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Modeling the impact of changing sexual behaviors with opposite-sex partners and STI testing among women and men ages 15–44 on STI diagnosis rates in the United States 2012–2019

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ABSTRACT

Objective: To estimate the potential contributions of reported changes in frequency of penile-vaginal sex (PVS), condom use and STI screening to changes in gonorrhea and chlamydial diagnoses from 2012 to 2019.

Methods: An agent-based model of the heterosexual population in the U.S. simulated the STI epidemics. Baseline was calibrated to 2012 diagnosis rates, testing, condom use, and frequency of PVS. Counterfactuals used behaviors from the 2017-2019 NSFG, and we evaluated changes in diagnosis and incidence rates in 2019.

Results: Higher testing rates increased gonorrhea and chlamydia diagnosis by 14% and 13%, respectively, but did not reduce incidence. Declining frequency of PVS reduced the diagnosis rate for gonorrhea and chlamydia 6% and 3% respectively while reducing incidence by 10% and 9% respectively. Declining condom use had negligible impact on diagnosis and incidence.

Conclusion: Understanding how changing behavior drives STI incidence is essential to addressing the growing epidemics. Changes in testing and frequency of PVS likely contributed to some, but not all, of the changes in diagnoses. More research is needed to understand the context within which changing sexual behavior and testing are occurring.

1. Introduction

Between 2012 and 2019, reported cases of gonorrhea (GC) and chlamydia (CT) increased for almost all demographic groups, although the magnitude of trends varied by age, sex, race, and pathogen (Centers for Disease Control and Prevention,

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2019). In 2019, a total of 1,808,703 CT cases and 616,392 GC cases were reported to CDC. STIs contribute to substantial morbidity in addition to anxiety, infertility, relationship strife, and childhood disabilities (National Academies of Sciences E and and Medicine, 2021). A recent study estimated that GC/CT accounted for $1 billion of the $15.9 billion (2019 dollars) in total lifetime direct medical cost attributable to incident STI in 2018 (Chesson et al., 2021). Our ability to address the STI epidemic is further affected as new infections are becoming more difficult to treat with the emergence of drug-resistant strains for some STIs (CDC. Antibiotic Resistance Threats in the United States, 2019; Krupp & Madhivanan, 2015; Varshney, 2023).

The drivers of STI are multi-level, including sexual behaviors, health-care seeking, sexual networks, health system policies, health-care access, provider bias, socioeconomic issues, societal values, and policies, and the interactions and dependencies within and between these levels (Krieger, 2008; National Academies of Sciences E and and Medicine, 2021). Analyses of the National Survey of Family Growth (NSFG), (Centers for Disease Control and Prevention, 2021) a nationally representative survey of U.S. households, identified trends in sexual behaviors and STI screening with unclear impacts on STI incidence and diagnoses. For example, one study that evaluated sexual risk and protective behaviors among sexually-active females ages 18–44 using the NSFG 2006–2008, 2008–2010 and 2011–2013 found no overall trends in concurrency, non-monogamous sex partners in the last 12 months, or condom use at last sex (Aholou et al., 2017). Another study used data from NSFG 2002, 2006–2010 and 2011–2017 to evaluate condom use among males ages 15–29. They reported divergent trends in condom use at last sex with significant declines among males with STI risk factors while condom use increased or remained stable among those with no STI risk factor (Copen et al., 2020). A more recent study (Katz et al., 2022) analyzed data from respondents ages 15–44 who reported sex with an opposite-sex partner in NSFG 2008–2019, and found significant declines in condom use at last vaginal sex, mean number of vaginal sex acts, and proportion of condom-protected sex acts in the past 4 weeks with opposite-sex partners. Past-year testing for CT and any STI increased among females.

The changes in behaviors described above are in some instances consistent with changes in reported STI diagnoses and in others not. For example, we would expect declining condom use to be associated with increasing reported STI. Conversely, we might expect reductions in penile-vaginal sex (PVS) frequency to facilitate reductions in STI incidence. We might also expect that increasing testing among females could result in either an increase in the number of diagnoses, even if there has been no change in the true incidence of STIs, or a decrease in the number of diagnoses over time as more individuals are treated earlier and have fewer opportunities to transmit. Thus, there is no clear pattern linking changes in reported sexual behavior, STI testing and diagnosis rates. Additionally, prior research has indicated that constellations of changes in behaviors like condom use and numbers of partners can have significant and highly varied impacts on STI incidence in different contexts (Garnett et al., 2008). In order to disentangle some of these divergent findings and the countervailing impacts these changes in behavior may have on STI diagnosis, we designed an agent-based stochastic network model to simulate the STI epidemic among 15-44-year-old males and females with opposite-sex partners in the US. Using our simulation, we estimate the impact of changes in sexual behaviors (condom use, the frequency of PVS, and STI testing) individually and in combination on STI diagnoses between 2012 and 2019 while taking into account both demographic and network structure.

2. Methods

The analysis used an agent-based simulation of N = 50,000 individuals that included networks of sexual partnerships overlaid with epidemic models of GC/CT transmission. The sexual partnership networks were represented as Exponential-family random graph models (ERGMs) and their dynamic extension temporal ERGMs (TERGMs) which allow for statistically principled simulation of network structure given a set of target statistics from empirical data (Hunter et al., 2008; Krivitsky & Handcock, 2014). We modeled networks of three interacting types of sexual partnerships: main partnerships, casual (but persistent) partnerships, and one-time sexual contacts. A unique TERGM or ERGM represented each type of partnership, but all the simulated partnerships occurred stochastically within the same population of individuals. The target statistics used by the ERGM/TERGM models to simulate the partnership networks were constructed from partnerships reported in NSFG. Two survey periods of NSFG (2011–2013 and 2017–2019) provided network and behavioral data. The surveys received ethical approval from the institutional review board at the National Center for Health Statistics. Our analysis of publicly-available data is not considered human subjects research.

The network models are described in detail in the “Networks of sexual partnerships” section of supplemental appendix A. Briefly, the formation of partnerships was dependent on the sex, race/ethnicity and age of both members of the partnership; the age difference; sex-specific age asymmetry; and the presence/absence of other partnerships. Partnership dissolution was dependent on partnership type and the age of the individuals in the partnership. Partnerships in the simulation formed and dissolved stochastically in discrete 1-week time steps.

The epidemic model overlaid on the partnership networks represented demography (entries, exits, and aging), interhost epidemiology (disease transmission), intrahost epidemiology (disease progression), and clinical epidemiology (disease diagnosis and treatment). Individual attributes related to these processes were stored and updated at every 1-week time step in each epidemic simulation.

The network models in this study were programmed using the *statnet* (Handcock et al., 2008) R package for network model estimation and simulation and the EpiModel (Jenness et al., 2018) software platform for epidemic modeling. The EpiModelHIV R package was used to incorporate STI-specific epidemiology. The software has been used to simulate STI

epidemics and interventions in numerous populations and contexts (Hamilton et al., 2018, 2019, 2020, 2023; Jenness et al., 2016, 2020; Luo et al., 2018; Maloney et al., 2021).

2.1. STI transmission and model calibration

GC/CT transmission and natural history was modeled stochastically. During each condomless PVS act there was a fixed sex-specific probability of acquiring a new infection from an infected partner. Specific rates and their calculation are described below. Recovery from untreated GC/CT infection occurred after the duration of infection exceeded the natural history of asymptomatic infection, also described below. Recovery from treated GC/CT infection occurred deterministically one week after treatment. Individuals were newly susceptible to reinfection immediately after recovery.

The probability of GC/CT acquisition as well as the duration of untreated infection were used as tuning parameters to calibrate our simulation. We used approximate Bayesian computation with sequential Monte Carlo sampling (ABC-SMC) methods for calibration. The ABC used four unique probabilities of acquiring GC/CT for males and females given exposure and two durations of untreated GC/CT infection for calibration. The ABC used uniform priors for all six parameters. We calibrated the model to STI diagnosis rates reported for 2012, (AtlasPlus) 107/100,000 U.S. population for GC and 453/100,000 U.S. population for CT. Surveillance estimates for GC/CT were obtained from AtlasPlus (AtlasPlus) and are not reported by transmission category so the national rates were used as approximations to the true rates among individuals with opposite-sex partners. The final estimates for the tuning parameters from the ABC were 0.8737 and 0.8108 probability of acquisition for males and females exposed to GC and 0.7769 and 0.8470 for males and females exposed to CT, and durations of 48.2 and 61.2 weeks for GC and CT infections if untreated. Full details of the calibration process are available in the “Model Calibration” section of appendix A.

Following calibration, we ran the simulation 10,000 times. Each simulation was run for 120 years (the burn-in period) using the post-calibration parameter estimates from the ABC. The 120-year burn-in period was used to reach epidemic equilibrium in the simulations. We evaluated the distance between the reported diagnosis rates in 2012 and the diagnosis rates at the final year of each of the 10,000 simulations to identify 10 unique simulations with diagnosis rates of GC/CT within 1% of those reported by CDC. (AtlasPlus) These 10 simulations were used as our seed simulations (the initial starting conditions in the analysis).

2.2. Simulations and analysis

In the analysis, we investigated two behaviors within relationships: the number of PVS acts and condom use per sex act. We used Poisson regression to predict PVS acts using partnership type and duration, race/ethnicity, age, and whether a member of the partnership is under age 18 as covariates in the predictive model. The estimated mean number of PVS acts per week reported in the 2011-13 NSFG was 1.74 and declined on average to 1.58 in 2017–2019. We modeled condom use within partnership types (main, casual, and one-time contacts) based on the frequency of condom use within reported partnerships. Respondents were asked about the number of total and condom-protected PVS acts in the last 4 weeks. Overall, the probability of using a condom was 27% in 2011–2013 and 25% in 2017–2019. The partnership-type-specific probabilities were 15% in main and 45% in casual in 2011–2013 and 14% in main and 40% in casual in 2017–2019. The specific predicted condom use probabilities in the model were based on the linear combination of partnership and individual attributes including age, race/ethnicity, sex, partnership duration, and if the partnership included an individual under age 18. Model specifications used to predict both PVS and condom use are in the “Behaviors within sexual partnerships” section of supplemental appendix A.

In addition to the within-partnership behaviors described above, we investigated the impact of testing for GC/CT. All respondents were asked if they had received an STI test in the prior 12 months. We did not have unique estimates for both GC/CT testing because the NSFG does not ask respondents to report if they have tested for GC/CT independently. Males are only asked to report if they have tested for any STI and female respondents report specifically about CT testing and testing for any other STI in the last year. Consequently, all tests in the simulation were assumed to be combination tests because we could not differentiate between rates of GC/CT testing from the NSFG testing data. Overall, annual testing in 2011–2013 was 23.03% and it increased to 24.03% in 2017–2019. Predicted testing in the simulation was based on the linear combination of the individual attributes sex, age, race/ethnicity, being in an ongoing main partnership, and being in an ongoing casual partnership. The linear model for predicting testing is described in the “STI testing and treatment” section of supplemental appendix A.

We simulated eight unique epidemic scenarios. Each scenario was run 600 times. In the first scenario, all parameters were based on estimates from the 2011–2013 NSFG; the simulation was started in 2012. This was our baseline model used as the reference for the other scenarios which represent all combinations of PVS frequency, condom use, and testing from the 2017-2019 NSFG. The outcomes of interest are the mean and 95% simulation intervals (SI) for GC/CT diagnosis rates per 100,000 and incidence per 100 person-years at risk from the 600 simulations of each scenario. The mean values are calculated at the end of 2019 in each simulation. The SI is the range within which 95% of the simulated values fall. The SI is a measure of overall variability due to stochasticity in the model and not an indication of statistical significance or confidence.

3. Results

CDC reported that GC/CT diagnosis rates were 106.7 and 453.4 per 100,000 population respectively in 2012 and increased to 187.8 and 551.0 per 100,000 respectively in 2019. (AtlasPlus) Our baseline model used behavior estimates from 2012; the diagnosis and incidence rates from those simulations are shown in figure B1 of appendix B. Our baseline simulation closely reproduced the reported diagnosis rates of GC/CT in 2012 (panels A and C, figure B1). Incidence was stable between 2012 and 2019 with mean GC incidence of 0.91 (95% SI = 0.1, 1.88) per 100 person-years at risk and mean CT incidence of 3.17 (95% SI = 1.78, 4.82) per 100 person-years at risk.

Table 1 presents the diagnosis rates and incidences of GC/CT at the end of 2019. The 2-percentage point decline in condom use between 2011-2013 and 2017–2019 alone had no appreciable impact on incidence or diagnosis of GC/CT between 2012 and 2019. Declining frequency of PVS alone reduced the diagnosis rates for GC/CT 6% and 3% respectively while reducing incidences by 10% and 9% respectively. Changes in testing alone increased GC/CT diagnosis by 14% and 13% respectively. These changes in diagnosis rates due to testing alone equated to 17.7% of the observed change in GC diagnosis rates reported in CDC surveillance from 2012 to 2019 (107/100,000 in 2012 to 188/100,000 in 2019) and 58.2% of the observed change in reported diagnosis rates for CT (453/100,00 in 2012 to 551/100,000 in 2019). The increase in testing between 2011-2013 and 2017–2019 did not reduce incidence in the simulation.

Fig. 1 shows the CT diagnosis rate in the baseline model and models that used 2017–2019 condom use, PVS frequency, testing and the three parameters combined from 2012 through 2019. Combined, the behavior changes from 2011-2013 to 2017–2019 increased the CT diagnosis rate in 2019 from 453 (95% SI = 354, 562) to 483.1 per 100,000 (95% SI = 372, 604), a 6.6% increase and 30.6% of the observed change in reported diagnoses, which increased by 22%–551.0 per 100,000 in 2019. Figure B2 adds the 95% SI to Fig. 1 which shows that some individual simulations with the combined behavior change reached or exceeded the observed diagnosis rate in 2019 even though they did not on average.

Fig. 2 shows the diagnosis rate of GC for the baseline model and models that used 2017–2019 condom use, PVS frequency, 2019 testing, and the three combined. Collectively, the behavior changes from 2011-2013 to 2017–2019 increased the diagnosis rate of GC from 104.1 (95% SI = 48, 164) to 110.7 per 100,000 (95% SI = 50, 174) in 2019, a 6.3% increase. This equated to only 7.9% of the observed change in reported diagnoses, which increased by 80% from 107 per 100,000 in 2012 to 187.8 per 100,000 in 2019. (AtlasPlus) For GC, none of the individual simulations that fell within the 95% SI produced GC diagnosis rates as high as the observed rate in 2019 (Fig. S4).

Fig. 3 shows the CT incidence rate over 10 years of simulation for the baseline model and models with 2017–2019 condom use, PVS frequency, testing, and the three combined. Change in the incidence rate in the simulation with just 2017–2019 PVS frequency, shown in green, is virtually indistinguishable from the incidence rate when all of the behavior changes are included, shown in yellow. This indicates that the decline in PVS is the primary driver of the decline in incidence in the simulation. Conversely, the increase in observed diagnosis rates shown in Fig. 1, is primarily driven by the increase in testing, but the impact is tempered when the decline in PVS is also included. Results were similar for GC (figure B4).

4. Discussion

There were substantial increases in reported CT/GC diagnoses in the U.S. between 2012 and 2019 (Centers for Disease Control and Prevention, 2019) in addition to significant changes in behaviors that may impact STI diagnosis (Katz et al., 2022). Our findings suggest that increases in STI testing may be contributing to the increase in diagnosis rates more so than an increase in incidence. Further, declining incidence due to a lower frequency of PVS masked some of the impact of higher testing rates on diagnoses, which would have accounted for 17.7% of the increase in GC diagnoses and 58.2% of the increase in CT diagnoses all else being equal. The improvement in testing is an important step forward for public health but more will need to be done to further improve testing if the goal is to drive down incidence. Current recommendations from

Table 1
The means and 95% simulation intervals for CT/GC diagnosis rates per 100,000 population and incidence per 100 person-years at risk from five simulation scenarios with differential condom use, frequency of penile-vaginal sex, and STI screening rates based on estimates from the 2011–2013 and 2017–2019 National Survey of Family Growth.

	Chlamydia diagnosis per 100,000 population	Gonorrhea diagnosis per 100,000 population
All 2012 (baseline)	453.0[τ] (354, 562)	104.1 (48, 164)
Condom use from 2019	453.1 (360, 556)	104.6 (52, 166)
Testing from 2019	**510.0 (406, 622)**	**118.9 (66, 182)**
Frequency of penile-vaginal sex from 2019	441.2 (342, 544)	97.4 (42, 156)
All three above	**483.1 (372, 604)**	**110.7 (50, 174)**
	Chlamydia incidence per 100 person-years at risk	***Gonorrhea incidence per 100 person-years at risk***
All 2012 (baseline)	3.17 [τ] (1.78, 4.82)	0.91 (0.10, 1.88)
Condom use from 2019	3.19 (1.78, 4.93)	0.88 (0.21, 1.88)
Testing from 2019	3.19 (1.78, 4.83)	0.94 (0.21, 1.98)
Frequency of penile-vaginal sex from 2019	**2.89 (1.57, 4.31)**	**0.82 (0.10, 1.77)**
All three above	**2.91 (1.57, 4.40)**	**0.86 (0.10, 1.77)**

[τ] The point estimates for diagnosis per 100,000 population and incidence per 100 person-years at risk are means from 600 simulations.

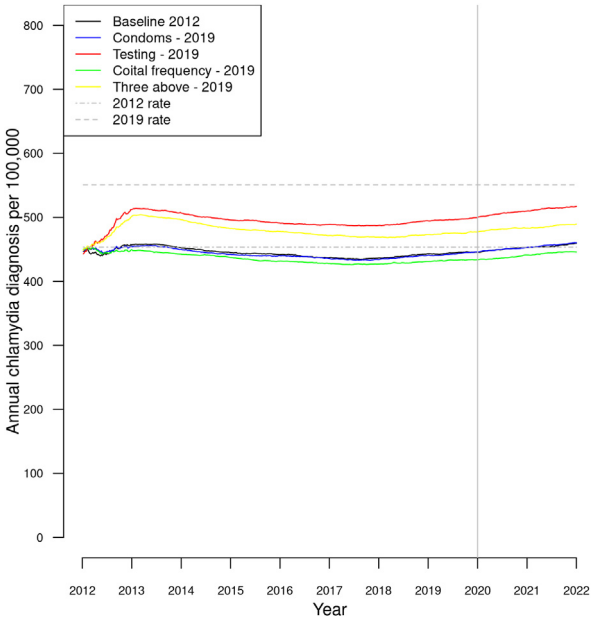

Fig. 1. Mean chlamydia diagnosis rate per 100,000 population from five simulation scenarios with differential condom use, frequency of penile-vaginal sex, and STI screening rates based on estimates from the 2011–2013 and 2017–2019 National Survey of Family Growth.

the U.S. Preventive Services Task Force (USPSTF) is for CT/GC screening for all sexually-active females under 25 and among women 25 years and older who are at increased risk (USPST et al., 2021) but the rates estimated from NSFG and simulated here fall well below the recommended level. Overall only 28.8% of females in the baseline model tested each year and only 30.4% of 19-24-year-old females. In 2019 testing among females improved, but was still just 31.6%. The CDC recommends at least annual screening for men who have sex with men (MSM) (Workowski et al., 2021) but neither CDC nor the USPSTF have specific recommendations for men with only female sex partners (MSW) (USPST et al., 2021). In our simulation using testing reported in 2017–2019, only 16.6% of males tested annually on average, and this is likely an over-estimate because the specific question asked of males in NSFG references any STI, not just GC/CT.

The combined behavior change modeled here accounted for 30.6% of the observed change in CT diagnoses on average, and in some individual simulations within the 95% SI, the diagnoses rate reached or exceeded the reported rate in 2019. However, the model only accounted for 7.9% of the observed change in GC diagnosis on average. The persistent under-prediction of diagnosis rates suggests that either the model is not capturing behavior change with enough granularity or the model is not including important additional changes between 2012 and 2019 that are associated with either STI incidence or diagnosis. Both are likely and are discussed in the limitations. In our simulations, declining condom use had no impact on incidence. The absence of impact may be due to the small change or an interaction between the way condom use was modeled, the duration of partnerships, the duration of untreated infection, and transmissibility rather than inefficacy. Condom use rates were averaged within demographic groups and partnership type which captures some of the heterogeneity in risk, but it did not capture the dichotomy between consistent condom users and inconsistent users. Consequently, in any partnership with duration, there is a high probability of multiple PSV acts, so a small change in the per-act probability of using a condom still could result in many condomless PVS acts. Given the high probability of transmission and long duration of untreated infection, the lack of impact is not surprising. This result could be quite different if the model captured consistent/inconsistent condom use or if very short-term and one-time partnerships were more common as observed among MSM. Condom use may also be correlated with individual, inter-relational, or network characteristics that we did not capture in our simulation.

This study had several other limitations. First, the simulation did not explicitly represent MSM, transgender people, or people who inject drugs, all key populations in STI epidemics. Consequently, we are not able to capture the intersections between these groups and people with opposite-sex partners who were the focus of this study. In addition, the STI diagnosis rates reported in AtlasPlus do not differentiate between MSW and MSM, leading to an overestimate of the observed STI diagnosis rates among the population of MSW modeled here. This is particularly true for our analysis of GC diagnosis. Surveillance data demonstrate that since 2010 the GC diagnosis rate among MSM has been much higher than the rate among MSW or women and that the rate among MSM has been increasing much more quickly (Centers for Disease Control and Prevention, 2019).

We also limited our analyses to PSV and urogenital screening. In nationally-representative data from 2010, 40% of 20-49-year-old women years reported ever having anal sex, and more than 20% aged 20–39 reported anal sex in the past year, (Herbenick et al., 2010) and rectal infections are not uncommon among women (Dewart et al., 2018). However, STI diagnosis

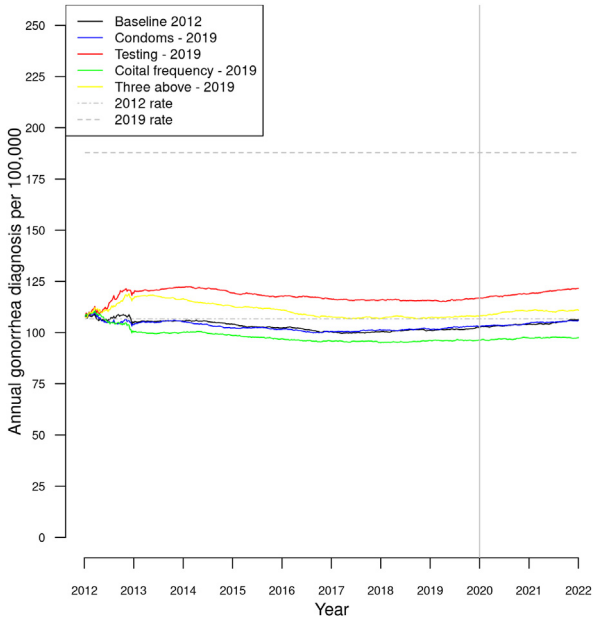

Fig. 2. Gonorrhea diagnosis rate per 100,000 population from five simulation scenarios with differential condom use, frequency of penile-vaginal sex, and STI screening rates based on estimates from the 2011–2013 and 2017–2019 National Survey of Family Growth.

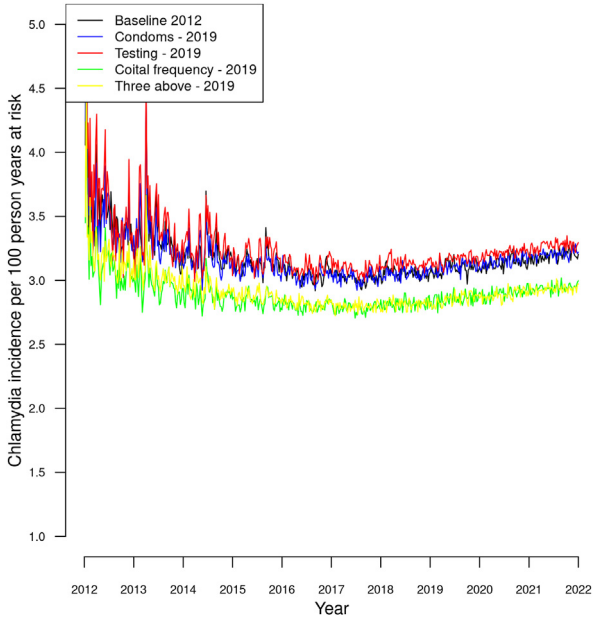

Fig. 3. Chlamydia incidence per 100 person-years from five simulation scenarios with differential condom use, frequency of penile-vaginal sex, and STI screening rates based on estimates from the 2011–2013 and 2017–2019 National Survey of Family Growth.

data from AtlasPlus are not site-specific nor are NSFG data on screening. Thus, we likely capture rectal diagnoses and rectal screening in the total counts, but we do not capture the additional transmission dynamics that may result from differential rates of anal sex, transmission probabilities during anal sex, or rectal screening rates. Similarly, neither oral sex nor pharyngeal GC are represented, despite being a potentially important transmission pathway and reservoir (Javanbakht et al., 2018; Weinstock & Workowski, 2009). We also did not include geographic and socio-economic heterogeneity or social determinants of health all of which can influence the distribution of STI transmission, testing, and treatment.

5. Conclusions

Increases in STI diagnosis can emerge as a result of increasing incidence or increased screening. Our analyses suggest that some of the observed increases in CT/GC diagnoses between 2012 and 2019 were likely due to screening, a positive development in the public health response to the STI epidemic. In addition, reductions in the frequency of PVS may actually be reducing incidence.

The decline in condom use remains cause for concern even if no epidemiologic impact was found here. It is not clear what is driving the decline in condom use. Perhaps use is waning with the proliferation of non-barrier alternatives for HIV and pregnancy prevention (Eisinger et al., 2019; Kann et al., 2018). Yet, condoms remain a low-cost, highly effective alternative for the prevention of HIV, pregnancy, and other STIs. Reversing this trend could be an important step for reducing STI and HIV transmission (Jones et al., 2019).

Understanding drivers of STI incidence is essential to addressing the growing epidemics. Changes in testing and the frequency of PVS likely contributed to some, but far from all, of the changes in diagnoses. More research is needed to identify more granular and context-specific changes in STI-related behavior among populations most impacted by STI in addition to understanding how these behavior changes fit into the larger context of the STI epidemic, including the impact of additional individual, interpersonal, institutional, community, and structural factors (National Academies of Sciences E and and Medicine, 2021).

Disclaimer

The findings and conclusions are solely the responsibility of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention.

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CRediT authorship contribution statement

Deven T. Hamilton: Conceptualization, Formal analysis, Methodology, Project administration, Software, Visualization, Writing – original draft. **David A. Katz:** Conceptualization, Data curation, Writing – review & editing. **Laura T. Haderxhanaj:** Conceptualization, Writing – review & editing. **Casey E. Copen:** Conceptualization, Data curation, Writing – review & editing. **Ian H. Spicknall:** Conceptualization, Writing – review & editing. **Matthew Hogben:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2023.10.005.

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