An Equilibrium Model of the HIV/AIDS Epidemic: An Application to ART and Circumcision in Malawi

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HIV is killing 2 million people annually worldwide.
  - 2.7 million new infections each year.

Most affected continent: Africa.

About 60% of all HIV+ in Africa are female, compared to about 30% in North America and Western Europe.

Reasons: most transmissions through heterosexual sex + higher transmission risk for women.

Policy debate: circumcision, ART, condom use, treating STDs, finding a vaccine.

What can economists add?
What We Do

- Build model of sexual behavior.
- Allow for behavioral responses and general equilibrium effects.
- Parameterize model to capture stylized features of sex, marriage, and HIV in Malawi.
- Focus on gender asymmetry in transmission.
- Use model to explore policies.
Main findings

- Model captures well cross-country data on circumcision and HIV.
- Benefits of circumcision likely much larger than extrapolating from field experiments would suggest.
- ART likely not behind the recent HIV decline in Malawi.
- Condom policy may backfire.
- Treating other STDs (reduction in transmission) would work well, even though it would not be measurable in field experiment.
Related Literature

- Few theoretical studies of HIV: Kremer (QJE 1996), Magruder (Demography 2011).
- Large literature using epidemiological simulations: ignore changes in risky behavior.
Environment

- Rational model of sexual behavior.
- Men and women.
- Risky behavior choices (modeled as search in 3 different markets):
  - sex vs. abstinence
  - casual vs. long-term relationships
  - condom use
- Heterogeneity:
  - People differ in degree of patience.
  - Stochastic aging: young vs. mature (also differ in patience).
  - Circumcised or not (permanent type).
  - On ART or not (only some experiments).
  - Healthy or HIV infected – with and w/o symptoms.
- HIV determined in equilibrium.
- HIV status realized at end of period (private information)
- Exogenous death and divorce, exogenous births.
Choose first, where to search (protected, unprotected, LT).

Searching for a partner is costly.

More search effort → improves odds of finding a partner, $\pi$.

In LT market:

$$V_l = \max_\pi \left[ \pi \tilde{V}_l + (1 - \pi) V_s - C_l(\pi) \right],$$

where search cost is

$$C(\pi) = \frac{\omega}{1 + \kappa} \left( \frac{\pi}{\frac{1}{2} - \pi} \right)^{1 + \kappa}$$

Similar in the short term market.
Benefits from Search: Sex

- **Utility from sex:** $u > p$.
- **Sex in LT relationships:**
  - Always unprotected: $u$.
  - Additional utility benefit/cost: $\ell$.
  - Sex every period until partner gets symptoms, exogenous break-up (prob. $\xi$) or own death.
Baseline non-transmission probability (for a male having unprotected sex with a female): $\gamma_u$
- Higher when male is circumcised.
- Higher when using a condom.
- Higher when partner is on ART treatment.
- Lower for women (except, no circumcised women).

Everyone gets (anonymously) tested and knows own infection status after one period: $\phi = 1, 0, t$.

Each period, infected people get treated with probability $q$ (ART is an absorbing state).

Lag from infection to symptoms
- Probability of showing symptoms conditional on infection $\alpha$ (lower for treated people).

People with symptoms do not have sex (too sick).

Lag from symptoms to death: $\delta_2$ (for tractability, couples die together).
Life-time Value of Unprotected Sex (w/o ART)

Value function (for infected men):

$$\tilde{V}_u^\beta(0, x) = \ln(y - t_u) + u + \beta \left\{ \alpha A + [1 - \alpha] V_i^\beta(0, x) \right\}$$

Value function (for healthy men):

$$\tilde{V}_u^\beta(1, x) = \ln(y - t_u) + u + \beta \left\{ \left[ \hat{\phi} + (1 - \hat{\phi}) \gamma_u \chi(c) \right] V_i^\beta(1, x) \\
+ \left( 1 - \left[ \hat{\phi} + (1 - \hat{\phi}) \gamma_u \chi(c) \right] \right) V_i^\beta(0, x) \right\}$$

$x$: permanent type, including whether circumcised or not
$y$: period income
$A$: life-time value of a person with symptoms

Similar for women and when the person has protected sex.
All singles enter period with health status $\phi$ in $\{0,1,t\}$.

- Indicates search intensity choice at this node.
- Indicates sexual activity.

If no break-up,

- Match in long term market
- No match

Exogenous ($\varepsilon$) or endogenous (= partner symptoms) break-up

If infected,

- Symptoms ($\alpha$), Value: $A$
- Exogenous death ($\delta$)
- Stochastic Aging ($\eta$)
- Update status ($\phi'$), treatment ($q$)

Protected
Unprotected

Stochastic Aging ($\eta$)

Choose $\pi_u, \pi_p$
Stationary Equilibrium

- Three markets: protected, unprotected, long term sex.
- Prices \((t_u, t_p, t_l)\) adjust to clear all three markets:
  - \# of men having sex in given market = \# of women having sex.
- Aggregate fractions of people (health/sick/treated/circumcised) entering each market consistent with individual optimization.
Numerical Analysis

- Model too complicated for analytical results.
- Instead, we use parameterized version of model
- Numerical benchmark that captures stylized features in Malawi
  - Some parameters are chosen based on direct data analogs.
  - Remaining parameters chosen to match some key moments
- Perform counterfactual analyses to study prevention policies:
  - male circumcision
  - anti-retroviral drugs
  - treating other STDs (or inventing a vaccine)
  - improving condoms
- Special focus on
  - importance of behavioral changes.
  - importance of general equilibrium effects.
Data sources:
- Most data is from DHS 2004 (including micro data).
- HIV specific parameters: from medical literature.
Parameterization - a priori

- quarterly model
- $\xi = 0.03$ (divorce prob.)
  - twice reported divorce risk (no polygyny nor affairs)
- $y = 320$ (quarterly income per working age person)
- $\delta = 0.006$ (non HIV-related death hazard)
- probability of HIV transmission (per act):
  - 0.0048 (for men unprotected sex)
  - double for women
  - reduced by 70% when using condoms
  - further reduced by 60% when circumcised (for men)
  - further reduced by 2/3 when partner on ART
  - scaled up to quarterly risk in model
- $\alpha = 0.025$ (10 yrs from infection to symptoms)
- $\delta_2 = 0.125$ (2 yrs from symptoms to death)
- 20% of males are circumcised
- No one is treated in benchmark
Parameterization - Calibration

Remaining parameters are chosen to match a set of targets:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>joy of protected sex</td>
</tr>
<tr>
<td>$u$</td>
<td>joy of unprotected sex</td>
</tr>
<tr>
<td>$\ell$</td>
<td>extra benefit/cost of LT relationship</td>
</tr>
<tr>
<td>$A$</td>
<td>continuation value of life with symptoms</td>
</tr>
<tr>
<td>$[\beta_{min}, \beta_{max}]$</td>
<td>mature discount factor, assumed uniform</td>
</tr>
<tr>
<td>$\bar{i}$</td>
<td>further discount for young people</td>
</tr>
<tr>
<td>$\eta$</td>
<td>prob. of becoming mature</td>
</tr>
<tr>
<td>$\omega_{ST}$</td>
<td>search cost in ST market (level)</td>
</tr>
<tr>
<td>$\omega_{LT}$</td>
<td>search cost in LT market (level)</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>search cost (curvature)</td>
</tr>
</tbody>
</table>
### Model Fit (11 Moments)

<table>
<thead>
<tr>
<th>Observation</th>
<th>Data</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIV/AIDS rate, %</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>- Males</td>
<td>10</td>
<td>8.6</td>
</tr>
<tr>
<td>- Females</td>
<td>13</td>
<td>12.1</td>
</tr>
<tr>
<td>Fraction of all sex that is casual, %</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Condom use for casual sex, %</td>
<td>39</td>
<td>33</td>
</tr>
<tr>
<td>% (of) Singles that had casual sex in past year</td>
<td>37</td>
<td>53</td>
</tr>
<tr>
<td>% Singles</td>
<td>33</td>
<td>48</td>
</tr>
<tr>
<td>% Married by age 22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Males</td>
<td>58</td>
<td>57</td>
</tr>
<tr>
<td>- Females</td>
<td>90</td>
<td>63</td>
</tr>
<tr>
<td>% Married by age 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Males</td>
<td>100</td>
<td>98</td>
</tr>
<tr>
<td>- Females</td>
<td>100</td>
<td>98</td>
</tr>
<tr>
<td>% of deaths related to HIV</td>
<td>29</td>
<td>25</td>
</tr>
</tbody>
</table>
Non-targeted Moments

We also look at additional model implications.

- HIV rates by age.
- Timing of marriage.
- Singles by age.
- Cross-country data on circumcision.

Model works surprisingly well.
HIV Rates, by Age - Men vs. Women

![Graph showing HIV rates by age for men and women with model and data, smoothed curves.]
Fraction Currently Single, by Age

- Model
- Data

Age categories: 0, 0.2, 0.4, 0.6, 0.8, 1, 15, 20, 25, 30, 35, 40, 45, 50
Male Circumcision and HIV

- Circumcision rates vary across countries.
- Circumcised men are less susceptible to HIV.
- Cross-country data shows negative correlation HIV vs. circumcision.

\[ y = -0.1509x + 0.1517 \]
\[ y = -0.0508x + 0.113 \]
### Regressions

**Dependent variable:** HIV rate  
**Number of countries:** 32

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Coefficient</th>
<th>Coefficient</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumcision</td>
<td>-0.1122***</td>
<td>-0.07655**</td>
<td>-0.0796**</td>
<td>-0.064</td>
</tr>
<tr>
<td>Log GDP p.c.</td>
<td>0.0314***</td>
<td>0.0293***</td>
<td>0.0288***</td>
<td>0.0296***</td>
</tr>
<tr>
<td>ART</td>
<td>0.0816</td>
<td>0.104**</td>
<td>0.105*</td>
<td>0.098</td>
</tr>
<tr>
<td>syphilis</td>
<td>0.0025</td>
<td>0.0029</td>
<td>0.003</td>
<td>0.0045</td>
</tr>
<tr>
<td>muslim</td>
<td></td>
<td>-0.002</td>
<td>-0.00056</td>
<td>-0.0012</td>
</tr>
<tr>
<td>christian</td>
<td></td>
<td></td>
<td>-0.00039</td>
<td>-0.00065</td>
</tr>
<tr>
<td>condom price</td>
<td></td>
<td></td>
<td></td>
<td>-0.268*</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.72</td>
<td>0.73</td>
<td>0.74</td>
<td>0.79</td>
</tr>
<tr>
<td>N</td>
<td>32</td>
<td>31</td>
<td>31</td>
<td>23</td>
</tr>
</tbody>
</table>
We used evidence from field experiments as model input to determine what circumcision does to an individual man.

Note that using evidence on circumcised individuals to extrapolate what 100% circumcision would do, would lead to incorrect conclusions.

In our model, circumcising a small group of additional men: prevalence rate of 8%, so they are healthier than average (9%). But circumcising everyone would lead to an overall HIV rate of only 4%. i.e. half that.

Reason: compounding and fewer singles.

<table>
<thead>
<tr>
<th></th>
<th>benchmark</th>
<th>100% circumcision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>not circ.</td>
<td>circumcised</td>
</tr>
<tr>
<td>%infected</td>
<td>9%</td>
<td>8%</td>
</tr>
<tr>
<td>casual sex</td>
<td>14%</td>
<td>22%</td>
</tr>
<tr>
<td>condom use</td>
<td>35%</td>
<td>27%</td>
</tr>
<tr>
<td>singles</td>
<td>49%</td>
<td>53%</td>
</tr>
</tbody>
</table>
Other Policy Experiments

- ART treatment
- Better condoms?
- Treating other STDs (or partial vaccine)
Anti-retroviral Therapy (ART)

- Introduced in Malawi in 2005.
- ART affects people in several ways:
  - feel better
  - live longer
  - less infectious to other people

**ART in Malawi**

![Graph showing the increasing percentage of infected on ART in Malawi from 1998 to 2016.](image-url)
Was ART successful in reducing HIV?

- Clearly HIV declined over time.
- From a govt report in Malawi: “Malawi’s rapid and successful Antiretroviral Therapy scale-up from 2004 to 2014 has critically influenced the trajectory of the HIV epidemic …”

![HIV prevalence graph](image-url)
Was ART successful in reducing HIV?

- Note that ART cannot be the whole story, as HIV started declining prior to the introduction of ART.
- Anticipation effects would go into the wrong direction.
- Still, ART may have contributed to declining HIV prevalence.
In model, infected people get treated with probability $q$ (absorbing state).

- Treated people are less infectious to others (by factor $2/3$).
- They are also less likely to develop symptoms (by factor $1/2$), and accordingly live longer (10 years on average).

Increase $q$ over time, in line with the data.
- Model gives, at various levels of treatment, long-term HIV rate.
- Upper bound on fraction of the HIV decline likely due to ART.
ART in the Model

- HIV-Data
- HIV-Model
- ART/sick

Graph showing trends over time.
But higher levels of ART promising

Reasons for the hump-shape:
- People engage in riskier behavior along all dimensions (more sex, less condoms, less marriage).
- Sex is also safer.
- Second effect dominates only if enough infected are treated.
More pleasurable condoms

Example: quadrupling condom pleasure (from 1.4 to 5.5)
- condom use almost doubles (32 to 59%)
- more people remain single (48 to 62%)
- more singles have sex (53 to 66%)
- HIV rate goes up by 60% (10 to 16%)
Reducing Transmission Risk (e.g. treatment of other STDs)

- singles engage in riskier behavior
- not captured in epid. experiment, thus “true” effect smaller.
- transmission risk lower not just for self, but also partners.
- typically not true in small field experiments. Thus benefits from large experiment much larger than extrapolating from field experiment.
- may explain why 8 of 9 studies of STD treatment delivered flat results (Padian et al, 2010).
Equilibrium model of sexual behavior.
Captures stylized features of sex, marriage, and HIV in Malawi.
Replicates cross-country relationship: HIV & circumcision.
Policy experiments:
  - Benefits of circumcision likely much larger than extrapolation from field experiments would suggest.
  - ART likely not behind the recent HIV decline in Malawi.
  - Condom policy may backfire.
  - Treating other STDs (reduction in transmission) would work well, even though it would not be measurable in field experiment.