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

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Motivation

- HIV is killing 2 million people annually world wide.
  - 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.
- Randomized field experiments: Duflo et al (AER 2015), Thornton et al (AER 2008), Dupas (AEJ applied 2011): useful input for us.
- Some cross-sectional studies: Oster (QJE 2005), Lakdawalla et al (QJE 2006), Auld et al (BE Press 2006).
- Malawi: de Paula et al (JAE 2014), Delavande et al (Restud 2016).

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.

Economic Choices: Search Effort

- Choose first, where to search (protected, unprotected, LT).
- Searching for a partner is costly.
- More search effort $\rightarrow$ improves odds of finding a partner, π.
- In LT market:

$$V_l = \max_{\pi} \left[\underbrace{\pi \widetilde{V}_l}_{\text{matched}} + \underbrace{(1-\pi) V_s}_{\text{unmatched}} - C_l(\pi) \right],$$

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: ℓ.
    - Sex every period until partner gets symptoms, exogenous break-up (prob. ξ) or own death.

Cost of Sex: HIV

- Baseline non-transmission probability (for a male having unprotected sex with a female): γ_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 α (lower for treated people).
- People with symptoms do not have sex (too sick).
- Lag from symptoms to death: δ_2 (for tractability, couples die together).

Life-time Value of Unprotected Sex (w/o ART)

Value function (for infected men):

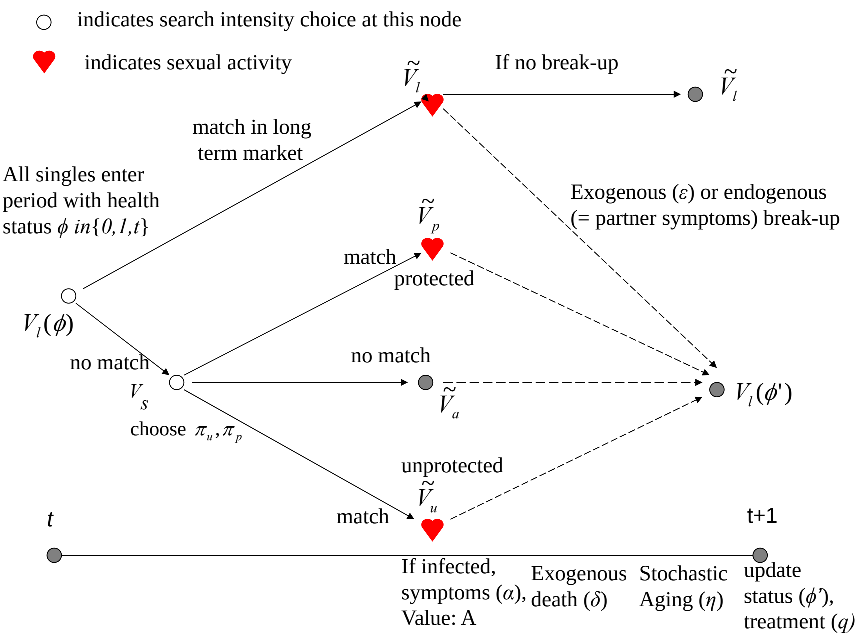
$$\widetilde{V}_u^{\beta}(0,x) = \ln(y - t_u) + u + \beta \left\{ \alpha A + [1-\alpha] V_I^{\beta}(0,x) \right\}$$

Value function (for healthy men):

$$\begin{aligned} \widetilde{V}_u^{\beta}(1,x) &= \ln(y - t_u) + u + \beta \Big\{ \left[\hat{\phi} + (1-\hat{\phi})\gamma_u \chi(c) \right] V_I^{\beta}(1,x) \\ &\quad + \left(1 - \left[\hat{\phi} + (1-\hat{\phi})\gamma_u \chi(c) \right] \right) V_I^{\beta}(0,x) \Big\} \end{aligned}$$

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.



indicates search intensity choice at this node
indicates sexual activity
$\tilde{V}_l$
If no break-up
$\tilde{V}_l$
match in long term market
All singles enter period with health status ϕ $in\{0,1,t\}$
Exogenous (ε) or endogenous (= partner symptoms) break-up
$\tilde{V}_p$
match
protected
$V_l(\phi)$
no match
no match
V_s
$\tilde{V}_a$
$V_l(\phi')$
choose π_u, π_p
unprotected
$\tilde{V}_u$
t
match
t+1
If infected, symptoms (α), Value: A
Exogenous death (δ)
Stochastic Aging (η)
update status (ϕ'), treatment (q)

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.

Malawi Data

- Data sources:
  - Most data is from DHS 2004 (including micro data).
  - Supplemented with data from MDICP (2001, 2004).
  - 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:

Parameter	Meaning
p	joy of protected sex
u	joy of unprotected sex
ℓ	extra benefit/cost of LT relationship
A	continuation value of life with symptoms
$[\beta_{min}, \beta_{max}]$	mature discount factor, assumed uniform
$\frac{\iota}{\beta}$	further discount for young people
η	prob. of becoming mature
ω_{ST}	search cost in ST market (level)
ω_{LT}	search cost in LT market (level)
κ	search cost (curvature)

Model Fit (11 Moments)

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

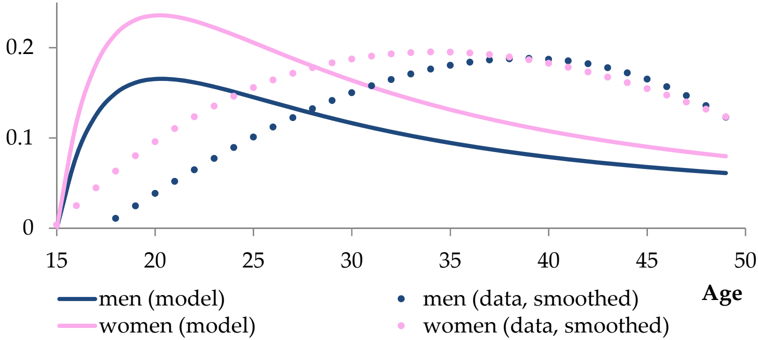
Non-targeted Moments

We also look at additional model implications.

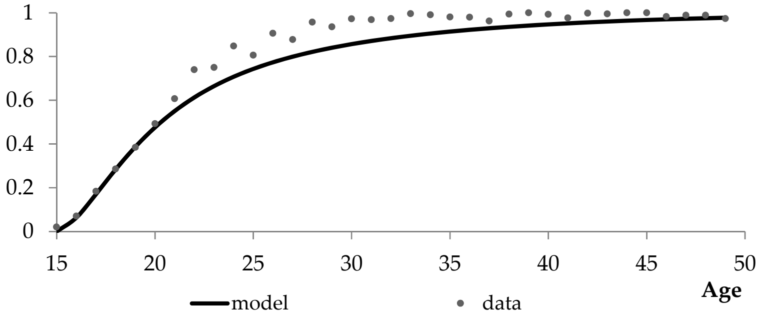
- HIV rates by age.
- Timing of marriage.
- Singles by age.
- Cross-country data on circumcision.

Model works surprisingly well.

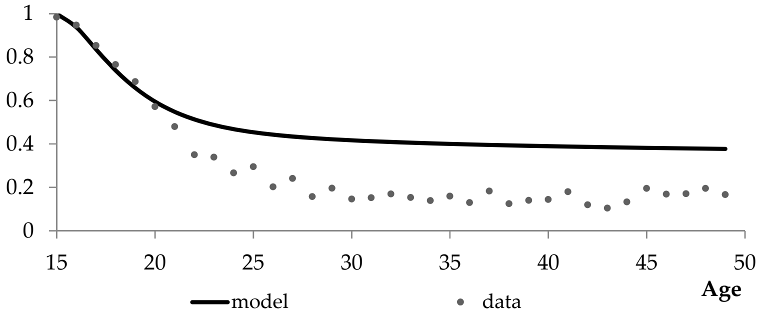
HIV Rates, by Age - Men vs. Women



Fraction Ever Married, by Age

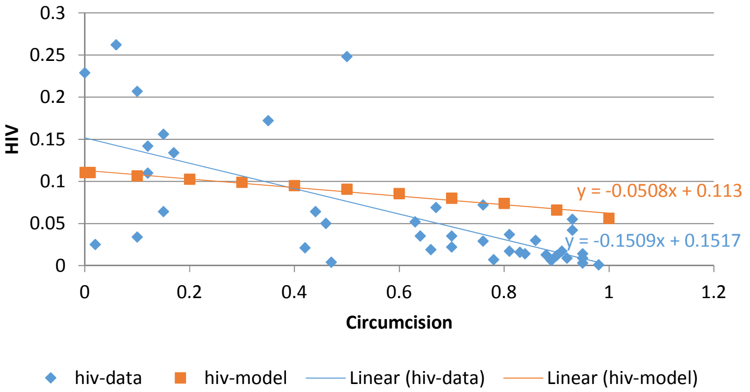


Fraction Currently Single, by Age



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



Regressions

Dependent variable: HIV rate
Number of countries: 32

circumcision	**-0.1122*** **	**-0.07655** **	**-0.0796** **	**-0.064**
Log GDP p.c.	0.0314***	0.0293***	0.0288***	0.0296***
ART	0.0816	0.104**	0.105*	0.098
syphilis	0.0025	0.0029	0.003	0.0045
muslim		-0.002	-0.00056	-0.0012
christian			-0.00039	-0.00065
condom price				-0.268*
R^2	0.72	0.73	0.74	0.79
N	32	31	31	23

Male Circumcision in Small Field Experiments

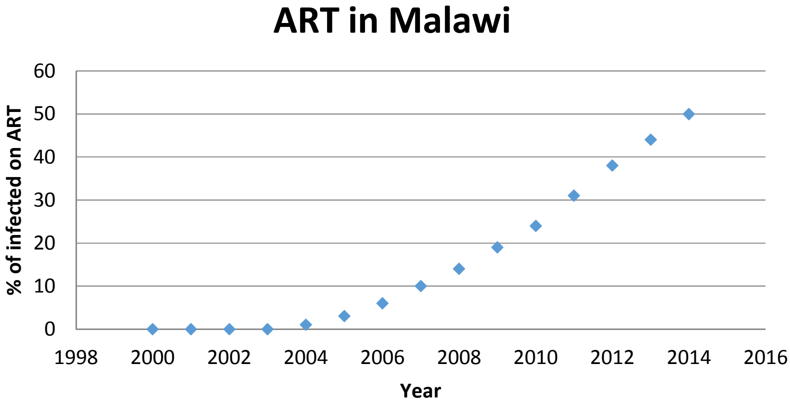
- We used evidence from field experiments as model input
  $\rightarrow$ determine what circumcision does to an individual man.
- Note that using evidence on circumcised individuals to extrapolate what 100% circumcision would do, would lead to incorrect conclusions.
- In our model, circumcising a small 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.

	benchmark		100% circumcision
	not circ.	circumcised	everyone
%infected	9%	8%	4%
casual sex	14%	22%	29%
condom use	35%	27%	22%
singles	49%	53%	59%

Other Policy Experiments

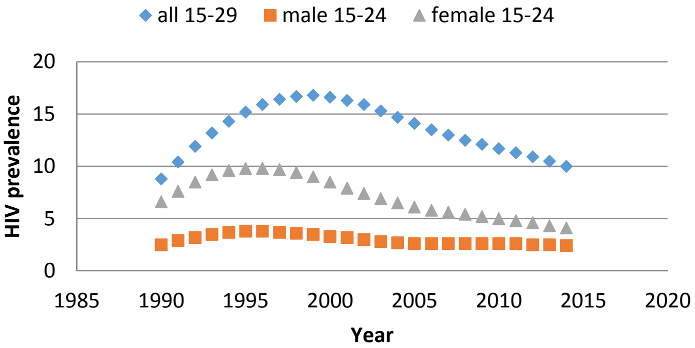
- ART treatment
- Better condoms?
- Treating other STDs (or partial vaccine)

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

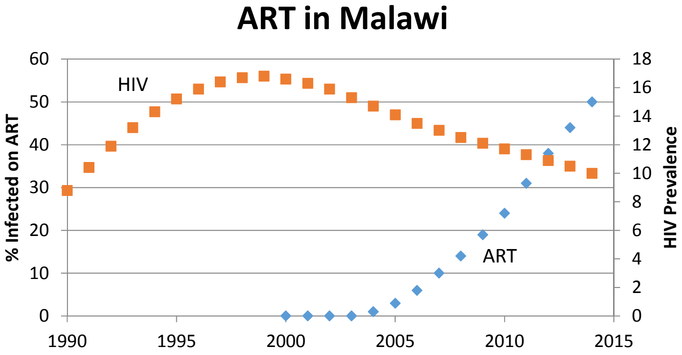


Was ART successful in reducing HIV?

- 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 . . . "



Was ART successful in reducing HIV?

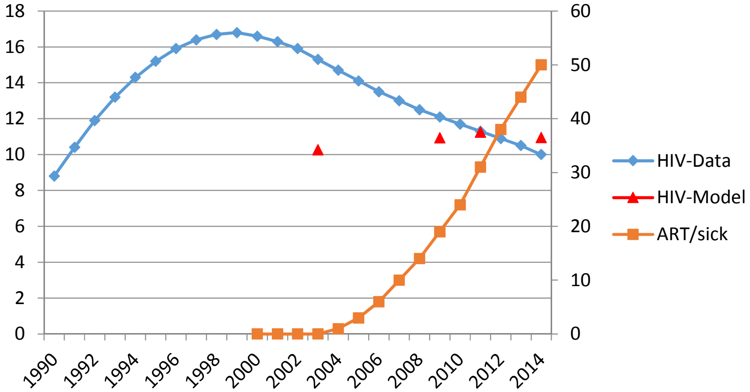


- Note that ART cannot be the whole story,
  as HIV started declining prior to the introduction of ART.
- Anticipation effects would go into the wrong direction.
- Still, ART may have contributed to declining HIV prevalence.

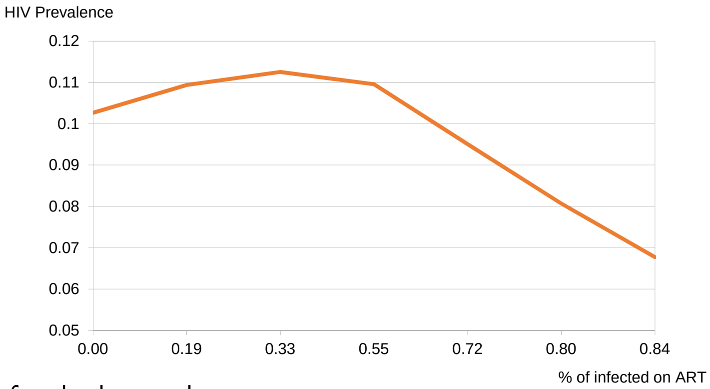
Quantify ART's Contribution to HIV$\downarrow$ using the Model

- 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.
  $\rightarrow$ Model gives, at various levels of treatment, long-term HIV rate.
  $\rightarrow$ Upper bound on fraction of the HIV decline likely due to ART.

ART in the Model



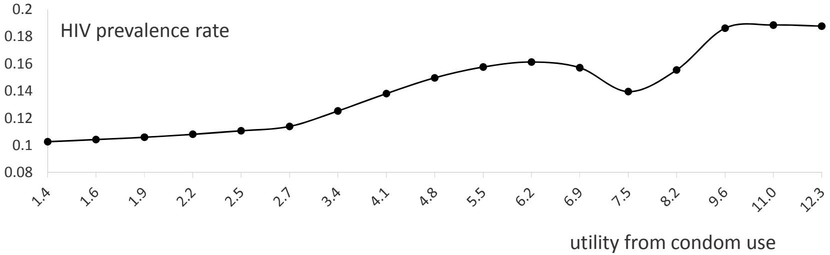
But higher levels of ART promising



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.

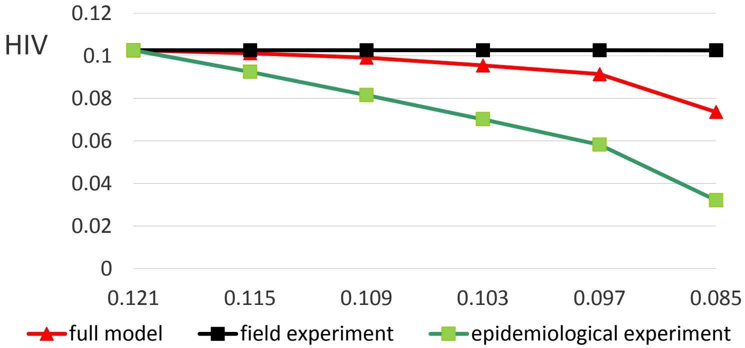
More pleasurable condoms



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).

Summary

- 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.