A Double-risk Monitoring and Movement Restriction Policy for Ebola Entry Screening at Airports in the United States

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Abstract

This paper provides an alternative policy for Ebola entry screening at airports in the United States. This alternative policy considers a social contact tracing (SCT) risk level, in addition to the current health risk level used by the CDC. The performances of both policies are compared based on the scenarios that occur and the expected cost associated with implementing such policies. Sensitivity analysis is performed to identify conditions under which one policy dominates the other policy. This analysis takes into account that the alternative policy requires additional data collection, which is balanced by a more cost-effective allocation of resources.

Introduction

The 2014 Ebola Hemorrhagic Fever outbreak in West Africa has drawn significant worldwide attention and concern. As of 31 January 2016 (updated 3 February 2016), a total of 28,639 cases and 11,316 deaths have been attributed to Ebola¹, figures that are assumed to significantly underestimate the actual scope of the outbreak. In the United States, there were also two imported cases and two locally acquired cases reported in September/October 2014.¹

This outbreak stimulated high-level discussions about how to prevent the global transmission and spread of Ebola. One strategy, recommended by the World Health Organization (WHO), is exit screening at airports for passengers who depart from countries with Ebola.² Passengers with a high-risk exposure to or symptoms of Ebola are denied boarding under this approach. With exit screening from such countries, out of approximately 80,000 departing travelers from August to November 2014, none were reported as symptomatic with Ebola.³ However, since the physical condition of a passenger can deteriorate during a long international flight, entry screening at destination countries was also instituted as an auxiliary precaution to prevent the entry of passengers with Ebola into their country.

The United States Centers for Disease Control and Prevention (CDC) is the national public health organization responsible for Ebola prevention and control within the United States. The United States Ebola entry screening procedure and Monitoring and Movement of Persons with Potential Ebola Virus Exposure policy are designed, reviewed, and published by the CDC⁴. The United States initiated entry screening in August 2014 and enhanced its entry screening program after the first imported Ebola case was diagnosed. The majority of passengers entering the United States from the affected West African countries (94%) arrived at one of five major

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international airports (New York – JFK, Washington-Dulles, Newark, Chicago-O'Hare, and Atlanta-Hartsfield)⁴ (note that beginning in late October 2014, all such passengers were required to flying into these five airports). Through November 2014, approximately 12,000 such passengers arrived in the United States, but no confirmed cases were reported among these passengers based on entry screening. Between 11 October 2014 and 10 November 2014, 1,993 such travelers entered the United States, with 86 (4.3%) referred for additional evaluation and 7 of these 86 (8.1%) referred for medical evaluation.³

The tradeoff between monitoring costs and policy efficiency is a fundamental issue for the Ebola entry screening problem. At the two extremes, for Ebola entry screening, if all passengers are monitored and movement restricted without considering the capacity of local public health departments and health facilities, and associated opportunity costs (such as days lost from work), the societal risk will be minimized. Alternatively, if all passengers are permitted to leave freely with no subsequent monitoring and no movement restrictions, the societal risk of exposure to Ebola will be greatest, with the lowest incurred monitoring costs. Balancing between these two extremes with available resources is the objective of the problem considered in this paper.

The current CDC entry screening policy relies on passengers displaying Ebola symptoms and identifying some level of exposure to Ebola.⁵ Both of these factors can be used to define a health risk level to capture the possibility of a passenger having Ebola. Based on this health risk level, a decision on monitoring and movement restrictions is made. Although the health risk level is determined by symptoms and exposure to Ebola, there are other risk levels that can be taken into consideration. For example, the difficulty of implementing social contact tracing (SCT) is important since contact tracing of a confirmed but not initially monitored or movement restricted Ebola patient may be prohibitively expensive (in terms of both direct expenditure and time) if a

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large number of cases must be handled. The SCT risk level is assessed by considering the potential number and type of social contacts that would need to be traced if a person has not been movement restricted and is later diagnosed with Ebola. Based on information such as a passenger's job and social activities, a SCT risk level can be assessed. For example, a person with a high SCT risk level would be someone who works in the service sector, such as at fitness club, which puts them in contact with many people per day, across a diverse footprint of backgrounds. Another such example is a person who frequents popular bars, restaurants, or entertainment venues, who also is in direct and close contact with many people during such events. Combining the health risk level and the SCT risk level may provide a more robust classification of passengers.

According to official announcements from WHO⁶ and the CDC⁷, Ebola patients are not contagious until they have shown symptoms. Since early Ebola related symptoms are similar to many other diseases, and hence, Ebola patients may be easily misdiagnosed, this could result in large (and unnecessary) social contact tracing costs.

An alternative Ebola screening policy at US airports is proposed. A SCT risk level is included in this alternative policy, in addition to the health risk level used by the current CDC policy⁸. The performances of both policies are compared based on all possible scenarios related to a given passenger and the expected cost per passenger (henceforth referred to as expected cost) associated with implementing such policies. A sensitivity analysis is performed to identify threshold levels (i.e., classifications for passengers based on health risk and SCT risk levels) at which one policy dominates the other policy (i.e., one policy has lower expected costs than the other policy) in the two-monitoring-level case. The resulting analysis provides insights on conditions under which the alternative policy dominates the current policy, by showing when the

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alternative policy more cost-effectively allocates resources, even with additional data collection requirements.

Methods

The screening procedures of both the current CDC policy and the alternative policy are briefly described. The cost for all possible scenarios and the expected cost are estimated with an evaluation model. The sensitivity ratio method and threshold level estimation are used for conducting sensitivity analysis.

Current CDC Policy Screening Procedure

According to guidance from the CDC⁸, entry screening has three main components: signs and symptoms, exposure levels, and body temperature. Using these components, the health risk level is determined for a passenger, resulting in a classification at one of four levels: “High Risk”, “Some Risk”, “Low (but not zero) Risk” and “No Identifiable Risk”. “High Risk” refers to passengers who had direct contact with Ebola patients without appropriate personal protective equipment (PPE). “Some Risk” refers to passengers who were in close contact with Ebola patients, or had direct contact while wearing appropriate PPE. “Low (but not zero) Risk” refers to passengers who had brief contact with a person in the early stages of Ebola while not wearing appropriate PPE, or direct contact with Ebola suspected-patients while wearing PPE in countries without widespread transmission. “No Identifiable Risk” refers to all other passengers, who have had no measureable exposure. Based on the results of the screening, two types of monitoring could be taken: active monitoring² and direct active monitoring². For direct active monitoring, movement restrictions may be required, such as controlled movement and non-congregate public activities².

Alternative Policy Screening Procedure

The alternative policy uses both the health risk level in the CDC policy plus a secondary SCT risk level based on social contact tracing risk. Ebola's infectiousness and incubation period may result in large social contact tracing costs, both in money and in time, when an Ebola patient is later diagnosed and not initially monitored or movement restricted (note that this would occur if the person was not forthright with their exposure risk). To implement the alternative policy requires adding questions to the questionnaire currently used at airports when collecting information for the health risk level.

Based on the information provided by the two risk levels, public health agencies have access to more data to make a better informed monitoring decision. Each individual passenger scenario needs to be carefully considered and assessed for public health policy makers to make decisions that are in the best interest of public health.

Below is an outline for how the alternative policy can be implemented. Note that the current CDC policy does not contain Step 2.

Step 1: Determine the health risk level based on the current questionnaire and medical symptom evaluation;

Step 2: Determine the SCT risk level based on a passenger's occupation and social interaction information from the questionnaire;

Step 3: Make a monitoring and movement restriction decision based the two risk levels;

Step 4: Check whether the passenger has become ill with Ebola within 21 days of the last potential exposure.

The alternative policy can weigh the importance of the two risk levels in any manner. However, it is reasonable to place a higher priority on the health risk level, since the SCT risk level only becomes an issue if a passenger has not been initially monitored or movement restricted but is later diagnosed with Ebola.

Enumerating Possible Scenarios

Enumerating all possible scenarios for a passenger can provide an overall scope of the policy performance. It is typically nontrivial to enumerate all possible scenarios that a passenger may encounter since there are so many different levels and types of risks. In this analysis, a limited number of risk levels are applied to the entry screening. For the health risk level, based on the current CDC policy, four levels are used (“High Health Risk” (HH), “Moderate Health Risk” (MH), Low Health Risk” (but not zero) (LH), and “No Identifiable Health Risk” (NH)). For the SCT risk level, three levels are used (high social contacts (HS), medium social contacts (MS), and low social contacts (LS)). A three-monitoring-level case is considered when comparing the two policies in different scenarios, which complies with the current CDC policy. In a three-monitoring-level policy, there are three options for the monitoring and movement restriction levels¹² (or simply, monitoring levels): the high level is direct active monitoring with movement restriction for 21 days (HQ); the medium level is direct active monitoring with minimum movement restriction for 21 days (MQ); and the low level is to active-monitoring with no movement restriction (LQ). Therefore, given that there are four health risk levels and three SCT risk levels, then there are 36 unique scenarios that must be considered.

The policies are evaluated based on the costs associated with the different scenarios. The parameters of the resulting models are determined from data available on actual screening done at airports⁹ and expert opinion.^{10,11} The inputs of the model are the four health risk levels (h), as defined by the CDC, the three SCT risk levels (s), and the disease status (d). The entry screening data is collected from questionnaires and measurements. The decision variable is the monitoring and movement restriction decision (q) (i.e., the action taken for a passenger). There are two types of costs: direct costs and indirect costs. Direct costs are the monitoring costs and the treatment

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costs. Indirect costs are the costs of social contact tracing since it is expended on the contacts of the passengers rather than the passengers directly. For simplicity, a linear combination of these two types of costs is used.

The **cost function** for each possible scenario is

$$O_{q,s,d} = 21 C_{monitor} + d \gamma_q C_{social} \beta_s + d C_{treatment}, \text{ where}$$

$O_{q,s,d}$ = cost per passenger under **monitoring and movement restriction** level q (HQ , MQ , LQ), SCT risk level s (HS , MS , LS), and disease status d

$C_{monitor}$ = daily cost of **monitoring and movement restriction** level q (C_{HQ} , C_{MQ} , C_{LQ}) for one passenger,

d = disease status variable on whether the passenger in this scenario becomes ill with Ebola ($d = 1$) or not ($d = 0$),

γ_q = contact tracing ratio for **monitoring and movement restriction** level q , defined as the fraction of social contacts to be covered in contact tracing for level q ,

C_{social} = social contact tracing cost per contact,

β_s = number of social contacts given social contact tracing level s ,

$C_{treatment}$ = treatment cost for a person who becomes ill with Ebola.

Sensitivity Analysis

The lack of reliable data makes it necessary to use sensitivity analysis to assess the impact of input data variations on the costs for the different scenarios. The sensitivity analysis is conducted using a sensitivity ratio (SR), which computes the ratio of the relative change in the output of interest to the relative change in the input parameter of interest (a type of gradient measure), done one input at a time. To illustrate, let X_1 , X_2 represent the value of any single input parameter before and after changes, respectively while O_1 , O_2 represent the value of the output before and after these input changes. Then $SR \equiv ((O_2 - O_1) / O_1) / ((X_2 - X_1) / X_1)$. By definition, a positive (negative) SR value means that increases in the input parameter result in increases (decreases) in

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the output. Moreover, the magnitude of SR measures the influence that the input parameter has on the output.

Optimization Model Analysis

The two policies are also evaluated based on the expected cost, given the distribution of the passenger health risk level and SCT risk level. To evaluate the robustness of the advantage of either policy, we conduct an optimization model analysis for different input parameters. In this analysis, we consider a two-monitoring-level case rather than the above mentioned three-monitoring-level case. In a two-monitoring-level case, there are two options for the monitoring and movement restriction levels: the high level is direct active monitoring with movement restriction for 21 days (HQ); and the low level is active-monitoring with no movement restriction (LQ). The two-monitoring-level optimization model will provide insights into how the current CDC policy can benefit from an extra SCT level.

Table 1 provides the probability distribution used in this analysis, which is estimated based on monitoring data reported in Stehling-Ariza et al.⁹ and Witt O'Brien's¹² with each row corresponding to one of the four levels for the health risk levels (with $\alpha_h \equiv$ probability of becoming ill with Ebola for health risk level h) and each column corresponding to one of the three SCT risk levels (with $\theta_s \equiv$ number of social contacts for SCT level s). Each entry $P_{h,s}$ in the table depicts the proportion of passengers with health risk level h and SCT level s .

Insert Table 1

The monitoring and movement restriction decision in the two-monitoring-level case is determined by setting up a threshold level in each risk dimension. Passengers who pass both threshold levels (health and SCT risk) are movement restricted and directly monitored (HQ). Threshold levels represent the lowest risk levels in which a passenger will be movement

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restricted and directly active monitored. The proportions in Table 1 are used to compute the probability of a passenger being movement restricted and directly monitored ($P(HQ)$), the expected number of social contacts of an Ebola patient not movement restricted ($E(S)$) and the probability of a passenger becoming ill with Ebola ($P(d=1)$), which are used to compute the expected monitoring costs, the expected social contact tracing costs and the expected treatment costs.

The probability of a passenger being movement restricted and directly monitored (HQ) is computed as the probability that a passenger passes both thresholds. Let $h_{threshold}$ and $s_{threshold}$ denote these thresholds, for the health risk level and the SCT risk level, respectively. Then

$$P(HQ) = \sum_{h \geq h_{threshold}, s \geq s_{threshold}} P_{h,s}$$

The expected number of social contacts of an Ebola patient is computed as the expected number of social contacts if the passenger not movement restricted (LQ) becomes ill with Ebola. Then

$$E(S) = \sum_{h < h_{threshold}, \text{ or } s < s_{threshold}} \alpha_h \beta_s P_{h,s}$$

The probability of a passenger becoming ill with Ebola is computed as the probability of infection for each risk level times the probability of a passenger in each risk level. Then

$$P(d=1) = \sum_h \alpha_h \sum_s P_{h,s}$$

The expected costs under the two-monitoring-level policy with threshold levels ($h_{threshold}, s_{threshold}$) is

$$E[O_{h_{threshold}, s_{threshold}}] = 21(P(HQ)C_{HQ} + (1-P(HQ))C_{LQ}) + E(S)C_{social} + P(d=1)C_{treatment}$$

The first objective of the optimization model is to identify the threshold levels that minimize the expected cost, given the number of passenger social contacts. The second objective is to assess how these threshold levels change as the number of social contacts change.

Results

The cost for each scenario is computed using the **cost function for each possible scenario**, with the current CDC quarantine policy used as a baseline to evaluate the alternative policy.

Cost Patterns of **Two** Policies

To address the complications associated with imprecise or unavailable data for the direct and indirect costs, the following assumptions are made: 1) Given the SCT risk level and the disease status, the cost is not affected by the health risk level. Therefore, the health risk level does not contribute to the costs for each scenario. 2) The sum of the **monitoring** costs, the contact tracing costs and the treatment costs is used (rather than treating the problem as a multi-objective optimization problem). 3) The values of the input parameters used in the sensitivity analysis are chosen based on values reported in the **literature**^{10,11}.

The costs for the alternative policy and the CDC policy were computed across different scenarios; these values are reported in Table 2, in US\$1000. In general, people who are not ultimately diagnosed with Ebola have significantly lower costs, since they do not incur any treatment cost. For the **three-monitoring-level** policy, the costs for the 18 different scenarios under the alternative policy and the costs for the 6 different scenarios under the CDC policy are reported in Table 2.

Insert Table 2

Sensitivity Analysis

First, a sensitivity analysis is performed on infected passenger scenarios (i.e., a passenger becomes ill with Ebola) under **the three-monitoring-level** alternative policy to compute the sensitivity ratios (SR) for each input parameter of interest. A relative change of 0.10 for each input parameter is applied, one parameter at a time. Sensitivity ratios (SR) are reported as a

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measurement of the parameter sensitivity. For non-infection scenarios (i.e., a passenger does not becomes ill with Ebola), the only input parameter varied is the **monitoring** cost. Therefore, Table 3 only lists the sensitivity ratios (SR) for the infection scenarios.

Insert Table 3

Optimization Model analysis

Optimal threshold levels for the alternative policy are defined as two threshold levels ($h_{threshold}$, $s_{threshold}$) that minimize the expected costs $E[O_{h_{threshold}, s_{threshold}}]$. These optimal threshold levels vary as a function of the number of social contacts for a passenger $\{\beta_{LS}, \beta_{MS}, \beta_{HS}\}$. In this **optimization model**, optimal threshold levels with respect to varying values for β_{LS} are reported for different **sets**, which are defined by a pair of ratios as in the first column of Table 4. In Table 4, the sets of pairs of values in the first column consist of two ratios. The first ratio is β_{MS}/β_{LS} , the number of social contacts associated with the medium SCT risk level (MS) divided by the number of social contacts associated with the low SCT risk level (LS). The second ratio is β_{HS}/β_{LS} , the number of social contacts associated with the high SCT risk level (HS) divided by the number of social contacts associated with the low SCT risk level (LS). When β_{LS} falls in the designated range listed in Table 4, the optimal threshold levels for the alternative policy are provided. **The threshold levels for the CDC policy in the two-monitoring-level case is (HH, LS) , which is treated as a special case of the alternative policy (see Table 4).**

Insert Table 4

Conclusions

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The costs for each combination of **monitoring** level, social contact tracing level, and disease status are shown in Table 2. For the **monitoring** level LQ and MQ , the costs increase with an increase in the SCT risk level. Moreover, for a given SCT risk level, the costs increase with an increase in the **monitoring** level. For the **three-monitoring-level** alternative policy, the medium **monitoring** level (MQ) has a lower positive slope in the cost function with respect to the SCT risk level, when compared to the low **monitoring** level (LQ). At the low SCT risk level, the costs of low and medium **monitoring** levels are similar. With an increasing SCT risk level, the costs of the medium **monitoring** level increase slightly while the costs of the low **monitoring** level increase to nearly as much as the high **monitoring** level.

Changes in the input model parameters, such as the **monitoring** costs, the social contact tracing costs and the treatment costs, impact the costs in all scenarios. From the sensitivity analysis results (see Table 3), the **monitoring** costs have the lowest SR among all the three input parameters considered $\{C_{monitor}, C_{social}, C_{treatment}\}$. This ratio increases with increases in the **monitoring** level and decreases with increases in the social contact tracing level. The SR of the social contact tracing cost decreases with increases in the **monitoring** level and increases with increases in the SCT risk level. The SR of the treatment costs is the largest among the SR of the three input parameters since treatment costs are large relative to the **monitoring** costs or social contact tracing costs across all the scenarios. The SR of the treatment costs decrease with increases in the **monitoring** level and increases with increases in the SCT level. Moreover, when the **monitoring** level is high (HQ), the SR for the three input parameters remain stable with increases in the SCT level since no social contact tracing costs are incurred.

The alternative policy uses more passenger information than the current CDC policy, and hence, leads to more scenarios (see Table 2). The alternative policy can be used to provide

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practical guidelines for the current CDC policy. In particular, the current CDC policy corresponds to a particular case of the alternative policy with threshold levels (HH, LS) (for a two-monitoring-level policy; see Table 4). Table 4 shows that the threshold levels (HH, LS) is the optimal threshold level for the alternative policy when the number of social contact traces β_{LS} falls within specific intervals for different $\{\beta_{MS}/\beta_{LS}, \beta_{HS}/\beta_{LS}\}$ values. When β_{LS} falls outside these intervals, as shown in Table 4, (MH, LS) is the optimal threshold level when β_{LS} is large (greater than 2100) and (MH, HS) is the optimal threshold level when β_{LS} is small (less than 100). These two pairs of optimal threshold levels can only be obtained through the alternative policy, since the alternative policy provides more detailed passenger information by using their SCT risk level.

The results in Table 4 also indicate the tradeoff across the cost patterns for the alternative policy. According to the formula for computing the expected cost, when the number of social contacts is low (i.e., $\{\beta_{LS}, \beta_{MS}, \beta_{HS}\}$ are small), the expected social contact tracing costs are low. Therefore, the monitoring costs become the dominant cost component in the expected cost. When the number of social contacts is high (i.e., $\{\beta_{LS}, \beta_{MS}, \beta_{HS}\}$ are large), the expected social contact tracing cost is high. Therefore, the social contact tracing costs become the dominant cost component in the expected cost. The optimal alternative policy balances the monitoring costs and social contact tracing costs. When β_{LS} falls into specific intervals in Table 4, requiring a high monitoring level for people with a medium health risk level (MH) and a high SCT risk level (HS) is the optimal alternative policy, which also dominates the CDC policy. However, when β_{LS} falls outside these intervals, then it would be optimal to requiring a high monitoring level for people with a high health risk level (HH) and a low SCT risk level (LS) , which is consistent with the

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CDC policy. These observations position the CDC policy as a special case of the alternative policy.

The results from enumerating all the scenarios and the **optimization model** analysis show that the alternative policy can have lower costs than the current CDC policy under certain circumstances. Therefore, although the alternative policy requires additional data collection, this extra effort can be balanced by a more cost-effective allocation of resources.

Limitations of Analysis

There are several limitations for the results reported in this paper. First, the specific values used for the costs and the thresholds are computed using a probability distribution and values that are either from the literature or can be classified as “best guesses” based on information in the literature ^{9,10,11}. Second, the computational results capture several scenarios, but do not cover the entire range of situations that may be faced at entry screening. Although the values reported provide insights into the policies, the input data is not sufficiently precise to provide an absolute measure of expected costs. Rather, in their current form, the models are most useful when used to compare different scenarios, to provide a relative measure of performance for the scenarios discussed. However, if more accurate input data become available, the absolute measures of performance may provide useful insights to shape entry screening policy and enhance public health.

The optimization model analysis is conducted for the two-monitoring-level alternative policy, while optimization for a three-monitoring-level policy is under investigation. A three-monitoring-level policy will result in a more complex optimization model, with two pairs of threshold values to be optimized at the same time. Although the two-monitoring-level alternative policy has this limitation, it can be viewed as a first step optimization for the three-monitoring-

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level alternative policy. A lack of available reliable data would also limit the implementation of the optimization of the three-monitoring-level policy. Therefore, the aim of this paper is to illustrate relative policy comparisons rather than provide the optimal thresholds for the alternative policy.

Summary

An alternative **monitoring and movement restriction** policy for Ebola entry screening at airports in the United States is introduced. The performances of both the CDC policy and the alternative policy are compared and analyzed using a **scenario-cost-based sensitivity analysis and an expected-cost-based optimization model analysis**. The alternative policy requires additional passenger input data beyond what is required to implement the CDC policy, by taking into account not only a passenger's exposure to Ebola, but also the potential to conduct social contact tracing if **they are not initially monitored or their movements are not initially restricted** yet later become ill with Ebola. The results presented provide information and guidance for public health decision-makers to enhance the current CDC policy, by using additional information that may impact and influence **monitoring and movement restriction** decisions. Indeed, using a secondary risk level such as the potential footprint for social contact tracing level may be a useful consideration when the current CDC policy is evaluated. Although the implementation of the secondary risk level requires additional data collection costs and time, the potential societal and public health benefits may justify such expenditures and efforts.

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References

A Double-risk Monitoring and Movement Restriction Policy for Ebola Entry Screening in U.S.

1. Centers of Disease Control and Prevention. 2014 Ebola Outbreak in West Africa. March 20, 2015. Available at: <http://www.cdc.gov/vhf/ebola/outbreaks/2014-west-africa/index.html>. Accessed March 22, 2015.
2. World Health Organization. WHO Interim Guidance for Ebola Virus Disease: Exit Screening at Airports, Ports and Land Crossings. November 16, 2014. Available at: http://apps.who.int/iris/bitstream/10665/139691/1/WHO_EVD_Guidance_PoE_14.2_eng.pdf. Accessed March 5, 2015.
3. Centers for Disease Control and Prevention. Airport Exit and Entry Screening for Ebola — August–November 10, 2014. *Morbidity and Mortality Weekly Report*. December 2014;63(49):1163-1167.
4. Centers of Disease Control and Prevention. Enhanced Ebola Screening to Start at Five U.S. Airports and New Tracking Program for all People Entering U.S. from Ebola-affected Countries. October 8, 2014. Available at: <http://www.cdc.gov/media/releases/2014/p1008-ebola-screening.html>. Accessed March 6, 2015.
5. Centers for Disease Control and Prevention. Fact Sheet: Screening and Monitoring Travelers to Prevent the Spread of Ebola. March 16, 2015. Available at: <http://www.cdc.gov/vhf/ebola/travelers/ebola-screening-factsheet.html>. Accessed March 26, 2015.
6. World Health Organization. Frequently asked questions on Ebola virus disease. August 2014. Available at: <http://www.who.int/csr/disease/ebola/faq-ebola/en/>. Accessed March 23, 2015.
7. Centers for Disease Control and Prevention. Transmission. February 12, 2015. Available at: <http://www.cdc.gov/vhf/ebola/transmission/index.html>. Accessed March 22, 2015.
8. Center for Disease Control and Prevention. Interim U.S. Guidance for Monitoring and Movement of Persons with Potential Ebola Virus Exposure. October 2015. Available at: <http://www.cdc.gov/vhf/ebola/exposure/monitoring-and-movement-of-persons-with-exposure.html>. Accessed February 7, 2016.
9. Stehling-Ariza, T., Fisher, E., Vagi, S., Fechter-Leggett, E., Prudent, N., Dott, M., Daley, R., Nonkin Avchen, R., . Monitoring of Persons with Risk for Exposure to Ebola Virus Disease — United States, November 3, 2014–March 8, 2015. *Morbidity and Mortality Weekly Report (MMWR)*. July 2015;64(25):685-689.

A Double-risk Monitoring and Movement Restriction Policy for Ebola Entry Screening in U.S.

10 Bloomberg. Bill for Ebola Adds up as Care Costs \$1,000 an Hour. October 2014. Available at: <http://www.bloomberg.com/news/articles/2014-10-07/bill-for-ebola-adds-up-as-care-costs-1-000-an-hour>. Accessed October 9, 2015.

11 The Wall Street Journal. The High Cost of Quarantine. October 2014. Available at: <http://www.wsj.com/articles/the-high-cost-of-quarantine-and-who-pays-for-it-1414546114.html>. Accessed October 9, 2015.

12 Witt O'Brien's. First Imported Case of Ebola Confirmed in the United States: Are Hospitals Prepared? October 2, 2014. Available at <http://www.wittobriens.com/go/doc/2000/2370506/First-Imported-Case-of-Ebola-Confirmed-in-the-United-States-Are-Hospitals-Prepared->. Accessed February 7, 2016.

Table 1: Probability distribution of passengers with two risk levels, $P_{h,s}$

	$LS(\beta_{LS}=20)$	$MS(\beta_{MS}=100)$	$HS(\beta_{HS}=200)$	Total
$NH (\alpha_{NH}=10^{-5})$	0.023	0.38	0.045	0.45
$LH (\alpha_{LH}=10^{-4})$	0.026	0.45	0.053	0.53
$MH (\alpha_{MH}=10^{-2})$	0.00065	0.011	0.0013	0.013
$HH (\alpha_{HH}=10^{-1})$	0.00035	0.0059	0.00070	0.0069
Note: Numbers may not sum up to the exact values due to rounding.				

Table 2: Costs per passenger (US\$1000) for scenarios under the three-monitoring-level alternative policy and the current CDC policy

Alternative Policy: Have Ebola		SCT level		
		LS	MS	HS
Monitoring level	LQ	524.2	604.2	704.2
	MQ	523.0	531.0	541.0
	HQ	710.0	710.0	710.0
Alternative Policy: Don't have Ebola		SCT level		
		LS	MS	HS
Monitoring level	LQ	4.2	4.2	4.2
	MQ	42.0	42.0	42.0
	HQ	210.0	210.0	210.0

CDC Policy: Have Ebola		
Monitoring level	LQ	620.2
	MQ	532.6
	HQ	710.0

CDC Policy: Do not have Ebola		
Monitoring level	LQ	4.2
	MQ	42.0
	HQ	210.0

Table 3: Sensitivity ratios (SR) for various infectious scenarios in the **three-monitoring-level** alternative policy

	$C_{monitor}$	C_{social}	$C_{treatment}$
(LQ,LS)	0.0080	0.038	0.95
(LQ,MS)	0.0070	0.17	0.83
(LQ,HS)	0.0060	0.28	0.71
(MQ,LS)	0.040	0.0038	0.96
(MQ,MS)	0.040	0.019	0.94
(MQ,HS)	0.039	0.037	0.92
(HQ,LS)	0.30	0	0.70
(HQ,MS)	0.30	0	0.70
(HQ,HS)	0.30	0	0.70

Table 4: Optimal threshold levels for the **two-monitoring-level** alternative policy for different **sets** $\{\beta_{MS} / \beta_{LS}, \beta_{HS} / \beta_{LS}\}$ with varying β_{LS}

Sets of $\{\beta_{MS} / \beta_{LS}, \beta_{HS} / \beta_{LS}\}$	β_{LS} Intervals	Optimal thresholds for health risk and SCT risk levels
{5,25},{5,50}, or {5,100}	[1, 411]	(<i>MH,HS</i>)
	[412, 3000]	(<i>HH,LS</i>)
{10,25},{10, 50}, or {10,100}	[1, 205]	(<i>MH,HS</i>)
	[206, 2057]	(<i>HH,LS</i>)
	[2058, 3000]	(<i>MH, LS</i>)
{20,25}, {20,50}, or {20,100}	[1, 102]	(<i>MH,HS</i>)
	[103, 1028]	(<i>HH,LS</i>)
	[1029, 3000]	(<i>MH, LS</i>)