Circular Migrations and HIV Transmission: An Example of Space-Time Modeling in Epidemiology

Aditya Khanna

International Clinical Research Center
Department of Global Health
University of Washington

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Collaborators

Dr. Dobromir Dimitrov  Fred Hutchinson Cancer Research Center

Dr. Steven Goodreau  Anthropology  University of Washington
Outline

- Background and Objectives
- Conceptualizing the Models
- Compartmental Models and Results
- Network Models and Results
Circular Migrations
Objectives and Background
Two Primary Aims

Motivation

How are the transmission dynamics of HIV impacted by the interaction between acute HIV infection and rates of circular migration?
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Motivation
How are the transmission dynamics of HIV impacted by the interaction between acute HIV infection and rates of circular migration?

Question
How do compartmental and network-based modeling methods compare in their analysis of the system?

The focus is on improving our theoretical understanding of a circular-migration system and how to best model it.
Circular Migrations: Definition and Concept

Definition

Periodic movement of individuals between two or more locations (Quinn 1994)
Epidemiological Setting

Migrations as a Factor in HIV Transmission

Possible Reasons (Lurie 2000, 2006)

Migrants may:
1. Change partners more frequently
2. Form partnerships with high-risk individuals
3. Spatial-Temporal Structure: Migrants may have a higher number of relationships that overlap in time (but these partnerships occur in different places)
Relational Overlap: Concurrency

Concurrency: Temporal Overlap in partnerships [Morris and Kretzschmar (1995-6-7)]

Sequential Monogamy

A&B

B&C

Time
Relational Overlap: Concurrency

Concurrency: Temporal Overlap in partnerships [Morris and Kretzschmar (1995-6-7)]

Sequential Monogamy

A&B

B&C

Time

Concurrency

A&B

B&C

Time
Circular Migrations & Concurrency

While the concurrency structure may appear similar to sequential monogamy, it is not!

Active Partnership: When migrant is in same location as partner
Concurrency Mechanism I: Path-Doubling
Concurrency Mechanism I: Path-Doubling

A&B

B&C

Time
Concurrency Mechanism II: Path-Acceleration

A&B

B&C

Time
Concurrency Mechanism II: Path-Acceleration

A&B

B&C

Time
Epidemiological Consequences of Concurrency in Circular Migrations

Path-Doubling is present, path-acceleration is contingent upon frequency of migration
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Acute HIV Infection
Epidemiological Consequences of Concurrency in Circular Migrations

Path-Doubling is present, path-acceleration is contingent upon frequency of migration

Acute HIV Infection

Interaction of concurrency and acute infection magnifies potential for disease transmission
Circular Migrations

Conceptualizing the Models
The System

Assumptions

1. 50% Male, 50% Female
2. 50% Location-A, 50% Location-B
3. Heterosexual Contact
4. No Migrating Females
Description of Actors in the Population

24 state variables, defined by

1. Susceptible or Acute or Chronic or Late
2. Migrant or Non-Migrant
3. Male or Female
4. Locations A and B
Transfer Diagram: Infection Transmission, Stages of Infection, and Human Migrations
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Non-Migrant Men

Women

Migrant Men

A

SUSCEPTIBLE → ACUTE → CHRONIC → AIDS

SUSCEPTIBLE → ACUTE → CHRONIC → AIDS

SUSCEPTIBLE → ACUTE → CHRONIC → AIDS
Transfer Diagram: Infection Transmission, Stages of Infection, and Human Migrations
Constraints on System

Migrant Men

Location A

Location B

Non-Migrant Men

Location A

Time

Partnership Active in A

Partnership Active in B

Time

Migrant-Men have twice as many partners as non-migrant men.
Migrant men and non-migrant men have equal number of sex-acts.
Number of sex-acts for women is set to balance number of sex-acts for men.
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Circular Migrations
Compartmental Models
Compartmental Modeling

Model Formulation
- Aggregate individuals in “compartments” and model average behavior
- We use ordinary differential equations to formulate these models
- An S-I model with infection-stages and vital processes of birth and death

Features of Compartmental Models
- Classical method to build epidemiological models
- Computationally inexpensive and help formulate dynamics of the system
- Limited in their scope to model temporal overlap in partnerships
Two Interpretations of Compartmental Models

Explore two definitions of “contact”: As a coital act, and as a long-term partnership

<table>
<thead>
<tr>
<th>Definition</th>
<th>Transmission Probability</th>
<th>Partner-Change Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact as partnership</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Contact as act</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
Simulation Details

- 24 state variables and a corresponding set of 24 differential equations
- System is evolved in weekly time-units

Evaluating Impact of Migration Frequency

- Plot prevalence trajectories at migration intervals of 3 weeks and 30 weeks
- Consistent with descriptions of data in South Africa
- This set-up considers intervals longer and shorter than the window of acute infection
Results from Compartmental Models

Contact as Act

\[ R_0 = 1.58 \]

Contact as Partnership

\[ R_0 = 1.19 \]
High partner change rate in contact-as-act produces a larger epidemic fast

Difference in $R_0$ mathematically demonstrates that contact-as-act is more efficient with regards to disease transmission

Framework suggests no impact of migration frequency on epidemic
Circular Migrations
Network Models
Network Modeling

- Explicit modeling of individuals and their relationships
- Allows for more realistic representation of temporal overlap in partnerships
- Computationally expensive, but software tools now available via the statnet project
Steps in Network Modeling

- Build a network model as similar as possible to the compartmental models
- Extend the model in suitable ways to capture features of the system not representable using compartments
- Model transmission of infection in both models
- Simulate these networks over time and infection transmission processes on the network to examine scenarios of interest
We Experiment with two types of Network Models

Type I: Basic Models

1. Set up to be identical to compartmental models in representation of partnerships, migrations, and infection transmission
We Experiment with two types of Network Models

Type I: Basic Models
1. Set up to be identical to compartmental models in representation of partnerships, migrations, and infection transmission

Type II: Restricted Models
1. Multiple partners of migrant men are required to be distributed across both locations
2. Explore clockwork migrations
Mathematical Representation of Network Models

- Consider a set of \( n \) social actors and a relationship between each pair of actors.
- Define a graph \( Y \) with \( 1, \ldots, n \) actors. Then

\[
Y_{ij} = \begin{cases} 
1 & \text{if relationship exists from actor } i \text{ to actor } j \\
0 & \text{else}
\end{cases}
\]

- Note: The tie is the variable of interest.
- Also called socio-matrix, adjacency matrix, or network (undirected, here).
Graph Visualization
Exponential Random Graph Models (ERGMs)

\[ P_{\theta,Y}(Y = y) = \frac{\exp\{\theta^T g(y)\}}{\kappa(\theta, Y)} \]

where

\[ \kappa(\theta, Y) = \sum_{z \in Y} \exp \{\theta^T g(z)\} \]

\( g(y) \): vector of statistics, \( \theta \) vector of parameters

\( Y \): Random Variable representing a graph, \( y \): Particular realization of \( Y \)
Separable-Temporal ERGMs (Krivitsky, 2008)

\[ Y^t \]: Network at time \( t \); \( Y^{t+1} \): Network at time \( t + 1 \)

\[ Y^+ \]: Formation Network; \( Y^- \): Dissolution Network
At any given time, are two people in a partnership?
Are they in the same location (i.e. is the partnership active)?
Is the partnership sero-discordant?
If yes, probability of disease transmission is $> 0$.
Precise value of probability depends upon how long the infected partner has been infected.
Disease Transmission in Network-Models

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2. Are they in the same location (i.e. is the partnership active)?
3. Is the partnership sero-discordant?
4. If yes, probability of disease transmission is $> 0$.
5. Precise value of probability depends upon how long the infected partner has been infected.

Evaluating Impact of Migration Frequency

As in the compartmental framework, we plot prevalence trajectories at migration intervals of 3 weeks and 30 weeks.
Results from Network Models

Basic Models
As similar to compartmental models as possible

Restricted Models
Multiple partners of migrant men in both locations
Results from Network Models: Clockwork Migrations

Basic Models
As similar to compartmental models as possible

Restricted Models
Multiple partners of migrant men in both locations
Network Models: Reasons for Differences

Basic Models
As similar to compartmental models as possible

Restricted Models
Multiple partners of migrant men required to be in both locations

Delayed path-acceleration

- Difference in size of epidemic in basic and restricted models
- Difference in prevalence-trajectory in migration-intervals shorter and longer than acute phase
What did we learn?

- Migrations at intervals shorter than acute infection may produce a larger epidemic than migrations at longer intervals.
- The implication is that the behavior of migrants traveling shorter distances that return home more frequently may have a greater effect on prevalence than the behavior of long distance migrants.
- However, given our theoretical focus, we cannot yet draw such a conclusion.
What did we learn?

- Migrations at intervals shorter than acute infection may produce a larger epidemic than migrations at longer intervals.
- The implication is that the behavior of migrants traveling shorter distances that return home more frequently may have a greater effect on prevalence than the behavior of long distance migrants.
- However, given our theoretical focus, we cannot yet draw such a conclusion.
- But, to even consider the potential effect of migration frequency on HIV transmission, we need network models.
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