Demand Forecasting for Ebola Responses

By: Robert C. Rains III
Advisor: Dr. Jarrod Goentzel

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Summary: An expeditionary clinical intervention to contain an outbreak has significant supply chain challenges due to the nature of the mission. In-patient services for isolated suspect and confirmed cases require uninterrupted support in material, facility, and staff requirements. Settings are frequently in austere environments that create capacity constraints and long lead times for fulfillment. To resolve these challenges a clear methodology for demand forecasting is critical. This research project looks at determining the service requirements of an Ebola response by modeling patient flow. This holistic approach seeks to contend with the internal and external dynamics that makes each response unique.

Prior to MIT, Robert worked for PAE's International Logistics and Stabilization Team. Working Ebola responses on the ground in 2014/15 Liberia and Sierra Leone, 2017/18 in Uganda, and 2018/19 in DRC created interest in better understanding the causes and providing solutions to outbreak response challenges.

KEY INSIGHTS

1. **Ebola-negative, instead of Ebola-positive, patients are the prime drivers of operational capacity space, material consumption, and staff requirements.**
2. **Increasing the speed between sample collection and test results drastically improves the absorbative capacity of the isolation and treatment network.**
3. **Managing Ebola-negative patients by improving diagnostic velocity becomes increasingly more important when dealing with larger catchment areas.**

Introduction

The accelerating global trends of urbanization, interconnectivity, and population mobility are creating increasingly favorable conditions for outbreaks of high threat pathogens. This will drive an associated increase in frequency, severity, and velocity of future outbreaks. Expeditionary clinical interventions to contain outbreaks will play a critical role in localizing instead of globalizing this danger. However, there are still significant unanswered challenges to improving outbreak response operations.

Outbreak responses are resource intense, logistically complicated, multi-disciplinary endeavors that require rapid deployment of highly specialized staff, structures, and systems. The complexity of expeditionary interventional outbreak response presents numerous supply chain management challenges that need resolution to provide successful outcomes. The dynamics of each response are unique and will continue to change in future responses. This hampers the efficacy of using historical data and regression analysis of previous responses to provide answers for future outbreaks.

Successful outcomes require preventing service failures by ensuring there are enough beds to hold patients and materials on-hand for clinical care. However, operational complexity and environmental challenges create significant obstacles in consistently predicting the patient census that determines these service requirements. Chief among these challenges is accurately forecasting the operational capacity and in-patient service requirements unique to each setting and outbreak.

The results of this project show that the Ebola outbreak is not the primary driver of operational capacity and service requirements. Instead, Ebola-negative cases isolated from the endemic disease population overwhelmingly represent the patient majority. The result of this census majority expands the outbreak response service requirements.

Model Overview

This paper presents a model for forecasting the facility space, materials needed, and staff required to prevent a service failure during an outbreak response. This model uses anticipated patient flow during to determine the patient census and their cumulative patient days. Service requirements are calculated as a dependent variable of these patient flow metrics. This paper also explores varying catchment area size and diagnostic velocity to measure the impact the system will incur as a result.

The model follows patient flow from point of origin in the Ebola disease infected (Ebola-positive) and endemic disease infected populations (Ebola-negative) entering the Ebola isolation and treatment (EIT) network through discharge. This model demonstrates that Ebola-negative rather than Ebola-positive patients are the primary driver of capacity and service requirements in the EIT network once a tipping point in the endemic disease population is reached. Furthermore, capacity and service requirements of isolating Ebola-negative patients can be substantially reduced by improving time between sample collection and testing for Ebola (diagnostic velocity).

In this paper the EIT capacity and service requirements are forecasted using a model that consists of an Ebola and endemic disease afflicted population, epidemiological investigation and surveillance (EIS) efforts that results in capture rate, and the patient-length-of-stay (PLOS) in the EIT network. The external variable is the population size the response has to target, i.e. the catchment area, in order to contain and localize the outbreak. The internal variable is the diagnostic velocity between sample collection and patient results.

This model is then used to vary the external, catchment area, and the internal, diagnostic velocity, to provide comparisons of the expected patient census and the corresponding capacity and service requirements necessary to accommodate in-patient provision of care. Comparing the scenarios where diagnostic velocity and catchment size are varied demonstrates that there is a tipping point where the primary driver of EIT capacity and service requirements switches from Ebola-positive to Ebola-negative patients. The significance of this finding is that the Ebola-negative population drawn from the endemic disease population is likely to be a more dominant factor in response planning than the Ebola-positive patients produced from the actual Ebola outbreak.

The variability of the internal variable, diagnostic velocity, demonstrates that Ebola-positive patient EIT absorption is best mitigated by improving diagnostic velocity. These scenario comparisons

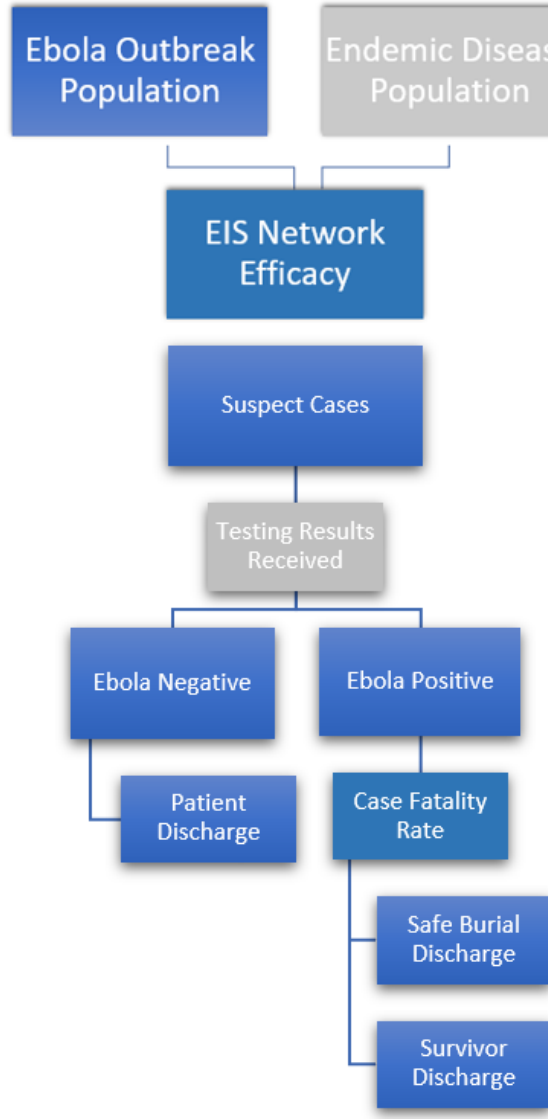

Figure 1: Patient flow from population source via EIS efficacy through isolation network to discharge

show that as the catchment area increases, diagnostic velocity becomes an increasingly critical factor in sizing the isolation and treatment network infrastructure and service requirements. This is due to the Ebola-negative population functioning as the prime driver of service requirements for the EIT network and their PLOS being reduced in-line with increased speed in diagnostic turnaround time.

Metric and Scenario Selection

As provided in the model overview we have two populations, EIS efficacy rate, diagnostic velocity, case fatality rate, and PLOS by type that we need to assign values to produce our results. A nominal outbreak using averages from previous responses was used to determine the time period of the response scenario and Ebola population during that time. This nominal outbreak was locked for all subsequent scenarios in order to contrast the impact of varying diagnostic velocity and catchment area.

The catchment areas selected for comparison ranged between 100K and 1.2M to provide scenarios that would reflect a small rural setting up to a major urban center. The endemic disease prevalence rate that would establish the Ebola-negative population is based on endemic disease prevalence as a function of the catchment area. Information on malaria prevalence in DRC provided by recent World Bank Data weighted by rates of malaria symptom presentations were used to calculate the frequency that malaria would meet case definition for Ebola. The two populations, Ebola and Endemic diseases, create the pool that EIS will pull from to provide suspect cases to the EIT network.

To determine the efficacy of the EIS campaign a logarithmic function for determining growth coverage in a bounded population was used with a y-intercept of 10% which reached full coverage at 120 days. This efficacy rate creates an increasing flow of suspect cases based on an increasing percentage pulled from the endemic and Ebola disease population through the response. This efficacy rate was locked for all scenarios.

The suspect cases pulled from the two populations are then split into Ebola-positive and Ebola-negative categories following testing. This split is equal to the flowrate coming from the endemic and Ebola populations entering isolation. Ebola-positive patients are further split into two types based on a case fatality rate which determines the percentages of survivor and fatal cases. Reporting from the 2018/19 DRC outbreak was used to put the case fatality rate at 0.58 for all scenarios.

Ebola-negative patients are discharged immediately upon receiving diagnostic confirmation which sets their PLOS equal to diagnostic velocity. PLOS for the Ebola-positive population was based on historical values from the Sierra Leone response during the 2014/15 West Africa outbreak. These values list survivors as staying in isolation on average 15.33 days while fatal cases stay for 4.58. The Ebola-positive PLOS was locked for all scenarios while the diagnostic velocity was varied between 0.5 to 4 days. This range is in line with previously observed time periods for receiving diagnostic confirmation during responses.

The combination of patient type and flow rate multiplied by their associated PLOS provides us with each scenario's cumulative patient days. The cumulative patient days is the independent variable which service requirements and operational capacity can then be calculated. The service requirements are the equivalent of 3.92 per patient day for staff contact and associated personal protective material consumed. Operational capacity (e.g. bed-count) is equal to peak census achieved during the response.

Results

Using the selected metrics in the model across 16 scenarios provided output that is summarized in Table 1. As provided in the table the Ebola-positive census and corresponding days stays constant throughout the scenarios. Despite this consistency the required bed-count and incurred patients days show large variance. The bed-count from peak census ranges from as few as 27 to as high as 463. While the cumulative patient days ranges from 1228 to 6342. All of this variance is the result of Ebola-negative patient flow and diagnostic velocity changes.

POP: 100,000	Lab Velocity			
	3-Day	2-Day	1-Day	.5 Day
Total Positive Census	127	127	127	127
Total Negative Census	146	146	146	146
Total Survivor Days	818	818	818	818
Total Fatal Days	337	337	337	337
Total Negative Days	438	292	146	73
Cumulative Days	1593	1447	1301	1228
Peak Census	53	43	32	27
POP: 300,000	Lab Velocity			
	3-Day	2-Day	1-Day	.5 Day
Total Positive Census	127	127	127	127
Total Negative Census	432	432	432	432
Total Survivor Days	818	818	818	818
Total Fatal Days	337	337	337	337
Total Negative Days	1296	864	432	216
Cumulative Days	2451	2019	1587	1371
Peak Census	120	85	53	37
POP: 600,000	Lab Velocity			
	3-Day	2-Day	1-Day	.5 Day
Total Positive Census	127	127	127	127
Total Negative Census	865	865	865	865
Total Survivor Days	818	818	818	818
Total Fatal Days	337	337	337	337
Total Negative Days	2595	1730	865	432.5
Cumulative Days	3750	2885	2020	1588
Peak Census	232	156	84	52
POP: 1,200,000	Lab Velocity			
	3-Day	2-Day	1-Day	.5 Day
Total Positive Census	127	127	127	127
Total Negative Census	1729	1729	1729	1729
Total Survivor Days	818	818	818	818
Total Fatal Days	337	337	337	337
Total Negative Days	5187	3458	1729	864.5
Cumulative Days	6342	4613	2884	2020
Peak Census	463	308	155	85

Table 1: Summary results of scenario outputs generated by model

Patient Days for Determining Service Requirements (P/(N+P)/P Ratio Rows Show Ebola-Positive Population Percentage of Patient Days and Requirements Sum)								
	Total Service Requirements (Includes Fixed) by Diagnostic Requirements							
	3-Day	Req	2-Day	Req	1-Day	Req	.5 Day	Req
Ebola-Positives (P)	1155	4528	1155	4528	1155	4528	1155	4528
100K Negative (N)	1593	7337	1447	6764	1301	6192	1228	5906
P/(N+P) Ratio	42%	38%	44%	40%	47%	42%	48%	43%
300K Negative (N)	2451	11844	2019	10150	1587	8457	1371	7610
N/P Ratio	32%	28%	36%	31%	42%	35%	46%	37%
600K Negative (N)	3750	18668	2885	15277	2020	11886	1588	10193
N/P Ratio	24%	20%	29%	23%	36%	28%	42%	31%
1.2M Negative (N)	6342	32285	4613	25507	2884	18729	2020	15342
N/P Ratio	15%	12%	20%	15%	29%	19%	36%	23%

Table 2: Service requirements calculated based on cumulative patient days and ratio of Ebola-positive percentage

Utilizing the cumulative patient days, we are able to apply the service requirements formulas derived from our service protocol:

Ebola-Negative = (Lab Result Time x 3.92) + 4
Ebola-Positive Survivor = (15.33 x 3.92) + 4
Ebola-Positive Fatality = (4.58 x 3.92) + 4

The results of this are provided in Table 2 across each of the scenarios. These results show that Ebola-positives consume between 12% to 43% of the service requirements during our response scenarios. It also shows that in outbreaks with large catchment areas we can reduce the service requirements by over 50% by speeding up diagnostic velocity.

Conclusions

The analysis demonstrates that the larger the catchment area the more the challenge of coping with Ebola-negative patients in the suspect population of the EIT network will become. Diagnostic velocity is in a critical enabler in determining the absorbative capacity of the network. Increasing the speed for diagnostic results will greatly reduce the operational capacity and service requirements to support the outbreak response in the case management pillar.

The Ebola disease is not the only viral outbreak that would require an expeditionary clinical interventional response to prevent the emergence of a pandemic. The issue of having to contend with endemic diseases that present similarly to the disease targeted by an outbreak response will likely follow a similar trajectory as Ebola. Outbreak responses of all types will need to make planning around endemic disease afflicted population a major hallmark of outbreak response planning. This is especially pertinent since the role Ebola-negative patients plays an outsized role in determining the capacity and service requirements necessary for the response.

The trend over the last decade in outbreak response in sub-Saharan Africa demonstrates that increasing outbreak responses will have to respond to urban or larger population catchment areas. While there has been discussion and research on demonstrating the increase in rate of infectivity that occurs in urban areas that has become ingrained in response planning the role of the endemic disease population has not. Even with significantly higher R0 from crowded and cramped conditions of urban outbreaks, from the perspective of operational capacity and service requirements, bigger outbreaks will not produce as much of a demand for bed-space and patient care as the population at large.