmission only to a limited degree. In any event, quarantine seems to be pillar of the federal government’s planned response to pandemic influenza or similar diseases.

Historically, there have been difficulties with obtaining a high level of compliance from people placed in quarantine who are not symptomatic. In 1893, public health authorities in Muncie, Indiana, implemented a quarantine to try to control a smallpox outbreak. Citizens challenged the smallpox diagnosis and resisted the quarantine. Violators were jailed, but the quarantine effort was ultimately abandoned after violence occurred and resistors shot several officials.
In 1918, quarantine of individuals was not used on a wide scale in the United States to control influenza. However, the province of Manitoba, Canada, responded to influenza by requiring the quarantine of affected homes and quarantine placards to be placed in public view. It is estimated that quarantine resulted from only about 60 percent of cases. Influenza was easy to misdiagnose as a cold. Furthermore, some people did not report their infections to avoid quarantine, and there were allegations that some physicians colluded with patients not to report cases. Contemporaries judged the efforts “lamentably inefficient in checking the spread of the disease.”

Quarantine has its roots in the control of plague in medieval Europe, initially in the requirement that ships entering the port of Venice had to wait 40 days before offloading people or cargo. English authorities isolated people diagnosed with plague during the epidemic of 1665, and shut up household contacts with the infected people in houses clearly marked with a red cross and “Lord, have mercy on us.” It is unclear to what extent the quarantine orders were followed. One account exists in which friends of people quarantined in a tavern broke down the door and allowed out the people contained inside. There are other accounts of people breaking out of shut up houses, but also of many houses that were shut up and, presumably, those inside made no serious efforts to leave. However, an odd order was issued in August of 1665 that indicates the quarantines may have been frequently broken. London’s mayor instructed healthy citizens to stay in their houses after 9 o’clock in the evening because those shut in their houses would be allowed out after this time; this apparently was done to keep them from breaking out of their houses during the rest of the day.

Early reports during the SARS epidemic hinted at similar problems with quarantine enforcement. In Taiwan’s capital, Taipei, health authorities closed down a housing project after
suspected SARS patients were determined to live inside.\textsuperscript{50} The facility’s residents were quarantined, but before civilian and military police surrounded the building, about 40 percent of the people who lived there fled.\textsuperscript{51} A similar event occurred at the Amoy Gardens apartment complex in Hong Kong. A faulty sewage system caused the infection of about 300 residents or their contacts.\textsuperscript{52} A quarantine order for the building was issued, but when police arrived to enforce it, they found the majority of the apartments empty.\textsuperscript{49}

Subsequent research, however, found a fairly high rate of quarantine compliance. Officials in Taiwan surveyed 100 people in home quarantine, and found 85 home; 70 of whom were reported to have never broken quarantine.\textsuperscript{49} However, Taiwan quarantined between 130,000\textsuperscript{53} and 150,000 people\textsuperscript{43} and the selection methods utilized for this survey are unclear, so the degree to which the people surveyed represent the general population is unknown. In any event, though, it seems clear that the number of people who broke quarantine substantially exceeded the 286 who were penalized legally for doing so.\textsuperscript{53}

Officials from Singapore’s Ministry of Health reported that 7863 people were given orders to remain in home quarantine; only 26 of these were subsequently found to have broken quarantine and were penalized. Singapore had a fairly rigorous surveillance system – including the placement of cameras in private homes and large-scale use of private security firms to augment law enforcement – to ensure quarantine, so these numbers are likely accurate.\textsuperscript{54} However, it is doubtful that such results would be duplicated in the United States, as such enforcement mechanisms are unlikely to pass legal, ethical, or political muster; one study found that 67 percent of Americans oppose video monitoring to enforce quarantine.\textsuperscript{55}

In Toronto, between 13,000\textsuperscript{56} and 30,000\textsuperscript{57} people were placed in quarantine. Quarantine was initially voluntary, and quarantine orders were only issued for those people who failed to
comply with the initial quarantine request. Only 27 quarantine orders were issued.\textsuperscript{49} It is unclear whether this low rate of mandatory orders reflects high compliance or low surveillance and enforcement, but the large discrepancy in estimates of the number of people quarantined – which resulted from record keeping and notification issues – indicates that enforcement was inexact.\textsuperscript{57} Quantitative research on compliance is scarce, but one study found that four percent of health care workers broke quarantine to get food, three percent to provide transportation to others, and other factors were ranked as greater impediments to compliance but not reported quantitatively.\textsuperscript{57} However, self-reported levels of compliance were high,\textsuperscript{57, 58} though a quarter of respondents in one study characterized being quarantined as a “major problem.”\textsuperscript{59}

A couple of studies report factors associated with quarantine compliance during SARS in Toronto, but only qualitatively. The primary reasons people reported for complying with quarantine was to protect others or to be “good citizens.”\textsuperscript{57, 58} As expected, when people felt more vulnerable to infection, compliance with quarantine was more strict,\textsuperscript{58} even to the extent that some health professionals who perceived high risk implemented self-quarantine of a duration and extent that exceeded official recommendations.\textsuperscript{57} Several factors were deemed substantial barriers to compliance (though little information is available on people who actually broke quarantine). The most important of these was financial – the concern that one would lose pay while in quarantine. Additionally, there was confusion about what was required because of differences in instructions by different jurisdictions.\textsuperscript{57} Of lesser concern, but still reported by a fairly high number of people, were concerns about logistical matters (such as getting groceries and transporting family members and psychological stress from quarantine. About five percent reported “such high stress that they were tempted to break quarantine.”\textsuperscript{57} Interestingly, no adults reported fear of penalties as their most important cause of compliance, and 80 percent of those
who knew of the penalties stated that they had no influence on their compliance, and that breaking quarantine entailed little or no fear of being caught. Though Toronto had fewer than 400 cases, the large number of people in quarantine overwhelmed civil government’s ability to monitor and enforce compliance.  

The only research that quantitatively investigates determinants of quarantine compliance does so by surveying people to determine intent to comply in a future epidemic. The most comprehensive of these investigates determinants of opposition to a quarantine during a hypothetical terrorist release of smallpox. It found that 77 percent of respondents would submit to being quarantined voluntarily, which is similar to the 83 percent of respondents to a recent Harvard School of Public Health study who stated they would agree to quarantine if exposed to avian influenza, and the 75 percent who said they would comply with quarantine in the event of a terrorist attack using Rift Valley fever virus. In the smallpox study, opposition to a mandatory quarantine policy was most strongly associated with a couple of measures of trust in government: a belief that government would abuse its power (odds ratio of 1.9) and a belief that government will threaten personal liberties (odds ratio of 1.5). A high degree of perceived personal risk was associated with decreased opposition to quarantine (odds ratio of 0.6). Additionally, having children was associated with decreased opposition (odds ratio of 0.7) and being aged between 30 and 49 was associated with increased opposition when compared to those over the age of 50 (odds ratio of 1.5). The trust in government variables were themselves independently associated most highly with political party identification (with Independents and Democrats being significantly more likely to distrust government than Republicans). Additionally, those from the northeast or north-central parts of the country were significantly less likely to believe government would abuse its power than those from the south once one
controlled for party identification.\textsuperscript{60}

Fear that government will abuse its power during a disease emergency is a reasonable one, based in a long historical record. Many European countries scapegoated and slaughtered Jews during the plagues of the mid-14\textsuperscript{th} century.\textsuperscript{63} English authorities shut up the houses of the poor while concealing cases among the rich in the 1665 plague and used the disease as a pretext to persecute religious dissenters.\textsuperscript{40} The burden of quarantine was differentially applied to immigrant Jews from Eastern Europe when cholera broke out on ships in New York’s harbor.\textsuperscript{64} American immigration officials abused Mexican day laborers out of fear that they would bring typhus across the border with them early in the 20\textsuperscript{th} century.\textsuperscript{65} Any quarantine policy that is likely to have public legitimacy must both be a fair use of governmental powers and be trusted by the public.\textsuperscript{66}

One additional study compared support for quarantine in the United States with Singapore, Hong Kong, and Taiwan, three countries that experienced widespread quarantine during SARS.\textsuperscript{55} Support for quarantine is similar in America and Hong Kong (76 and 81 percents, respectively), but lower than it is in Singapore and Taiwan (89 and 95 percent).

Among those Americans who initially supported quarantine, 30 percent said they would no longer support it if breaching quarantine could result in arrest, which was significantly different than the 18 percent of Singaporeans who answered likewise. Forty percent of Americans reported being very concerned about losing wages if they were quarantined, and equal percentage were very concerned about losing a job or business, and 45 percent about being unable to obtain medical care or medications while in quarantine. Interestingly, while 80 percent of Americans trusted their health providers to give them information during an epidemic, only 40 percent said they trusted government health officials’ information and only 27 percent said they
trusted the media.  

Quantitation of Models

The best form for a compartmental model of influenza to take is an SEIR model, which would reflect the biology and epidemiology of influenza. Estimates based on research on the duration for which infected people shed virus indicate a latent period of about 1.9 days and an infectious period of 4.1 days. These correspond to the average amount of time one would be in the E and I compartments of the model, respectively. Data on immunity during the 1918 pandemic is scarce, but some evidence indicates that people infected in the pandemic’s first wave were protected during the second wave. Thus, one could assume that one can only be infected once during the initial pandemic season of transmission.

The use of an SEIR model also fits well with the behavioral interventions likely to be used against a novel strain of influenza, or another novel disease. Preventive behaviors such as facemask wearing and avoidance of crowded places, as well as other hygienic behaviors, such as handwashing, would be targeted to susceptible people. Quarantine would only apply to those people who have been exposed to disease and are not yet ill. Similarly, isolation applies only to those who are presently ill. The presence of immunity for those people who have recovered from illness would allow them to safely care for others and fulfill other necessary roles in a society where all interactions are curtailed to prevent disease transmission, though evidence on the behavior of people during an epidemic who have recovered from disease is lacking.

Behavior during an epidemic is best modeled using the four core constructs of the Health Belief Model: perceived susceptibility (U), perceived severity (V), perceived benefits / intervention efficacy (F), and perceived barriers (B). The other two constructs – self-efficacy
and cues to action – have been insufficiently studied in the contexts of epidemics to allow usable estimates of their effects on behavior. Furthermore, to the extent that they have been studied, their effects are inconsistent. Most importantly, there are theoretical reasons to avoid them. The actions that would be taken in response to epidemics are relatively simple to carry out. Thus, impediments to their successful completion are likely to be due more to barriers to completion than a lack of self-efficacy. Similarly, many of the cues to action would be in the form of official messages, and their modes of action would likely be through their effects on how people perceive the disease (severity and susceptibility) and how people perceive the interventions (benefits). For the sake of simplicity and non-repetition, there is little reason to add self-efficacy to the model.

The parameters for all four SEIR components are similar in form, with the HBM explanatory variables dichotomized to either a high or low level. These variables interact to produce a probability of action, the response variable. Because the quantitative data is reported as the results of logistic regression, for the sake of ease, the quantitation reported in this paper will use the same format. Thus, the probability of acting \((P)\) will take the general form:

\[
P = \frac{(\omega_0 \ast \omega_1 U \ast \omega_2 V \ast \omega_3 F \ast \omega_4 B)}{[1 + (\omega_0 \ast \omega_1 U \ast \omega_2 V \ast \omega_3 F \ast \omega_4 B)]}
\]

In the formula above, the dichotomous variables \(U, V, F, \) and \(B\) take a value of one when the perceived level of these are high and a value of zero when low. \(\omega_0\) refers to an underlying odds of behavior when all four variables are low, and \(\omega_i\) are the odds ratios associated with the high level of each variable, and these can be estimated directly from the literature. No test for interaction between these variables has been conducted, so they are assumed to be independent
Behavior by People in the Susceptible Component

Consistent with the research on SARS, it is assumed that the primary motivation for preventive behaviors is self-protection. As described in the literature review, the primary variables that predict the wearing of facemasks or avoidance of crowded areas are the degree to which a person perceives themselves to be susceptible (U), the disease to be severe (V), and the preventive behavior to be efficacious (F). Barriers (B) were not found to be important for these behaviors, but might be for other preventive behaviors not considered in this paper. When one compares the reported values for $\omega_1$, $\omega_2$, $\omega_3$, and $\omega_4$ in the literature they are similar (that is, the confidence intervals substantially overlap) regardless of whether one is estimating them for avoidance of crowded places or for facemask wearing, so they will be treated as the same value regardless of what behavior by susceptible people one is trying to predict. However, the $\omega_0$ values differ by preventive behavior, reflecting, perhaps, different beliefs about the ability to engage in the behavior or other behavior-specific factors.

Estimates of the odds ratio associated with perceived susceptibility to infection most frequently ranged from 2.4 to 2.7. Thus, one can estimate $\omega_1$ to be approximately 2.5. Estimates of the odds ratio associated with perceived disease severity were most frequently in the 1.6 to 2.2 range. One can estimate $\omega_2$ to be approximately 2.0. Estimates of the odds ratio associated with perceived efficacy of the preventive behavior most frequently ranged from 1.4 to 2.7. One can thus also estimate $\omega_3$ to be about 2.0. For both of these behaviors, we assume that the odds ratio associated with barriers is 1.0; thus, this is the value of $\omega_4$.

The value of $\omega_0$ cannot be estimated as directly, as no studies in the literature reported the
likelihood of engaging in preventive behaviors among those who perceived all four variables lowly. However, it can be estimated by using the lowest reported rate of preventive behavior in the literature associated with a low value of at least one of the variables. For facemask wearing, this is 12 percent, and it is 41 percent for avoidance of public places. These values correspond to a baseline odds ($\omega_0$ value) of about 0.15 for mask wearing and 0.7 for avoidance of crowded places.

Thus, the equations for the likelihood of each preventive behavior by susceptibles are as follows:

$$P_M = \frac{[0.15 \times 2.5(U) \times 2.0(V) \times 2.0(F) \times 1.0(B)]}{1 + [0.15 \times 2.5(U) \times 2.0(V) \times 2.0(F) \times 1.0(B)]}$$

$$P_A = \frac{[0.7 \times 2.5(U) \times 2.0(V) \times 2.0(F) \times 1.0(B)]}{1 + [0.15 \times 2.5(U) \times 2.0(V) \times 2.0(F) \times 1.0(B)]}$$

The initial distribution of high and low values of each explanatory variable would have to be determined for a given disease and location. Methods of control would be effective to varying degrees against different diseases, and the risk of infection and severity of the disease would also vary significantly, so one would expect significant variation in the distribution of the explanatory variables for different diseases; however, there is no reason to believe that the relationship between the values taken by the variables and people’s behavior would change. These levels may be changed exogenously during the course of the epidemic by risk communications that are effective to varying degrees. Unfortunately, the quantitative relationship between the effectiveness of communication efforts and the levels of these variables has not been sufficiently researched as to be estimable.
One can also infer likely changes in the level of the variables based on progression of an epidemic. One can assume that people are more likely to feel susceptible when disease is prevalent in area. This proposition has not been directly tested, but there is evidence to support it in the increased precautionary behaviors taken by people who had a history of contacts during the SARS epidemic in Hong Kong.35 Similarly, one can assume that those people who have had contacts with those people who develop severe disease are more likely to perceive the disease as more severe. Thus, in the model, populations with low perceived susceptibility would likely switch to high perceived susceptibility as fatalities increase.

Behavior by People in the Exposed Component

The reasons why people comply with quarantine orders are different than face masking or hygienic measures, and a model that seeks to explain quarantine compliance should reflect this. Most people reported that they wore facemasks to protect themselves,30 while people comply with quarantine orders primarily to protect others.57, 58 Thus, one would expect that people’s compliance with quarantine is a function of the degree to which they believe staying home stops transmission, the degree to which they feels that others are vulnerable if one does not comply with quarantine (which is likely reflected in one’s own risk perception), the degree to which one perceives transmission to entail severe results, and the degree to which one believes that barriers make compliance impossible. These factors are consistent with the findings of the quantitative and qualitative research on quarantine compliance. Another variable, the ability of authorities to compel compliance is assumed to be unimportant due to the degree to which the number of people in quarantine would exceed the state’s enforcement abilities in a large-scale outbreak.66

Unfortunately, the quantitative research on quarantine compliance that is presently
available has not fully investigated the HBM constructs. It has instead focused on trust in
government, as well as susceptibility to disease. However, one could make some assumptions
that, while not optimal, are reasonable under what is known about how people perceive risks.
There is evidence that trust in the source of a message results in it being accepted, and distrust
results in it being rejected.\textsuperscript{69} Presumably, during an outbreak of a novel disease, the source of
people’s perceptions of severity, susceptibility, and effectiveness of quarantine will come largely
from official sources. Thus, one might assume that people with a low level of trust in the
messages are likely not to act consistent with messages to comply with quarantine and have low
scores for perceived severity, susceptibility, and effectiveness. The opposite would be true for
people with high trust in official sources. With this assumption in mind, and the assumption that
everyone with high perceived susceptibility, severity, and benefits and no barriers would comply
with quarantine, a model can be created that uses the variables as the model for those in the
susceptible block of the SEIR model, though it is slightly modified:

\[
P_Q = (1-B) \cdot \left[ \frac{(\omega_0 * \omega_1 U * \omega_2 V * \omega_3 F)}{(\omega_0 * \omega_1 U * \omega_2 V * \omega_3 F)} \right]
\]

In this construction, the barriers variable (B) measures the same construct but takes a
slightly different form to comply with the available data. Instead of being the odds ratio
associated with high perceived barriers, it is the proportion of the population that perceives
barriers too severe to allow compliance. If data on perceived barriers were available, it would be
optimal for all of the estimates for behavior to take the same form.

The rate of substantial barriers will be population-specific; however, among Canadians
quarantined for SARS, 11 percent reported major emotional difficulties due to being confined,
10 percent reported major problems from not being paid, six percent from inability to communicate with family, three percent from inability to get medicine, and four percent from inability to get food or water. Assuming overlap in these categories, one could estimate that about 20 percent of the general population would face barriers that preclude compliance with quarantine. However, well-executed programs to compensate people in quarantine might lower this, as the Singapore’s experience with SARS seems to indicate. On the other hand, epidemic disease in impoverished areas would almost certainly increase the barrier rate, but no research has actually been conducted to test this hypothesis.

Baseline intent to comply with quarantine is likely quite high. One study of Americans found that 93 percent would agree to quarantine if exposed to SARS, and a qualitative study of quarantined Canadians found that all “reportedly agreed with the need for quarantine.” The quantitative data reports that 77 percent would comply with a voluntary quarantine. Thus, it seems reasonable to estimate a baseline intent to comply at 80 percent, which would correspond to baseline odds \( \omega_0 \) of 4.

Two components of trust in government were found to be associated independently with opposition to quarantine, and one can assume that the relationship between trust and intent to comply with quarantine would track the relationship between trust and non-opposition to quarantine. A belief that government would abuse its power was associated with an odds ratio of opposition of 1.9, and a belief that government would threaten personal liberties was associated with an odds ratio of 1.5. Collapsing these into a single trust variable, one would expect the odds ratio of opposition associated with low trust to be 2.85. Thus, the odds ratio of compliance associated with low trust would be 0.35 or of 2.85 with high trust. These results were reported in a logistic regression model which also included perceived susceptibility to infection. If one
assumes that the trust variable is a surrogate for the susceptibility, severity, and benefits variables, then the results reported for trust in this paper would be a surrogate for those three with susceptibility held constant (i.e. for only severity and effectiveness). Thus, the odds ratio for high severity and benefits could be estimated to be 2.85. A high degree of perceived susceptibility of infection is inversely associated with opposition to quarantine. An odds ratio of opposition of 0.60 among those who perceive high susceptibility compared to those who perceive low susceptibility was reported by Taylor-Clark and others. This corresponds to an odds ratio of compliance of 1.7. This yields the following estimated equation for compliance with quarantine:

\[ P_Q = (1-0.2) \times \left( \frac{4 \times 2.85(V \times F) \times 1.7(U)}{1 + (4 \times 2.85(V \times F) \times 1.7(U))} \right) \]

As discussed for the previous component, the values of the explanatory variables can change in response to the course of the epidemic. One can presume, as was done for the previous model, that people with a low risk perception would switch to high risk perception when another agent in its social network becomes clinically ill. Similarly, one might expect the barrier rate to increase as the duration of time that a population is affected by disease increases and income and supplies become increasingly scarce, but no research has been conducted on this. Furthermore, trust in government is a variable that is susceptible to outside influences. Risk communications can either increase or decrease trust, as can the degree to which government’s response is perceived to be caring, open, and competent. However, it is unclear to what extent communications can drive trust; some research indicates that distrust damages the credibility of risk messages, making distrust self-perpetuating.
Behavior by People in the Infectious Component

Lastly, one must consider how the quarantine model should be altered to explain compliance with isolation orders. In what seems like a significant oversight, no research has been conducted on patient compliance with isolation during epidemics. However, one could surmise that the model would be essentially the same as quarantine for asymptomatic cases. For cases who have severe symptoms, one could assume that compliance will be 100 percent; patients that are bedridden are unlikely to break isolation. For those patients who have only moderate symptoms, the model should be the same as the quarantine compliance model, but presumably, all people in this block would have a high degree of perceived susceptibility.

Limitations of the Present Research

There are several areas that are in need of further research; this is largely because of the rarity of large scale epidemics and the speed with which they unfold. Nonetheless, little research exists on the determinants of actual compliance with any policy during a real epidemic. That which does exist is almost exclusively on SARS, which is probably a good model for influenza but may not be for diseases that are not transmitted by aerosol. There is also research on determinants of stated intent to comply with quarantine or hygienic measures in hypothetical outbreaks, but it is unclear to what extent intent would correspond to actual behavior. There is also some theoretical work that is derived from economic game theory that seeks to explain how people respond to epidemic disease; unfortunately, it is based on the dynamics of sexually transmitted infections,\textsuperscript{13,72} which are likely quite different than respiratory pathogens.

As discussed in this paper, some research has been conducted on those factors that influence preventive behaviors and quarantine compliance, though it is far too sparse,
particularly with respect to HBM constructs. Furthermore, there is an absence of research on the
degree to which these factors change in response to either public health interventions or the
progression of an epidemic. There is high quality research on how people perceive health risks
from environmental hazards\textsuperscript{73} and disasters,\textsuperscript{74} but little that deals directly with epidemics.
Similarly, there are papers that address how risk communication might influence people’s
behavior during an epidemic which make reasonable extrapolations from other types of crises,\textsuperscript{66, 75} but there seems to be no quantitative research that directly addresses population-level
communications during an epidemic.

There is also a lack of research on the extent to which people take cues about behavior
during epidemics from those near them. One could reasonably expect that, all other things being
equal, a person who lives in an area where no one complies with quarantine might be less likely
to comply than one who lives where everybody else does. The same might be true for preventive
behaviors, particularly behaviors like facemask wearing, for which it is quite clear what actions
others are taking. However, research on this for epidemic diseases like influenza does not
presently exist.

Lastly, there is no research on how people’s behavior changes once they have had a
disease and recovered. One might expect that recovered people would perceive no susceptibility
and thus not worry about taking risky behaviors. Thus, they might be likely to engage in pro-
social behaviors during an epidemic. However, it is also possible that people who have endured
substantial illness during an epidemic might not have any desire to be exposed to the pathogen
again, and avoid interacting with potentially ill people. Without research, any attempt to predict
the behavior of people in the recovered component of an SEIR model would be pure hypothesis.
Conclusion

Despite a shortcoming of quantitative research on some facets of behavior during epidemics, one can draw certain conclusions with a high degree of certainty. People are more likely to take protective behaviors when they feel highly susceptible to a disease or when they believe that acquiring the disease would entail severe consequences. People are also more likely to do the same when they believe that a behavior is likely to protect them. Though data is less available for compliance with quarantine and isolation, people are likely to comply more frequently when they believe the risk of disease is high and when they trust the entity that is requesting compliance. However, for some people, there will be insurmountable barriers to compliance, at least in the absence of a well-coordinated plan to address these barriers. In short, one must recognize that modeling how well a control method could work if people can be persuaded to carry it out is only part of the challenge. The effectiveness of any control effort will always depend both on its theoretical effectiveness and the way that people who are affected by it behave.
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