Modeling HIV/AIDS: Preferential ART Distribution in Resource-Constrained Countries

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Senior Mathematics Thesis
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4 May 2009
Personal Motivation

Nadia Abuelezam

Preferential ART Distribution
Background on HIV

HIV

Human Immunodeficiency Virus

HIV is transmitted through exchange of sexual fluids, blood exchange, or from mother to child.
Background on HIV

HIV
Human Immunodeficiency Virus

AIDS
Acquired Immune Deficiency Syndrome

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HIV
Human Immunodeficiency Virus

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Acquired Immune Deficiency Syndrome

HIV is transmitted through exchange of sexual fluids, blood exchange, or from mother to child.
33.2 million total cases worldwide in 2007 (UNAIDS and WHO)
Anti-retroviral Therapy (ART)

- Effective life long treatment
- Daily medication for remainder of life
- Yearly cost of 300-1200 dollars
RECOMMENDATIONS

Equity—or fairness—in access to HIV treatment and care, as well as other health and social services, has long been a preoccupation of WHO and UNAIDS. In January 2004, WHO and UNAIDS convened a joint consultation on ethics and equitable access to treatment and care for HIV/AIDS, which provided valuable insights and advice for this guidance document. Because equity can sometimes appear to be an abstract concept, WHO and UNAIDS have identified a number of concrete measures that can be taken in countries and communities to promote fairness in scaling up HIV care, in particular antiretroviral treatment (ART) and related services.

WHO and UNAIDS recommend that national policy makers, programme managers, representatives of civil society, and other partners at national and local levels undertake the following measures to promote equity in the distribution of HIV care in resource-limited settings:

1. Mobilize without delay a wide range of partners to scale up HIV treatment and care. Scale-up is not only an urgent public health and development priority but also an ethical and human rights imperative within the framework of a comprehensive response to AIDS.

2. Establish a broadly representative ethics advisory body (including people living with HIV) linked to the national AIDS programme or council to plan, promote, and monitor equity in the scale-up and distribution of HIV treatment and care services. The membership of this advisory body, and in particular its leader, must be highly respected for qualities of fairness, openness, and both personal and professional integrity.

3. Create opportunities for public dialogue on equitable access to HIV treatment and care. These may include media events and communications, public hearings, and both national and community meetings appropriate to the circumstances. Such events should aim to allow a wide range of stakeholders to provide their views and expertise as well as to be involved in making plans and setting priorities for equitable scale-up of HIV treatment.

4. Develop policies for scaling up HIV treatment that are firmly based in human rights and ethical principles. A main role of the ethics advisory body is to ensure that policy makers and programme implementers balance efficiency and utility goals with due attention to equity. In the absence of clear policies, the risk is great that access to care for people living with HIV will be based on arbitrary criteria, and will disadvantage particular individuals, especially members of vulnerable populations, in particular antiretroviral treatment (ART) and related services.

5. Identify vulnerable, marginalized, or other potentially underserved populations. Depending upon the local context, these groups may include women, children, the poor, rural populations, sex workers, injecting drug users, men who have sex with men, refugees, and migrants.

6. Consider the need for special policies and outreach programmes to prioritize these groups and to overcome barriers to their accessing care. The rationale for such prioritization should be clearly stated and the measures for facilitating access for these groups should be indicated.

7. The ethics body should help to ensure that a fair process is established for setting priorities in the distribution of HIV treatment. This process should include the following central elements:
   - a public mechanism for setting priorities that is transparent, broadly inclusive of stakeholders, and whose principles, procedures, and priorities are widely publicized to stakeholders and the public at large;
   - relevant reasons, principles, evidence, and information that are widely viewed by stakeholders as appropriate and pertinent to fair decision-making about policies and priorities;
   - an appeals mechanism that permits the reconsideration and revision of decisions and priorities concerning the equitable scale-up of HIV treatment services;
   - an enforcement mechanism which uses consistent criteria to monitor scale-up and which enforces adherence to equity-related principles. This enforcement mechanism must ensure that the fair process is public and inclusive, has an appeals process, and has other elements or conditions that the ethics body may deem necessary.

8. Define or adopt a set of five to seven measurable indicators to monitor the fairness of HIV treatment scale-up at the national and community level. Current monitoring and evaluation systems should be adapted to collect relevant information. Such indicators should allow monitoring not only of the policies adopted but also the processes by which policies are designed and programmes are implemented. Monitoring of the general health care system will reveal the extent to which the scaling-up of HIV programmes has an impact on the health infrastructure, the migration of personnel, health care financing, and the delivery of health care generally. At least one or two indicators should ensure that access by vulnerable, marginalized, or other potentially underserved populations, including women, is monitored.

9. Responsible officials, including the ethics advisory body, should use monitoring and evaluation data to ensure that HIV programmes are producing equitable results. These data should also be publicly available so that all stakeholders can contribute to decisions regarding necessary adjustments in HIV policies and programmes.
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Thesis Goals

**Question:** Are the WHO’s recommendations for fair treatment allocation also leading to effective disease control?
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- **Tool**: A mathematical model with which we can examine preferential ART treatment among population subgroups (specifically: women and rural areas).
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**Tool:** A mathematical model with which we can examine preferential ART treatment among population subgroups (specifically: women and rural areas).

**Goal:** Examine the effects of preferential treatment on the future spread of HIV in Uganda.
Accomplishments

- Developed two models (preliminary and advanced)
- Performed sensitivity analyses on both models
- Found and tested “basic reproductive number” for both models
- Completed a dynamical systems analysis for preliminary model
- Performed simulations to determine the effects of treatment

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Preferential ART Distribution
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Preliminary Compartment Model Structure

\[ S = \text{Susceptible} \]
\[ I = \text{Infected} \]
Full Compartment Model Structure

S = Susceptible
I = Infected
T = Treated
A = AIDS

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Model Equations

\[ \frac{dS_{W1}}{dt} = bN_{W1} - dS_{W1} - \frac{\beta_{MW} S_{W1} (c_1 l_{M1} + c_2 l_{M2})}{N_{M1} + N_{M2}} \]

\[ \frac{dl_{W1}}{dt} = \frac{\beta_{MW} S_{W1} (c_1 l_{M1} + c_2 l_{M2})}{N_{M1} + N_{M2}} - (d + q) l_{W1} - \tau_{W1} l_{W1} - \alpha l_{W1} \]

\[ \frac{dA_{W1}}{dt} = \alpha l_{W1} - \tau_{W1} A_{W1} - (l + d) A_{W1} \]

\[ \frac{dT_{W1}}{dt} = \tau_{W1} l_{W1} + \tau_{W1} A_{W1} - dT_{W1} \]
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\frac{dI_{W1}}{dt} = \frac{\beta_{MW} S_{W1} (c_1 I_{M1} + c_2 I_{M2})}{N_{M1} + N_{M2}} - (d + q)I_{W1} - \tau_{W1} I_{W1} - \alpha I_{W1}
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\frac{dS_{W_1}}{dt} = bN_{W_1} - dS_{W_1} - \frac{\beta_{MW} S_{W_1} (c_1 I_{M_1} + c_2 I_{M_2})}{N_{M_1} + N_{M_2}}
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Endemic Equilibrium

A steady state where a proportion of individuals is diseased.
Definitions: Equilibria

Endemic Equilibrium
A steady state where a proportion of individuals is diseased.

Disease-free Equilibrium
A steady state with no diseased individuals present.
Basic Reproductive Number, $R_0$

The number of susceptible people a single infected person could infect during a specified time period.
Definitions: $R_0$

**Basic Reproductive Number, $R_0$**

The number of susceptible people a single infected person could infect during a specified time period.

$R_0 > 1$ suggests an epidemic, $R_0 < 1$ suggests disease will die out.
For a basic SIR model: \( R_0 = \frac{\text{birth}}{\text{death}} \).

Method developed by van den Driessche and Watmough 2002:

\[
R_0 = \sigma (FV^{-1}),
\]

where \( F \) and \( V \) are 4x4 matrices that depend on the model equations and \( \sigma \) is the spectral radius.
Population Dynamics for $R_0 = 0.61131$

- $R_0 < 1$
  - Disease Free Equilibrium

Population Dynamics for $R_0 = 1.8339$

- $R_0 > 1$
  - Endemic Equilibrium

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Preferential ART Distribution
$R_0$ and Sensitivity Analysis

$R_0$ with Varying Transmission Probabilities

$R_0 < 1$
Disease Free Equilibrium

$R_0 > 1$
Endemic Equilibrium

Preferential ART Distribution
Preferential Treatment of Urban Populations

Women

Dynamics of Women in Population #1

Proportion of Women in Pop #1

Time (years)

Urban

Dynamics of Women in Population #2

Proportion of Women in Pop #2

Time (years)

Rural

Men

Dynamics of Men in Population #1

Proportion of Men in Pop #1

Time (years)

Dynamics of Men in Population #2

Proportion of Men in Pop #2

Time (years)

Susceptible
Infected
AIDS
Treated

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Preferential ART Distribution
Preferential Treatment of Rural Populations

Women

Urban

Dynamics of Women in Population #1

Proportion of Women in Pop #1

Time (years)

Rural

Dynamics of Women in Population #2

Proportion of Women in Pop #2

Time (years)

Men

Dynamics of Men in Population #1

Proportion of Men in Pop #1

Time (years)

Dynamics of Men in Population #2

Proportion of Men in Pop #2

Time (years)

Susceptible
Infected
AIDS
Treated

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Preferential ART Distribution
Preferential Treatment of Women

Women

Urban

Dynamics of Women in Population #1

Proportion of Women in Pop #1

Time (years)

Men

Men

Dynamics of Men in Population #1

Proportion of Men in Pop #1

Time (years)

Rural

Dynamics of Women in Population #2

Proportion of Women in Pop #2

Time (years)

Dynamics of Men in Population #2

Proportion of Men in Pop #2

Time (years)

- Susceptible
- Infected
- AIDS
- Treated

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Preferential ART Distribution
Preferential Treatment Urban Women

Women

Dynamics of Women in Population #1

Urban

Rural

Men

Dynamics of Men in Population #1

Dynamics of Women in Population #2

Dynamics of Men in Population #2

Susceptible
Infected
AIDS
Treated

Proportion of Women in Pop #1

Proportion of Men in Pop #1

Proportion of Women in Pop #2

Proportion of Men in Pop #2

Time (years)

Time (years)

Proportion of Women in Pop #1

Proportion of Men in Pop #1

Proportion of Women in Pop #2

Proportion of Men in Pop #2

Time (years)

Proportion of Women in Pop #1

Proportion of Men in Pop #1

Proportion of Women in Pop #2

Proportion of Men in Pop #2

Time (years)
Preferential Treatment Rural Women

**Dynamics of Women in Population #1**

- **Proportion of Women in Pop #1**

**Dynamics of Women in Population #2**

- **Proportion of Women in Pop #2**

**Urban**

**Dynamics of Men in Population #1**

- **Proportion of Men in Pop #1**

**Dynamics of Men in Population #2**

- **Proportion of Men in Pop #2**

Legend:
- × Susceptible
- Infected
- AIDS
- ▲ Treated

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Preferential ART Distribution
Conclusions

WHO recommendations may be fair but they may not be effective at combatting HIV long term.
Conclusions

WHO recommendations may be fair but they may not be effective at combatting HIV long term.

Shortcomings:
- Tested ONE set of parameters
- Used data from published sources
Future Work

- Incorporate same sex interactions and mother to child transmission
- Incorporate different viral levels or age levels
- Track resistant strains of HIV in the model
- Incorporate marital status compartments
Acknowledgements

- Prof. Lisette de Pillis
- Prof. Karl Haushalter
- Prof. Darryl Yong
- Suzanne Frantz and Claire Connelly
- Dean of Faculty Robert Cave
- Seanna Vine, Natalie Durgin, and Oksana Sergeeva
- The Italians
- Mathematics and Biology Departments
- Astronaut Scholarship Foundation
Preferential Treatment of Men

Dynamics of Women in Population #1

Women

Proportion of Women in Pop #1

Time (years)

0 20 40 60 80 100

0

0.2

0.4

0.6

0.8

1

Dynamics of Women in Population #2

Urban

Rural

Proportion of Women in Pop #2

Time (years)

0 20 40 60 80 100

0

0.2

0.4

0.6

0.8

1

Dynamics of Men in Population #1

Men

Proportion of Men in Pop #1

Time (years)

0 20 40 60 80 100

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Dynamics of Men in Population #2

Proportion of Men in Pop #2

Time (years)

0 20 40 60 80 100

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Susceptible

Infected

AIDS

Treated

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Preferential ART Distribution
Preferential Treatment of Men: High $\beta_{MW}$

Women

Dynamics of Women in Population #1

Proportion of Women in Pop #1

Time (years)

Dynamics of Women in Population #2

Proportion of Women in Pop #2

Time (years)

Urban

Men

Dynamics of Men in Population #1

Proportion of Men in Pop #1

Time (years)

Dynamics of Men in Population #2

Proportion of Men in Pop #2

Time (years)

Susceptible
Infected
AIDS
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