Modeling Infectious Diseases: Projecting Spread, Evaluating Interventions, and Resource Allocation

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MISSION

Make a positive “impact” through improved health & humanitarian systems worldwide

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**Prevention**
- Insecticide nets
- Indoor residual spraying
- Vaccines

**Surveillance**
- Monitoring of confirmed malaria cases

**Treatment**
- Rapid diagnostic tests and artemisinin-based combination therapy

*Source: Nigeria Health Online, 2016*
*Source: Medicins Sans Frontieres, 2015*
*Source: Making Malaria History, 2014*
**Prevention**

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Source: *Medicins Sans Frontieres, 2015*

Source: *Making Malaria History, 2014*

Source: *Nigeria Health Online, 2016*

Source: *Carter Center*
Disease Models → Decision-Making

- Understanding and projecting the disease spread
- Evaluating the impact of intervention strategies
- Estimating resource needs
- Resource planning and allocation

Geographically and over time, by sub-populations

Figure shows projected disease spread of flu after 90 days (Keskinocak/Swann team)
Infectious Disease Modeling

Disease progression in an individual – Natural history

Disease spread

https://www.cdc.gov/media/subtopic/Images.htm
https://www.cdc.gov/fungal/antifungal-resistance.html
https://en.wikipedia.org/wiki/Plasmodium_falciparum
Natural history – Example: Covid19

S: Susceptible
E: Exposed
I_p: Presymptomatic
I_A: Asymptomatic
I_S: Symptomatic
R: Recovered
I_H: Hospitalized
D: Dead

S-E-I-R
S-I-R
Disease spread – Example: Covid19

- Households
- Peer groups (e.g., workplace and schools)
- Community
- Household statistics, classroom sizes, age statistics
- Mobility & interaction patterns, e.g., workflow data
Disease spread - Transmission

- **Human-to-human**
  - Respiratory diseases (e.g., flu, Covid-19), STDs

- **Vectors/Animals**
  - Malaria, Guinea Worm

![Diagram showing the process of disease transmission](image)
Disease spread – Example: Malaria

**Mosquito**
- Natural death rate
- Percent of the population that bites per day
- Duration in the incubation stage
- Probability of a mosquito contracting malaria from a human in the incubation and infection stage
- Probability of contracting malaria from an asymptomatic person
- ...

**Human**
- Probability of contracting malaria from an incubating or infectious mosquito
- Duration in the incubation stage for each age group
- Probability of transitioning from slow recovery to immunity / fast recovery
- Lag from incubation to symptomatic, infectious
- Recovery rates
- ...

- Environmental or other risk factors
Disease spread - Transmission

- Human-to-human
  - Respiratory diseases (e.g., flu, Covid-19), STDs
- Vectors/Animals
  - Malaria, Guinea Worm

Figure 1.20 Complex Life Cycle of *Dracunculus medinensis* (Guinea worm)

*Image Description*
Guinea Worm Disease

~3.5 Million in 1986

25 in 2015
Guinea Worm Disease in Chad

Zero Human Cases in Chad For 9 years
Guinea Worm Transmission Model

- Agent-based model
- Environmental factors: temperature & rainfall → Worm burden in water → Rate of infection

https://www.ajtmh.org/view/journals/tpmd/103/5/article-p1942.xml

Agent-Based Simulation for Seasonal Guinea Worm Disease in Chad Dogs
Tyler Perini 1, Pinar Keskinocak 1, Zihao Lu 1, Ernesto Ruiz-Tiben 2, Julie Swann 1, 3, and Adam Weiss 2
<table>
<thead>
<tr>
<th>Scenario</th>
<th>ABATE</th>
<th>Tether</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>40%</td>
<td>76%</td>
<td>17%</td>
</tr>
<tr>
<td>Increased</td>
<td>70%</td>
<td>95%</td>
<td>17%</td>
</tr>
<tr>
<td>Decreased</td>
<td>20%</td>
<td>50%</td>
<td>17%</td>
</tr>
</tbody>
</table>
Disease spread - Transmission

- Human-to-human
  - Respiratory diseases (e.g., flu, Covid-19), STDs
- Vector
  - Malaria, Guinea worm
- Vehicles
  - Cholera, typhoid fever, salmonella
Cholera Transmission

- Oral-Fecal Pathway
  - Five F’s: Feces, Fingers, Flies, Fields, Fluids, Food

Cholera Worldwide

- 7 major pandemics in recorded history
- Many notable outbreaks since 1991. Examples:
  - 2008: Zimbabwe
  - 2010: Nigeria, Haiti, Dominican Republic
  - 2014: Ghana
- Cholera endemic in many places
- Overall, 1.4-4.3 million cases of cholera per year, leading to 28,000-142,000 deaths (WHO, 2014)

http://www.who.int/bulletin/volumes/90/3/11-093427/en/
doi: 10.2471/BLT.11.093427
Cholera Impact - Incidence (new cases) of disease and mortality differ by age


http://www.who.int/bulletin/volumes/90/3/11-093427/en/
doi: 10.2471/BLT.11.093427
Environmental or other risk factors

Piarroux et al (2009), The journal of field actions. (Democratic Republic of Congo)
Resource allocation – Example: Oral cholera vaccine

At supply level of 20M doses
~ 400,000 more cases

Targeting groups by age and region is the best strategy.

Simply targeting primarily the high-risk region, or children (who have the highest risk) is less effective.

Our Contribution

- Optimize OCV distribution policies to determine the best OCV allocation strategy to minimize cases or deaths:
  - Differentiate groups by age AND region, with varying risk levels
  - Consider fixed and varying vaccine efficacies based on age and years since vaccination
- Quantify cost-effectiveness of strategies


Examples of Interventions

- Pharmaceutical
  - Vaccines, antivirals

- Non-pharmaceutical
  - School closures, Travel restrictions, Physical distancing (e.g., voluntary quarantine), Age-based restrictions, ...

- Combined strategies: Testing, tracing, isolation

- Behaviors/Compliance (geographically, over time, subpopulations)

- How, where, when to allocate limited resources?
Infectious Disease Modeling

Disease progression in an individual – Natural history

Environment Interventions Behaviors

Disease spread

- Metrics/outcomes of interest (by age group, geographically, subpopulation, etc.)
  - New infections per time period, e.g., daily
  - Timing and magnitude of the “peak”
  - Total number of infections or % of population infected (IAR)
  - Number or % hospitalized or dead
  - Resource needs (e.g., hospital beds, ventilators)
COVID19 MODELING AND EVALUATING INTERVENTION STRATEGIES

Collaborators include: John Asplund, Ph.D.; Emma Baubly; Arden Baxter; Saurabh Doodhwala; Akane Fujimoto; Daniel Kim; Dima Nazzal, Ph.D.; Buse Eylul Oruc; Pelin Pekgun, Ph.D., Lauren Steimle, Ph.D.; Tyler Perini; Josh Rosenblum; Erik Rosenstrom; Nicoleta Serban, Ph.D.; Melody Shellman; Chris Stone; Julie Swann, Ph.D.; Inci Yildirim, MD, Ph.D.; April Yu; Georgia Tech Institute for People and Technology; GA Department of Public Health

Funding: “Integrated Systems Model to Inform State and Local Planning for the COVID-19 Pandemic,” Council of State and Territorial Epidemiologists (CSTE); RADx Underserved Populations (RADx-UP) program
Research insights

- Modeling the disease spread → Projections
- Evaluating the impact of interventions
  - School closures, Shelter-in-place, voluntary-quarantine
- Estimating resource needs
- Impact of interventions on society: “homebound days” versus reduction in disease spread
- Impact of testing/isolation depending on compliance
- Vaccine allocation – Benefits of serology testing
- Tradeoff between vaccine efficacy versus reach
- ...

...
## Scenarios for Physical Distancing

<table>
<thead>
<tr>
<th>Baselines</th>
<th>Feb 18</th>
<th>Feb 25</th>
<th>Mar 3</th>
<th>Mar 10</th>
<th>Mar 16</th>
<th>Apr 3</th>
<th>May 1</th>
<th>May 8</th>
<th>May 15</th>
<th>Sep 30</th>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>School Closure</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mar 16: School Closures</td>
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### Interventions

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>30% VQ</th>
<th>40% VQ</th>
<th>50% VQ</th>
<th>60% VQ</th>
<th>Mar 16: School Closures</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIP: 4 weeks</td>
<td>LOW QV</td>
<td>VSIP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Voluntary Quarantine (VQ):**
All household members stay home if there is a person with cold/flu like symptoms in the household, until the entire household is symptom-free.

<table>
<thead>
<tr>
<th>Scenario 2</th>
<th>40% VQ</th>
<th>50% VQ</th>
<th>60% VQ</th>
<th>Mar 16: School Closures</th>
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</thead>
<tbody>
<tr>
<td>SIP: 4 weeks</td>
<td>MEDIUM QV</td>
<td>VSIP</td>
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<table>
<thead>
<tr>
<th>Scenario 3</th>
<th>50% VQ</th>
<th>60% VQ</th>
<th>Mar 16: School Closures</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIP: 4 weeks</td>
<td>HIGH QV</td>
<td>VSIP</td>
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<table>
<thead>
<tr>
<th>Scenario 4</th>
<th>60% VQ</th>
<th>Mar 16: School Closures</th>
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</thead>
<tbody>
<tr>
<td>SIP: 5 weeks</td>
<td>LOW QV</td>
<td>VSIP</td>
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<thead>
<tr>
<th>Scenario 5</th>
<th>50% VQ</th>
<th>60% VQ</th>
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</thead>
<tbody>
<tr>
<td>SIP: 5 weeks</td>
<td>MEDIUM QV</td>
<td>VSIP</td>
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<th>Scenario 6</th>
<th>50% VQ</th>
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<th>Mar 16: School Closures</th>
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</thead>
<tbody>
<tr>
<td>SIP: 5 weeks</td>
<td>HIGH QV</td>
<td>VSIP</td>
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<thead>
<tr>
<th>Scenario 7</th>
<th>60% VQ</th>
<th>Mar 16: School Closures</th>
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<tbody>
<tr>
<td>SIP: 6 weeks</td>
<td>LOW QV</td>
<td>VSIP</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Scenario 8</th>
<th>50% VQ</th>
<th>60% VQ</th>
<th>Mar 16: School Closures</th>
</tr>
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<tbody>
<tr>
<td>SIP: 6 weeks</td>
<td>MEDIUM QV</td>
<td>VSIP</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Scenario 9</th>
<th>50% VQ</th>
<th>60% VQ</th>
<th>Mar 16: School Closures</th>
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<tbody>
<tr>
<td>SIP: 6 weeks</td>
<td>HIGH QV</td>
<td>VSIP</td>
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### VQ Levels

- **LOW QV:** 70% VQ with 20% weekly decrease and stabilize at 20%
- **MEDIUM QV:** 80% VQ with 5% weekly decrease and stabilize at 25%
- **HIGH QV:** 85% VQ with 3% weekly decrease and stabilize at 30%

**Shelter In Place (SIP):**
Start on April 3

**VSIP:** 60% VSIP and decrease to 40%, 20%, 5% weekly then continue at 5%
Daily new infections Projections In Georgia

https://journals.plos.org/plosone/article/authors?id=10.1371/journal.pone.0239798
Healthcare resource estimation

“You may build all the ICUs you want. You may have all the ventilators you need. But you will not have the staff you need,” del Rio said. “There simply are not enough ICU nurses or ICU doctors to take care of the patients.”
Research questions

- Modeling the disease spread
- Evaluating the impact of interventions
  - School closures & reopening, Shelter-in-place, voluntary-quarantine
- Impact of interventions on society: “homebound days” versus reduction in disease spread
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Health, society, economy, etc. – complex tradeoffs

Research insights

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- Evaluating the impact of interventions
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- Impact of interventions on society: “homebound days” versus reduction in disease spread
- Vaccine allocation – Benefits of serology testing?

S: Susceptible
Ia: Infected asymptomatic
Is: Infected symptomatic
ISOt_a: Infected diagnosed and in isolation, asymptomatic
ISOt_s: Infected diagnosed and in isolation, symptomatic
ISOnt_s: Infected not tested and in isolation, symptomatic
RC: Recovered confirmed
RU: Recovered unknown
Im: Immunized not previously infected
ImR: Immunized previously infected
D: Dead

Vaccine, Volume 39, Issue 35, 16 August 2021, Pages 5055-5063
Figure 2: Infection attack rate for the scenarios evaluated when the vaccine is available for 50% of the population and the vaccine efficacy is 90%.

- Highest IAR: High R0 and vaccination available after the peak.
- Impact of serology test highest when the vaccines are deployed close to the peak time
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- Tradeoff between vaccine efficacy versus reach
Tradeoffs between vaccine efficacy and reach

**Limited Resources**

**Allocation – How?**

**Vaccine-L**
- Low Efficacy
- Available later

**Vaccine-H**
- High Efficacy
- Available sooner
- Resource-intensive

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*Reach* of a vaccine

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**Figure 1**: IAR w.r.t. the percentage of resources allocated to vaccine-H

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Resource allocation for different types of vaccines against COVID-19: Tradeoffs and synergies between efficacy and reach.

Daniel Kim 1, Fehmi Pekgün 2, Inci Yıldırım 1, Pınar Keskinocak 1
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- Evaluating the impact of interventions
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- Impact of interventions on society: “homebound days” versus reduction in disease spread
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- Vaccine allocation – Benefits of serology testing?
- Tradeoff between vaccine efficacy versus reach
- Dashboards
Number of people vaccinated in subpopulation

\[ \frac{\text{Vaccinated in subpopulation}}{\text{Total number of people in subpopulation}} \times 100 \]

**Vaccination Rate per Hundred (%)**

- **Rate Differences**
  - Towns, Union, Greene, Glynn, Clay, Rabun, DeKalb, Clayton, Sumter, Dougherty, Pickens, Randolph, Lumpkin, Habersham, Rockdale, Cobb, Fulton, Chatham, Bibb, Murray, Gwinnett, Miller, Decatur, Clarke, Dade, Hart, Seminole, Floyd, Putnam, Stewart, Gilmer, Early, Crisp, Tift, Pulaski, Hall, Bleckley, Calhoun, Hancock, Whitfield...
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