Using Multiple Outcomes of Sexual Behavior to Provide Insights Into Chlamydia Transmission and the Effectiveness of Prevention Interventions in Adolescents

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Background: Mathematical models are important tools for assessing prevention and management strategies for sexually transmitted infections. These models are usually developed for a single infection and require calibration to observed epidemiological trends in the infection of interest. Incorporating other outcomes of sexual behavior into the model, such as pregnancy, may better inform the calibration process.

Methods: We developed a mathematical model of chlamydia transmission and pregnancy in Minnesota adolescents aged 15 to 19 years. We calibrated the model to statewide rates of reported chlamydia cases alone (chlamydia calibration) and in combination with pregnancy rates (dual calibration). We evaluated the impact of calibrating to different outcomes of sexual behavior on estimated input parameter values, predicted epidemiological outcomes, and predicted impact of chlamydia prevention interventions.

Results: The two calibration scenarios produced different estimates of the probability of condom use, the probability of chlamydia transmission per sex act, the proportion of asymptomatic infections, and the screening rate among men. These differences resulted in the dual calibration scenario predicting lower prevalence and incidence of chlamydia compared with calibrating to chlamydia cases alone. When evaluating the impact of a 10% increase in condom use, the dual calibration scenario predicted fewer infections averted over 5 years compared with chlamydia calibration alone [111 (6.8%) vs 158 (8.5%)].

Conclusions: While pregnancy and chlamydia in adolescents are often considered separately, both are outcomes of unprotected sexual activity. Incorporating both as calibration targets in a model of chlamydia transmission resulted in different parameter estimates, potentially impacting the intervention effectiveness predicted by the model.

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Chlamydia is the most commonly reported sexually transmitted infection (STI) in the United States, with 1.5 million cases reported nationally in 2015 and the greatest rate being among adolescents and young adults. Untreated chlamydial infection can lead to pelvic inflammatory disease, a leading cause of chronic pelvic pain that is also associated with an increased risk of ectopic pregnancy and infertility. The number of reported cases of chlamydia has been rising across the United States, motivating policy makers to call for new or expanded investments in measures to control or prevent these infections.[1] Mathematical modeling can provide important insights into prevention, screening, and treatment policies for the management of STIs such as chlamydia and can be used to inform where resources could be most efficiently invested.[2–9]

These models generally require estimates of a number of biological and behavioral parameters that are difficult or unethical to measure directly. In the case of chlamydial infection, a number of parameters fundamental to the infection natural history cannot be measured directly, including the per-act risk of chlamydia transmission from an infected partner to an uninfected partner, the time from infection to the development of symptoms, and the proportion of infections that are asymptomatic.[10]

To address this, unknown or uncertain parameters must be estimated through the process of model calibration, where select model parameter values are varied until model outputs fit observed trends.[11] Typically, these calibration targets are based only on data pertaining to the disease of interest (eg, chlamydia incidence). However, there are many other infections that also spread through sexual contact as well as other outcomes of sexual behavior (eg, pregnancy). Incorporating multiple outcomes of sexual behavior instead of just one into the calibration process may better inform the calibration process and, importantly, affect model predictions regarding intervention effectiveness.

In this analysis, we sought to calibrate a model of the spread of chlamydia among 15- to 19-year-old adolescents in Minnesota. We considered two calibration scenarios: one in which we calibrated to the historical rates of reported chlamydia cases alone and another where we expanded the model to also simulate the occurrence of pregnancy and included historical pregnancy rates as an additional calibration target. Pregnancy was selected as an additional calibration target because it is among the most commonly occurring outcomes of sexual behavior in adolescents.[12] We compared the two scenarios in terms of the calibrated parameter values, epidemiological predictions, and the predicted effectiveness of hypothetical prevention and screening interventions.

METHODS

Overview

We developed a compartmental model to simulate the dynamics of chlamydial infection and pregnancy among sexually

active adolescent men and women aged 15 to 19 years in Minnesota. The model was described as a system of differential equations implemented and solved in R v.3.2.2 using the deSolve package.[13,14] Point estimates or ranges of model input parameters were estimated from the Minnesota Student Survey (MSS),[15] the Healthcare Effectiveness Data and Information Set,[16] and published literature. The model was calibrated to statewide, sex-specific reported chlamydia cases alone (chlamydia calibration) and in combination with pregnancy rates (dual calibration), among 15- to 19 year-olds from 2005 to 2013 by varying uncertain model inputs, including parameters governing sexual behavior, chlamydial infection, and pregnancy risks. Model input parameter values and ranges used in calibration are reported in Table 1.

Mathematical Model

Chlamydial infection was modeled following an SITS framework—individuals progress from a susceptible state (S) to a symptomatic or asymptomatic infected state (I^s and I^a) and then back to the susceptible state, potentially passing through a treated state (T) for those whose infection is detected. Separate sets of compartments were included for men and women. In addition to their chlamydia status, women could also be pregnant or not. A state transition diagram of chlamydia and pregnancy dynamics is shown in Figure 1.

The population was further divided into 2 levels of sexual behavior (low risk and high risk), reflecting different numbers of sexual partners. The final model comprised a total of 24 distinct compartments reflecting chlamydia status, pregnancy status (for women), and sexual behavior. The full system of differential equations describing the compartmental model is provided in Supplemental Digital Content 1, http://links.lww.com/OLQ/A177.

Sexual Behavior

Sexual behavior parameters were primarily informed by the MSS, which is a statewide survey of ninth and 12th graders that was administered in 2004, 2007, and 2010.[15] An additional wave was administered in 2013 that sampled 11th instead of 12th graders. We therefore do not combine 2013 survey with other survey years. We categorized respondents into 2 sexual behavior groups (low risk and high risk) based on the number of partners that students reported in the previous 12 months: 2 or more sexual partners was considered high risk, while 1 or fewer sexual partner was considered low risk. We averaged over the 3 MSS waves to determine the average number of partners per year and the size of each risk group, stratified by sex. We only included heterosexual contact in the model and assumed that sexually active adolescents selected sexual partners of the opposite sex nonpreferentially with respect to risk group. To balance the number of sex partners reported by men and women, the average number of partners among high-risk women was adjusted (see Supplemental Digital Content 1), as studies of sexual behavior surveys find that sexual behavior tends to be under-reported and this under-reporting is more likely among individuals with higher numbers of sex partners rather than monogamous or abstinent individuals.[17,18] The number of sex acts per partnership was estimated through calibration and was assumed to be the same for both low- and high-risk adolescents.

Condom use was assumed to differ by risk group, with low-risk adolescents having higher condom use than high-risk. Risk group–specific condom use was estimated through calibration under the constraint that overall condom use in the model (averaged across risk groups) was consistent with the proportion of adolescents reporting condom use at last sex act across the three waves of the MSS.

Chlamydia Transmission

Susceptible men and women become infected at a rate β and $\kappa\beta$, respectively, per unprotected sex act with an infected individual. The multiplicative factor, $\kappa > 1$, reflects evidence of increased risk of male-to-female chlamydia transmission versus female-to-male.[23] We assumed that condom use reduced the risk of transmission by a factor ϕ. Parameters β, κ, and ϕ were estimated in calibration, with initial ranges taken from previous modeling studies and published literature.[19–22] Once infected, a proportion α of individuals develop an asymptomatic infection, while $1 - \alpha$ are symptomatic. Published estimates of α range from 0.65 to 0.96.[24,25] We varied this parameter in model calibration.

Treatment and Recovery From Chlamydial Infection

Infected individuals (both symptomatic and asymptomatic) can be detected through routine chlamydia screening and transition to the treated compartment. For nonpregnant women, this rate was taken from the Healthcare Effectiveness Data and Information Set database, which reports annual chlamydia screening rates among sexually active young (16- to 20-year-old) women.[16] The screening rate in the model changed annually to reflect increasing trends in Minnesota, where screening among women increased from 36% in 2005 to 48% in 2013 (Fig. S1, http://links.lww.com/OLQ/A177). In the absence of statewide STI screening rates in men, we assumed an annual screening rate that was proportional to the screening rate in nonpregnant women. This proportion was assumed to be less than 1 (ie, men are screened less frequently than women) and was estimated in calibration. We assumed that pregnant women are screened for chlamydia at a monthly rate of 1/3 such that the average time of screening occurs at the end of the first trimester, consistent with prenatal care guidelines.[30] In addition to routine screening, individuals with symptomatic infections were assumed to seek treatment in response to their symptoms at a rate reflecting the average incubation period of chlamydial infection plus a time delay in seeking care, which were both varied in model calibration.[26–29]

The recovery rate for individuals entering treatment, γ^{tx}, was calculated to reflect an average treatment duration of 7 days.[30] We assumed that individuals abstained from sexual activity during treatment. Individuals could also spontaneously recover from chlamydial infection and transition back to the susceptible state directly (without treatment) at a rate $\gamma^n = 1/12$ per month, reflecting published estimates of the duration of untreated chlamydial infection.[31s] (Supplemental references 31s–43s, Supplemental Digital Content 2, http://links.lww.com/OLQ/A178).

Pregnancy

Women become pregnant at a rate of τ per unprotected sexual contact, which was estimated through calibration to pregnancy incidence. This rate is reduced with the use of condoms, birth control pills, or long-acting reversible contraceptives (LARCs), which include intrauterine devices, injections, and contraceptive implants. The per-act relative risk of pregnancy using contraception was calculated from a recent review article of contraceptive failure rates under typical use in the United States.[32s] The relative risk of pregnancy when using both condom and a secondary method (pill or LARC) was calculated from the probability that both methods fail independently.

We used the 2013 MSS, which included questions about nonbarrier contraceptive methods not present in earlier waves, to estimate the overall proportion of sexually active adolescents using oral birth control pills and LARCs in 2013.[15] Similar to condom use, we allowed contraceptive use to differ between risk groups in calibration under the constraint that average use reflected that

TABLE 1. Model Input Parameter Values and Ranges Used in Calibration

Parameter	Value or Calibration Range	Source
Sexual behavior parameters		
Proportion of sexually active 15- to 19-year-olds who are high risk		15
Men	0.484	
Women	0.387	
Number of partners per year		15
Low-risk men	0.47	
Low-risk women	0.57	
High-risk men	3.12	
High-risk women	3.59	Calculated[17,18]
Number of sex acts per partnership	[0, 50]	Assumed
Chlamydia parameters		
Transmission probability per sex act		
Female-to-male, β	[0.03, 0.80]	19–22
Male-to-female (relative to female-to-male), κ	[1, 2]	23
Proportion of asymptomatic infection, α	[0.65, 0.96]	24,25
Annual rate of chlamydia screening in women, $\psi^{sc}(t)$, time-varying	0.35 – 0.48	16
Relative rate of chlamydia screening in men (vs women)	[0, 0.2]	Assumed
Incubation period, d	[1, 21]	26–29
Treatment delay, d		
Men	[1, 120]	Assumed
Women	[1, 120]	Assumed
Sensitivity of chlamydia screening test	0.93	40s,41s
Treatment duration, $1/\gamma^{tx}$, d	7	30
Duration of untreated chlamydia infection $1/\gamma^{n}$, mo	12	31s
Pregnancy parameters		
Pregnancy rate per sex act, τ	[0.0, 0.094]	42s
Average time to chlamydia screening during pregnancy, $1/\psi^{p}$, mo	3	30
Duration of pregnancy, $1/\gamma^{p}$, mo	7.5	35s,43s
Condom and contraception use		
Probability of condom use		
Overall, *p.condom*	[0.329, 0.728]	15
Low-risk adolescents	[*p.condom*, 1]	Assumed
Proportion of women using oral birth control pills		
Overall, *p.oral*	[0.143, 0.266]	15
Among low-risk women	[0, *p.oral*]	Assumed
Proportion of women using LARCs		
Overall in 2013, *p.LARC*	[0.056, 0.104]	15
Among low-risk women in 2013	[0, *p.LARC*]	Assumed
Annual growth rate LARC use from 2005 to 2013, λ	[1, 2]	Assumed
Relative reduction in chlamydia transmission rate with condom use, ϕ	[0.15, 0.9]	34s
Annual probability of failure to prevent pregnancy		32s
Condom use	0.18	
Oral birth control pills	0.09	
LARCs	0.039	
Demographic dynamics		
Aging out, υ	0.017	Calculated
Aging in, υ	0.017	Assumed

reported in the MSS. Extrapolating from national trends,[33s,34s] we assumed that oral birth control pill use in Minnesota was stable over time, while LARC use increased from 2005 to 2013 for both low-risk and high-risk adolescents. Long-acting reversible contraceptive use was assumed to follow an exponentially increasing function $f_{LARC}(t) = \mu^{*}\lambda^{(t\text{-}2005)}$, where $f_{LARC}(t = 2013)$ was set to reflect the level of LARC use reported in the 2013 MSS. The parameter λ was estimated through calibration. Figure S2 presents the mean time trend in LARC use and 95% confidence bounds, overall and stratified by risk group, generated by the calibration process.

Women who become pregnant transition to the pregnant compartment equivalent to their current chlamydia status. The rate at which pregnant women return to nonpregnant compartments in the model is equal to the inverse of the duration of pregnancy. Using Minnesota pregnancy and birth statistics, we calculated that 74% of pregnancies among adolescents aged 15 to 19 years old resulted in live births. Assuming that the vast majority of pregnancies not resulting in live births end within the first trimester and that pregnancies resulting in live births have an average duration of 38 weeks,[35s] we calculate a weighted average gestation of 7.5 months.

Population Dynamics

Adolescents age out of the model at a monthly rate of $\upsilon = 0.017$, reflecting the 5 years required to age through the modeled population (from 15 through 19 years old). New adolescents enter the model into the susceptible state when they become sexually active, which we assumed occurs at a rate equal to υ to maintain a constant sexually active population over time. Individuals entering the model were divided proportionally into low-risk

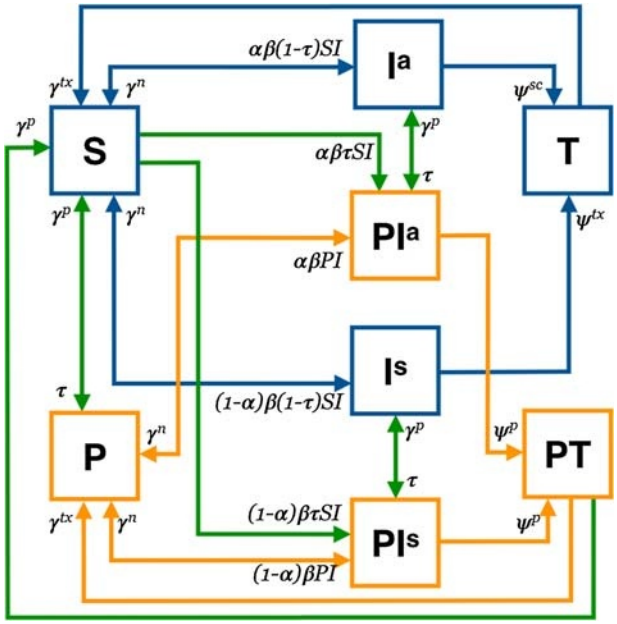

Figure 1. Model state-transition diagram of chlamydia infection and pregnancy among adolescent women. We only include heterosexual transmission in the model, so $I = I^a + I^s$ of the opposite sex. Note that adolescent males follow the same chlamydia dynamics with pregnancy states removed.

and high-risk sexual behavior groups. We assumed that individuals do not change their sexual risk behavior once they become sexually active.

Model Calibration

Calibration targets consisted of annual rates of reported cases of chlamydia from 2005 to 2013 among 15- to 19-year-olds in Minnesota stratified by sex. The corresponding model outputs were the monthly transitions from infected to treated compartments (as these transitions represent diagnosed infections), aggregated over each 12-month period separately for men and women. For the dual calibration scenario, annual pregnancy rates from 2005 to 2013 among 15- to 19-year-old women in Minnesota were included as additional calibration targets. The corresponding model outputs were calculated by aggregating monthly transitions from nonpregnant to pregnant compartments over each 12-month period. Before aggregating model results to match to 2005 targets, we ran the model for a 2-year burn-in period for each parameter set to allow model compartments to stabilize and eliminate any artifacts arising from the initial conditions.

We calibrated the model using a Bayesian calibration approach.[36s,37s] We assumed uniform prior distributions for all parameters based plausible ranges reported in the literature or 95% confidence intervals informed by the MSS, where applicable (Table 1). Posterior distributions were estimated by Markov Chain Montel Carlo simulation using the Metropolis Hastings algorithm. Additional details are provided in Supplemental Digital Content 1, http://links.lww.com/OLQ/A177.

TABLE 2. Summary Statistics of Posterior Distributions for Model Parameters Calibrated Using Chlamydia Cases Alone and in Combination With Pregnancy Calibration Targets (Dual Calibration)

	Chlamydia Alone			Dual Calibration			
	Mean	Mode	SD	Mean	Mode	SD	Effect Size
Sexual behavior parameters							
Number of sex acts per partnership	6.89	1.13	5.32	8.23	4.72	4.65	0.27
Chlamydia parameters							
Probability of transmission per sex act							
Female-to-male, β	0.163	0.044	0.129	0.097	0.039	0.047	0.68*
Male-to-female (relative to female-to-male), κ	1.518	1.973	0.283	1.505	1.320	0.279	0.05
Relative reduction in chlamydia transmission rate with condom use (ϕ)	0.546	0.623	0.215	0.540	0.591	0.206	0.03
Proportion of asymptomatic infection, α	0.909	0.948	0.040	0.886	0.916	0.046	0.53*
Relative rate of chlamydia screening in men (vs women)	0.083	0.083	0.051	0.099	0.111	0.055	0.31*
Incubation period, d	10.94	8.17	5.76	11.41	18.77	5.72	0.08
Treatment delay, d							
Men	69.46	111.41	33.43	66.93	69.42	32.37	0.08
Women	55.86	25.76	33.82	59.95	75.79	32.76	0.12
Condom and contraception use							
Probability of condom use							
Overall	0.535	0.493	0.112	0.618	0.601	0.062	0.91*
Low risk	0.708	0.745	0.155	0.941	0.987	0.048	2.03*
High risk	0.312	0.356	0.171	0.199	0.366	0.118	0.77*
Oral birth control pill use							
Overall				0.260	0.265	0.005	
Low risk				0.011	0.004	0.009	
High risk				0.654	0.667	0.017	
LARC use in 2013							
Overall				0.101	0.102	0.003	
Low risk				0.005	0.001	0.004	
High risk				0.252	0.255	0.009	
Annual growth rate LARC use from 2005 to 2013, λ				1.20	1.21	0.038	
Pregnancy parameters							
Pregnancy rate per sex act				0.039	0.018	0.019	

*Denotes moderate to large effect sizes (Cohen's d > 0.3).

Comparison of Calibration Scenarios

We evaluated the impact using different calibration targets on the estimated input parameter values, predicted epidemiological outcomes, and predicted impact of hypothetical interventions aimed at reducing chlamydia spread. Estimated parameter values were compared across the two calibration scenarios in terms of the summary statistics of the resulting posterior distributions. We calculated effect size in terms of Cohen's d to identify parameter distributions that significantly differed in mean estimates between the calibration scenarios (Cohen's d > 0.3).[38s] We also compared the number of reported cases, annual number of new infections (diagnosed and undiagnosed), and prevalence of chlamydial infection from 2005 to 2013 predicted by the model under each calibration scenario to assess the extent to which differences in calibrated parameter values resulted in different epidemiological predictions.

To assess the impact of calibrating to chlamydia targets alone or in combination with pregnancy on policy decisions, we compared the predicted effectiveness of hypothetical interventions under each calibration scenario that induced one of three behavior changes: a 10% absolute increase in condom use among high-risk adolescents; a 1.5 times increase in annual chlamydia screening rate among men; or a 10% absolute increase in the annual chlamydia rate among women. We projected the total number of infections averted under each intervention over 5 years and compared how these outcomes differed across the two calibration scenarios.

RESULTS

The mean, mode, and standard deviation of the posterior distribution of each calibrated parameter are presented in Table 2 for the two calibration scenarios. We found moderate differences in mean estimates (Cohen's d > 0.3) between the two calibration scenarios for the probability of condom use, overall and by risk group, the probability of chlamydia transmission per unprotected sex act, the proportion of chlamydial infections that are asymptomatic, and the relative rate of chlamydia screening among men. Calibrated values relating to condom use were the most impacted by the choice of calibration targets; including pregnancy as an additional calibration target led to higher levels of condom use among low-risk adolescents, but lower levels of condom use among high-risk adolescents compared with calibrating to chlamydia cases alone. Posterior distributions were also narrower under the dual calibration scenario (Fig. 2). The model-predicted estimates of reported cases (based on 1000 parameter values sampled from calibrated distributions) were well-matched to sex-specific rates of reported chlamydia cases from 2005 to 2013 in Minnesota among 15- to 19-year-olds for both calibration scenarios (Fig. 3). The dual calibration scenario resulted in a lower prevalence and fewer new chlamydial infections predicted by the model in both men and women compared with calibrating to chlamydia cases alone (Fig. 4). However, both calibration scenarios predicted a much higher number of new chlamydial infections (both diagnosed and undiagnosed) in women compared with men, whereas prevalence was predicted to be similar for men and women.

All hypothetical interventions resulted in fewer infections in both men and women under both calibration scenarios (Table 3). However, when calibrating to chlamydia cases alone, the model predicted a greater number of infections averted with increased condom use compared with the dual calibration scenario [158 (8.5%) vs 111 (6.8%)], potentially over-estimating the benefits of condom use promotion. Both calibration scenarios predicted far fewer infections averted with an increase in chlamydia screening among men or women. Calibrating to chlamydia alone

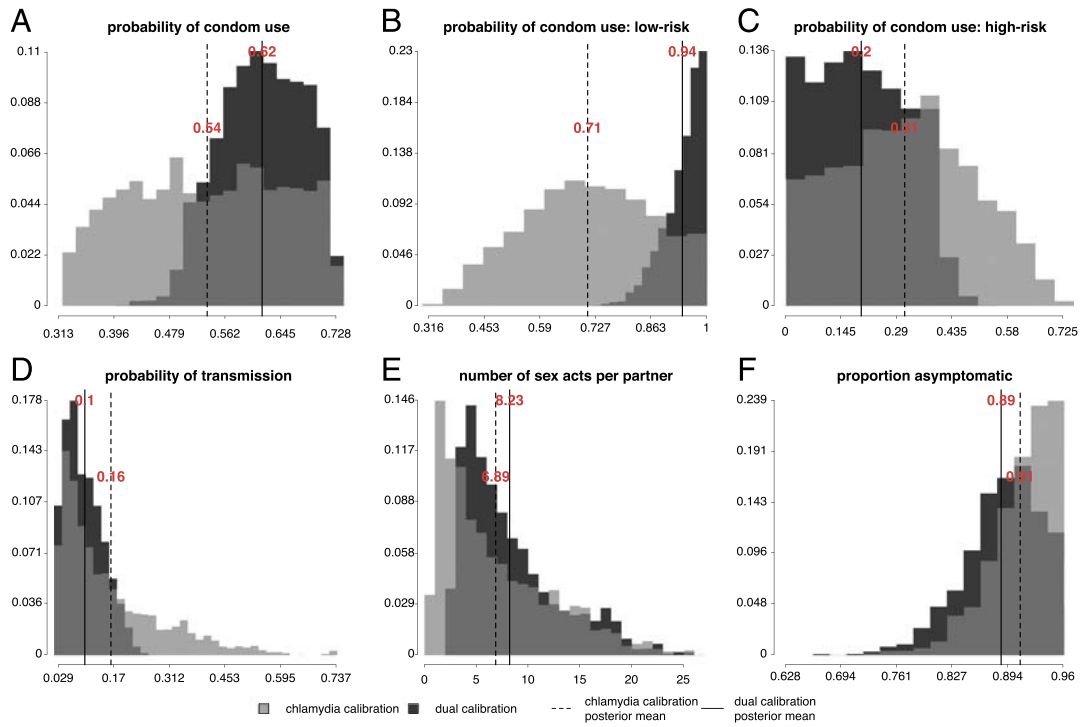

Figure 2. Posterior distributions of key model parameters relating to chlamydial infection, sexual behavior, and condom use when calibrating to chlamydia incidence alone (light gray) and in combination with pregnancy (dark gray). Posterior mean values under each calibration scenario are noted with a dashed (chlamydia calibration) or solid (dual calibration) line.

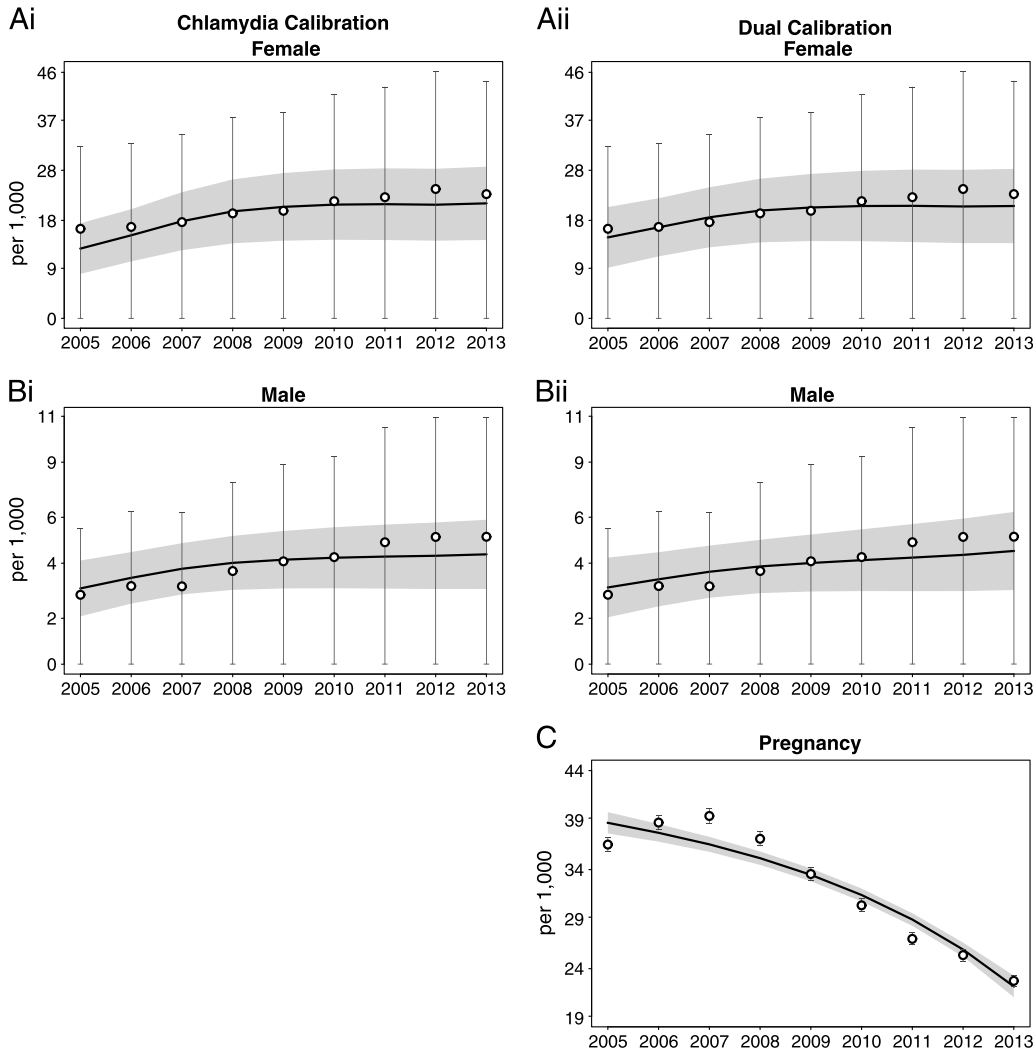

Figure 3. Reported chlamydia case rates (circles) with 95% confidence bars overlaid with mean model predictions (solid line) with shaded 95% confidence region per 1,000 15- to 19-year-old (A) women and (B) men when calibrating to (i) chlamydia incidence alone and (ii) in combination with pregnancy incidence from 2005 to 2013. Panel (C) shows reported pregnancy rates (circles) with 95% confidence bars overlaid with mean model predictions (solid line) with shaded 95% confidence region per 1000 15- to 19-year-old women from 2005 to 2013 resulting from calibration to both chlamydia and pregnancy targets.

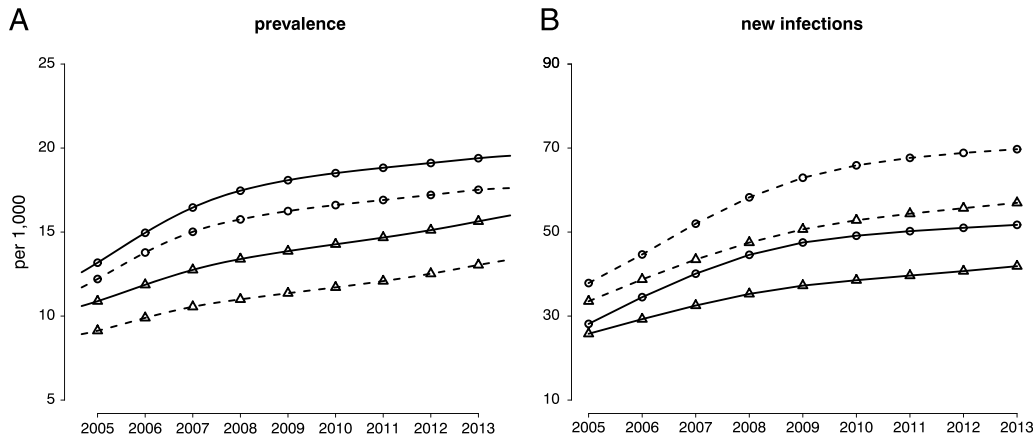

Figure 4. Model-predicted (A) prevalence and (B) annual new chlamydial infections from 2005 to 2013 per 1,000 15- to 19-year-old men (solid lines) and women (dashed lines) when calibrating to chlamydia cases alone (circles) or in combination with pregnancy incidence (triangles).

TABLE 3. The Predicted Mean Number of Chlamydial Infections and Infections Averted Over 5 Years Under Each Calibration Scenario for Hypothetical Interventions that Increase Condom Use or Annual Chlamydia Screening Rates

	Men		Women		Total	
	Chlamydia	**Dual**	**Chlamydia**	**Dual**	**Chlamydia**	**Dual**
Status quo (no intervention)						
Number of infections	796	705	1057	925	1853	1630
10% Absolute increase in condom use						
Number of infections	741	665	954	854	1695	1519
Infections averted, n (%)	55 (6.9)	40 (5.7)	103 (9.7)	71 (7.7)	158 (8.5)	111 (6.8)
1.5× Increase in annual chlamydia screening for men						
Number of infections	792	700	1046	913	1838	1613
Infections averted, n (%)	4 (0.5)	5 (0.7)	10 (1.0)	12 (1.3)	14 (0.8)	17 (1.0)
10% Absolute increase in annual chlamydia screening for women						
Number of infections	764	675	1035	904	1799	1579
Infections averted, n (%)	33 (4.0)	30 (4.3)	22 (2.1)	21 (2.3)	55 (2.9)	51 (3.1)

resulted in slightly fewer infections averted than the dual calibration scenario, although these differences were small and may not be significant.

DISCUSSION

Mathematical models of STIs, such as chlamydia, are generally calibrated only to outcomes related to the disease of interest. However, in this study, we find that when other outcomes of sexual behavior, in this case pregnancy, are incorporated as additional calibration targets, parameter estimates change, which in turn impacts the epidemiological outcomes and intervention effectiveness predicted by the model. This has implications for model-based analyses aimed at evaluating the effectiveness and cost-effectiveness of STI prevention interventions.

Given that the focus of our study was on chlamydial infection specifically among 15- to 19-year-old adolescents, pregnancy was a natural choice as an additional calibration target to inform sexual behavior. In Minnesota, adolescent pregnancy occurs at a rate similar to that of chlamydial infection: in 2013, there were 22.1 pregnancies and 23.3 cases of chlamydia per 1000 15- to 19-year-old women. Pregnancy statistics may also be more complete than STI surveillance numbers, which are under-estimates of true incidence owing to undetected asymptomatic infections and potential incomplete reporting. In contrast, adolescent pregnancy statistics are tallied from state vital statistics, which reflect live births, still-births or miscarriages, and abortions reported by healthcare providers.[39s] Thus, pregnancy not only serves as an additional outcome of sexual behavior to match in calibration but also may be a more accurately measured outcome.

Intuitively, incorporating additional calibration targets should avoid issues of over-fitting to a single outcome. However, calibrating to multiple outcomes of sexual behavior also requires increasing the complexity of the model to capture these outcomes. For example, we introduced additional parameters to model pregnancy, some of which required estimation through calibration. The inclusion of additional outcomes may also influence the dynamics of the primary outcome of interest. For example, in the model, pregnant women have a higher rate of chlamydia screening than nonpregnant women, but this is only "turned on" under the dual calibration scenario where we allow individuals to become pregnant.

We find that using additional calibration targets can result in more informed estimates for some parameters. For example, the addition of pregnancy targets narrowed the posterior distribution of the probability of condom use, whereas calibrating to reported chlamydia cases alone yielded an estimate that was essentially unchanged from the initial 95% confidence range calculated from the MSS data (Fig. 2). In addition to differences in parameter estimates, this analysis also demonstrates that the choice of which outcomes of sexual behavior to model and calibrate influences epidemiological predictions and the predicted effectiveness of certain interventions. However, we cannot conclude that including pregnancy in the model improves the accuracy of predicting chlamydia outcomes because the true incidence of chlamydia is unobserved.

Our model has several limitations. We only model heterosexual transmission of chlamydia; however, surveillance reporting also includes cases resulting from homosexual contact. In particular, if extragenital testing expands, the number of cases among men who have sex with men will likely constitute a larger proportion of male cases. We do not account for this changing case mix in the model. In the absence of any measure of assortativity by sexual risk group among adolescents in Minnesota, we assumed random mixing. Assumptions regarding sexual mixing have been shown to impact the dynamics of STIs.[2] Greater detail in sexual behavior questions is needed for surveys such as the MSS to inform mixing assumptions in mathematical models.

Both unintended pregnancy and STIs pose significant challenges to adolescent sexual health and stem from the same behaviors. However, organizations, policies, and interventions are often focused on addressing either teen pregnancy or STIs, but not both together. In this study, we demonstrate the utility of considering a more comprehensive picture of adolescent sexual health in the development phase of mathematical modeling of STIs. In addition to providing additional insights into unknown or uncertain sexual behavior parameters, this broader approach may be more appropriate for addressing the complex challenges of developing holistic policy, public health, and clinical strategies that are needed to support adolescent sexual health.

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