Cost-effectiveness of Interventions to Increase HPV Vaccine Uptake

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OBJECTIVES: We sought to prioritize interventions for increasing human papillomavirus (HPV) vaccination coverage based on cost-effectiveness from a US state perspective to inform decisions by policy makers.

METHODS: We developed a dynamic simulation model of HPV transmission and progression scaled to a medium-sized US state (5 million individuals). We modeled outcomes over 50 years comparing no intervention to a one-year implementation of centralized reminder and recall for HPV vaccination, school-located HPV vaccination, or quality improvement (QI) visits to primary care clinics. We used probabilistic sensitivity analysis to assess a range of plausible outcomes associated with each intervention. Cost-effectiveness was evaluated relative to a conservative willingness-to-pay threshold; $50 000 per quality-adjusted life-year (QALY).

RESULTS: All interventions were cost-effective, relative to no intervention. QI visits had the lowest cost and cost per QALY gained ($1538 versus no intervention). Statewide implementation of centralized reminder and recall cost $28 289 per QALY gained versus QI visits. School-located vaccination had the highest cost but was cost-effective at $18 337 per QALY gained versus QI visits. Scaling to the US population, interventions could avert 3000 to 14 000 future HPV cancers. When varying intervention cost and impact over feasible ranges, interventions were typically preferred to no intervention, but cost-effectiveness varied between intervention strategies.

CONCLUSIONS: Three interventions for increasing HPV vaccine coverage were cost-effective and offered substantial health benefits. Policy makers seeking to increase HPV vaccination should, at minimum, dedicate additional funding for QI visits, which are consistently effective at low cost and may additionally consider more resource-intensive interventions (reminder and recall or school-located vaccination).

WHAT’S KNOWN ON THIS SUBJECT: Human papillomavirus (HPV) vaccination offers substantial benefits for cancer prevention, yet uptake remains well below national targets. Although interventions to address low HPV vaccination coverage have been tested, the cost-effectiveness of these interventions over the long-term is unexplored.

WHAT THIS STUDY ADDS: We find 3 interventions for increasing HPV vaccination are cost-effective at common thresholds compared with status quo. HPV vaccination interventions are a high-value use of state funding and could prevent from 3000 to 14 000 incident HPV cancers over the next 50 years.

Dr Spencer conceptualized and designed the study, conducted analysis, drafted the initial manuscript, and reviewed and revised the manuscript; Drs Wheeler, Trogdon, Weinberger, Coyne-Beasley, and Brewer contributed meaningfully to study design and interpretation of the data and critically reviewed and revised the manuscript; and all authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

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Human papillomavirus (HPV) infections cause 34,800 cancers annually in the United States, 92% of which could be prevented through HPV vaccination. Yet, coverage remains low, with only 68% of US adolescents ages 13 to 17 having received at least 1 dose of HPV vaccine and only 51% up to date with all recommended doses. With limited and shrinking budgets for state-based government programs in preventive care and increasing centralization of primary care in cost-conscious health care systems, it is important to identify not just effective but high-value strategies for improving HPV vaccine uptake.

Programmatic interventions focused on primary care are more successful at increasing vaccination than interventions focused on risk perception or vaccine confidence. Successful HPV vaccination interventions, often led by state health departments or large health care systems, include facilitating action through parent reminders, prompting providers through clinical quality improvement (QI) efforts, and increasing access through school-located vaccination. Yet, direct comparison of the costs and benefits of vaccination interventions is rare, and connections to outcomes beyond vaccination are needed. In addition, state-based comprehensive cancer control plans reveal that, although nearly all states prioritize HPV cancer prevention, few are engaged in evidence-based activities to increase HPV vaccination. Therefore, we sought to provide state health departments and policy makers with empirical guidance for prioritizing HPV vaccine interventions based on value, defined as increased healthy life-years per dollar spent.

METHODS

To estimate the value of HPV vaccine coverage interventions, we developed a compartmental, dynamic model of HPV infection, transmission, and progression to cancer in a heterosexual US population. We compared cost, individuals vaccinated, cancer incidence, and quality-adjusted life-years (QALYs) associated with a statewide implementation of each of 3 evidence-based interventions for increasing HPV vaccination coverage versus no intervention (vaccination as normal) over a 50-year time horizon. We considered costs and benefits from the state perspective. The study was deemed exempt by the University of North Carolina’s Institutional Review Board. We followed best practices according to the Consolidated Health Economic Evaluation Reporting Standards.

HPV Transmission Model Overview

The model started with 5 million adults and children (the median population size of a US state) stratified by sex and age, corresponding to the US population. New individuals entered the population at birth according to estimated US fertility rates. All individuals progressed through 11 nonoverlapping age groups in which they could die of competing disease at age- and sex-specific mortality rates. Sexual transmission of HPV was based on a susceptible-infected-recovered-susceptible framework. We separately considered 7 vaccine-preventable types of HPV (16, 18, 31, 33, 45, 52, and 58) and a single combined estimate of high-risk HPV types without vaccine protection. Prevalent HPV infection could either be cleared or could progress at type-, sex-, and age-specific rates to 1 of 6 HPV cancers (cervical, vaginal, vulvar, penile, anal, and oropharyngeal). The full details of the model structure appear in the Supplemental Information.

The HPV vaccine has high efficacy against covered HPV types when the full series is completed, and partial series completion also confers substantial benefit. Therefore, we separately model vaccine initiation (receiving at least 1 HPV vaccine dose) and vaccine follow-through (completion of the full series among those with at least 1 dose), with the assumption that those who initiate but fail to complete the vaccine series receive only partial protection (one-half the efficacy of the full series).

Model Input Data

Model inputs came directly from large national data sources when available, with additional parameters drawn from other published estimates. Data on population age structure, births, and deaths came from 2010 census data and the Centers for Disease Control and Prevention (CDC) WONDER database. Data on sexual behavior, type-specific infectivity rates, and vaccine efficacy came from HPV modeling literature. Age- and type-specific HPV prevalence were generated by using the NHANES. Finally, data on HPV vaccine initiation and follow-through by age, sex, and year were derived from provider-verified estimates by using the 2006 to 2017 National Immunization Survey–Teen. Transitions through disease states for which direct estimates are not available (HPV progression, clearance, and natural immunity) were calibrated within a plausible range to match prevaccine HPV prevalence by type and age and HPV cancer incidence by sex, site, and age by using estimates from the Surveillance, Epidemiology and End Results Program.

Comparison Interventions

We evaluated 3 evidence-based interventions, assuming a one-time, year-long implementation. The population-level impact of each intervention is determined by a combination of 2 factors. Reach is the total number of individuals...
Table 1: Intervention Characteristics

<table>
<thead>
<tr>
<th>Target Population</th>
<th>Centralized Reminder and Recall, 11- to 17-y-Olds Included in Immunization Information System</th>
<th>School-Located Vaccination, 11- to 13-y-Olds in Public Middle Schools</th>
<th>Qi Visits, 11- to 17-y-Olds With Participating Providers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected reach</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11- to 13-y-olds</td>
<td>249,400</td>
<td>247,254</td>
<td>246,500</td>
</tr>
<tr>
<td>14- to 17-y-olds</td>
<td>219,300</td>
<td>0</td>
<td>216,750</td>
</tr>
</tbody>
</table>
| **Expected improvement in**  
  HPV vaccine initiation rate, % (range) |                                                                                                |                                                                      |                                                        |
| Girls 11–13              | 2.0 (1.0–6.0)                                                                                    | 13.0 (2.0–17.7)                                                      | 2.6 (0.9–4.2)                                         |
| Boys 11–13               | 5.0 (1.0–6.0)                                                                                    | 13.0 (2.0–17.7)                                                      | 2.6 (0.9–3.1)                                         |
| Girls 14–17              | 3.0 (1.9–6.0)                                                                                    | —                                                                    | 0.0 (0.0–3.3)                                         |
| Boys 14–17               | 2.0 (0.3–6.0)                                                                                    | —                                                                    | 0.0 (0.0–8.0)                                         |
| **Expected improvement in**  
  HPV vaccine follow-through rate, % (range) |                                                                                                |                                                                      |                                                        |
| Girls 11–13              | 8.0 (0.0–16.8)                                                                                   | 4.0 (0.0–18)                                                         | 0.0 (0.0–1.3)                                         |
| Boys 11–13               | 8.0 (0.0–16.8)                                                                                   | 4.0 (0.0–18)                                                         | 0.0 (0.0–1.3)                                         |
| Girls 14–17              | 8.0 (0.0–16.8)                                                                                   | —                                                                    | 0.0 (0.0–1.3)                                         |
| Boys 14–17               | 8.0 (0.0–16.8)                                                                                   | —                                                                    | 0.0 (0.0–1.3)                                         |
| **Cost per individual reached, $ (range)** | 2.10 (1.33–2.70)                                                                                  | 12.29 (9.22–15.36)                                                   | 0.14 (0.09–0.60)                                      |

—, not applicable.

*Estimated percentage point increase in vaccination in unvaccinated individuals.

†Estimated percentage point increase in vaccine follow-through rates in vaccine initiators.

‡Costs are updated to 2018 US dollars by using the Consumer Price Index.26

Centralized Reminder and Recall

Centralized reminder and recall uses a regional or statewide immunization information system that stores vaccination histories from participating providers and health departments.7 Eligible individuals (or their parents and/or guardians) receive a call, e-mail, text, or mailing about being due or past due for recommended vaccines. To estimate the potential intervention reach, we assume that 86% of adolescents have at least 1 record in the immunization information system.29–31 Estimates of effect account for missing or incorrect contact information. Resources involved in reminder and recall include staff time and intervention materials (eg, postage and printing for reminder letters).29,32 Studies suggest reminders increase HPV vaccine initiation in boys (5.0% [range: 1.0%–6.0%]) and girls (2.0% [range: 1.0%–6.0%]),33–35 and recall likely increases HPV vaccine follow-through for both groups (8.0% [range: 0.0%–16.0%]).33,36,37

School-Located Vaccination

In US school-located vaccination models, parents provide consent for their children to be vaccinated by trained community vaccinators at school.36,39 Because school-located health clinics are uncommon in the United States, we consider the model of holding mass vaccination days, which would potentially reach those ages 11 to 13 who attend a public school (87%).40 The costs for school-located vaccination include time and resources to create information materials, obtain permission from parents, schedule the event, administer the vaccination, and process insurance claims for privately insured adolescents.41 Given existing coverage of the HPV vaccine through the federally funded Vaccine for Children program and its designation as an essential health benefit through the Patient Protection and Affordable Care Act, we assume vaccine purchase costs are negligible.42 School-located vaccination is resource intensive and generates substantial improvement in HPV vaccine initiation for 11- to 13-year-old girls and boys (13.0% [range: 2.0%–17.7%]) as well as likely increasing follow-through (4.0% [range: 0.0%–18%]).41,43,44

Qi Visits

CDC funds state health departments to conduct Qi visits with primary care clinics participating in the Vaccines for Children program. The CDC Qi curriculum was originally called the Assessment, Feedback, Incentives eXchange program but was remodeled in 2019 as the Immunization Quality Improvement for Providers. These in person or webinar sessions provide clinic vaccination coverage estimates, facilitate goal setting, and support implementation of best practices.45 Effects potentially reach adolescents whose regular source of care is a participating clinic (85%). Costs for these Qi visits are those associated.
with travel and staff time for conducting training either in person or online.46,47 QI visits increase HPV vaccine initiation among adolescents from ages 11 to 12 (girls: 2.6% [range: 0.9%–4.2%]; boys: 2.6% [range: 0.9%–3.1%]); however, the impact on follow-through is small and not statistically significant (both: 0% [range: 0%–1.3%]).48

Outcome Measures

We considered total intervention costs from a state government perspective in 2018 US dollars. Because all intervention costs were assumed to occur in the first year, they were not discounted. We did not include savings resulting from increased vaccination (eg, lower cancer treatment costs) because the state government would not directly bear most of these costs in the future. We estimated the number of additional individuals initiating HPV vaccination, total cases of HPV cancers averted, and QALYs gained over a 50-year time horizon. By design, interventions affect primarily HPV vaccine initiation; however, we also report increases in HPV vaccine completion. QALYs associated with each intervention were calculated by using previously reported sex- and age-specific decrements associated with incidence of HPV cancer51 and were discounted at a rate of 3% per year. Outcomes are provided as incremental cost-effectiveness ratios (ICERs), which are used to report the additional cost per improved outcome (QALYs gained, additional individuals initiating HPV vaccine, or cancers averted).

Analyses

Using identical starting conditions, we simulated HPV vaccination, transmission, and cancer progression for 50 years after each intervention. We first report each outcome relative to no intervention then compare each sequentially to the next most effective alternative. Interventions were dropped from comparison when either dominated (the next best intervention was both more effective and less expensive) or dominated by extension (the next best intervention had a lower ICER).52 We performed both deterministic and probabilistic sensitivity analyses to assess the robustness of our findings. We varied all cost and effectiveness parameters by sampling 500 sets of values from a uniform distribution for each parameter across the range of these estimates. For cost per QALY gained, we compared against a conservative willingness-to-pay threshold, with interventions that cost $50,000 per QALY gained considered cost-effective.52 No willingness-to-pay thresholds have been established for cost per additional individual initiating and completing HPV vaccination or cost per cancer case averted. Therefore, we present cost-effectiveness acceptability curves for each outcome, indicating the percentage of considered probabilistic scenarios in which each intervention would be preferred across a range of possible willingness-to-pay thresholds.
Interventions reduced total cancer incidence over 50 years; 44 cases were averted for QI visits, 76 for reminder and recall, and 212 for school-located vaccination, which represent 3000 to 14000 cancers averted, if scaled to the full US population (330 million). The interventions also increased QALYs gained (an additional 42 QALYs for QI visits, 75 for reminder and recall, and 204 for school-located vaccination). The total intervention costs for the state were an estimated $64 855 for QI visits, $984 270 for reminder and recall, and $3 038 752 for school-located vaccination. Each intervention was well below the $50 000 per QALY threshold, when compared with no intervention (QI visits: $1538 per QALY gained; reminder and recall: $13 183 per QALY gained; school-located vaccination: $14 871 per QALY gained).

Interventions Compared With Each Other

Beyond the gains achievable by QI visits, the use of reminder and recall would result in an additional 33 QALYs for an additional $919 415 ($28 290 per QALY gained; Table 2). School-located vaccination dominates reminder and recall by extension (improved outcomes at a lower ICER); therefore, we compared school-located vaccination directly to QI visits. School-located vaccination results in an additional 254 QALYs gained, at just under 3 million in incremental cost, resulting in an ICER of $18 337 per QALY gained, making it cost-effective under conservative willingness-to-pay thresholds.

Comparing best- and worst-case scenarios from literature-based estimates revealed changes in per-

### TABLE 3 Best- and Worst-Case Cost-effectiveness of Interventions for Increasing HPV Vaccination

<table>
<thead>
<tr>
<th>Interventions</th>
<th>Total Cost, $</th>
<th>Incremental QALYs Gained Versus Next Best, n</th>
<th>Incremental Cost per QALY Gained Versus Next Best, $</th>
<th>QALYs Gained Versus No Intervention, n</th>
<th>Cost per QALY Gained Versus No Intervention, $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst-case costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QI visits</td>
<td>97 283</td>
<td>42</td>
<td>2307</td>
<td>42</td>
<td>2307</td>
</tr>
<tr>
<td>Reminder and recall</td>
<td>1 734 190</td>
<td>33</td>
<td>50 586</td>
<td>75</td>
<td>23 228</td>
</tr>
<tr>
<td>School-located vaccination</td>
<td>3 797 821</td>
<td>162a</td>
<td>22 817a</td>
<td>204</td>
<td>18 586</td>
</tr>
<tr>
<td>Best-case costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QI visits</td>
<td>41 693</td>
<td>42</td>
<td>989</td>
<td>42</td>
<td>989</td>
</tr>
<tr>
<td>Reminder and recall</td>
<td>623 571</td>
<td>33</td>
<td>17 898</td>
<td>75</td>
<td>8349</td>
</tr>
<tr>
<td>School-located vaccination</td>
<td>2 279 682</td>
<td>162a</td>
<td>10 213a</td>
<td>204</td>
<td>11 156</td>
</tr>
<tr>
<td>Worst-case effectiveness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QI visits</td>
<td>64 855</td>
<td>15</td>
<td>4388</td>
<td>15</td>
<td>4388</td>
</tr>
<tr>
<td>Reminder and recall</td>
<td>984 270</td>
<td>4</td>
<td>221 546</td>
<td>19</td>
<td>51 995</td>
</tr>
<tr>
<td>School-located vaccination</td>
<td>3 038 752</td>
<td>18a</td>
<td>166 232a</td>
<td>33</td>
<td>93 014</td>
</tr>
<tr>
<td>Best-case effectiveness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QI visits</td>
<td>64 855</td>
<td>72</td>
<td>900</td>
<td>72</td>
<td>900</td>
</tr>
<tr>
<td>Reminder and recall</td>
<td>984 270</td>
<td>56</td>
<td>16 421</td>
<td>128</td>
<td>7688</td>
</tr>
<tr>
<td>School-located vaccination</td>
<td>3 038 752</td>
<td>218a</td>
<td>13 610a</td>
<td>291</td>
<td>10 459</td>
</tr>
</tbody>
</table>

Costs and QALYs discounted at 3% per year.

a Indicates that school-located vaccination has dominance and extended dominance compared with reminder and recall intervention; comparisons were made to QI visits.
person intervention costs had minimal impact on the relative cost-effectiveness of alternatives (Table 3). Increasing intervention effectiveness similarly changed the absolute, but not relative, ICERs. However, at the lowest effectiveness, school-located vaccination resulted in only 33 QALYs gained, lower than the base case QALYs for either QI visits or reminder and recall (42 and 75, respectively) and only slightly higher than each of these interventions at their lowest effectiveness (15 and 19, respectively). When compared with QI visits, school-located vaccination was no longer cost-effective ($166 232 per QALY gained), making QI visits the preferred alternative across the worst-case effectiveness scenarios.

**Probabilistic Sensitivity Analysis**

Although the expected cost of the 3 interventions did not overlap, the total QALYs gained from each intervention revealed moderate overlap, with a particularly wide uncertainty range for the effectiveness of school-located vaccination (Fig 1). Relative to no intervention, all 3 interventions were cost-effective in 100% of the scenarios. When comparing interventions with each other at a willingness to pay of $50 000 per QALY gained, school-located vaccination was the preferred option in 83% of scenarios, reminder and recall was preferred in 12%, and QI visits were preferred in the remaining 5% of scenarios.

When considering short- and medium-term benefits, recommendations vary on the basis of a state’s willingness to pay for improved outcomes (Fig 2). When willing to pay at least $13 per additional initiator, $18 per completer, or $1500 per cancer case averted, QI visits were preferable to no intervention in most scenarios. Additional gains from school-located vaccination were not worth the additional costs until a state was willing to pay at least $350 per additional initiator, $420 per additional completer, or $26 000 per cancer case averted (Fig 2, Supplemental Fig 11). Even at higher thresholds, centralized reminder and recall remains preferable in a small percent of scenarios for all outcomes (10%–25%) because it would achieve similar or better outcomes to school-located vaccination at a similar or lower cost (dominant).

**DISCUSSION**

Statewide implementation of QI visits, centralized reminder and recall, and school-located vaccination were each cost-effective at increasing HPV vaccine coverage, relative to no intervention. The increases in HPV vaccination rates after a one-time implementation of these interventions led to a meaningful reduction in HPV cancers over 50 years. When compared with the status quo, all 3 interventions were well below standard cost-effectiveness thresholds in the United States, suggesting these interventions are a high-value use of state prevention resources.

If choosing among the 3 interventions, school-located vaccination is generally preferred because it has the largest impact and is cost-effective relative to alternatives. Policy makers, however, should interpret these findings with some caution because school-located vaccination may fail to be cost-effective or, in some cases, may be dominated, when gains are on the lower end of observed effectiveness. Finally, when considering shorter-term outcomes, QI visits are preferred to no intervention, even at low willingness-to-pay thresholds ($13 per initiator or $1500 per cancer averted), whereas school-located vaccination was only likely to be preferable when states were willing to pay at least $350 per individual initiating HPV vaccine or $26 000 per cancer case averted.

The effectiveness and cost-effectiveness of vaccine interventions have been studied extensively, but evidence suggests HPV vaccination rates may be harder to influence via policy or programmatic intervention compared with other vaccines, perhaps because of patient and provider hesitancy. Previous studies have revealed, for example, that reminder and recall interventions have an estimated median effect of 7 percentage points across other adolescent vaccines but an increase of only a 2 to 6 percentage points for HPV vaccination. Consistent with this, we find the cost per vaccine initiator is generally higher than what has been reported for other adolescent vaccines. However, when linking these vaccination gains to long-term outcomes, we find cost per QALY gained is even lower for HPV vaccination than for other vaccine-based interventions likely because of the relatively high population burden of HPV.

In our study, we examine HPV interventions from the perspective of a hypothetical US state, assuming demographics, disease burden, and vaccine uptake reflective of the United States as a whole. There is considerable variation across US states in HPV vaccine uptake, with lower initiation in states with a higher HPV cancer burden. Although our analysis presents cost-effectiveness across a range of intervention outcomes, the underlying characteristics of states could also influence the cost-effectiveness of these interventions, with states at a higher burden of HPV disease or lower HPV vaccination rates potentially seeing an even greater benefit from these interventions.

Our findings should be interpreted in light of the limitations of existing
intervention evidence, model simplifications, and project scope. First, we used the costs and reach associated with previous implementation of each intervention, which may vary by setting and may change at scale in ways we cannot capture here. States weighing intervention options would additionally need to consider contextual details of program implementation: for example, buy-in of school districts or providers as well as quality and completeness of immunization information systems, which could have an impact on program effectiveness. Secondly, we made several simplifications when modeling HPV infection. Notably, we only consider heterosexual transmission of HPV, a simplification made in nearly all models of HPV infection but one that may nonetheless obscure nuances of transmission patterns and populations with high rates of HPV cancers. We also note our model structure did not allow for the consideration of co-occurring infections. Although we retained the highest risk infections when multiple exposures occurred, we could not model an additive or multiplicative effect of concurrent infections. Our model estimated the intervention benefits specific to HPV vaccination and HPV cancers from the perspective of a state agency. We did not include vaccine cost, nor did we include cost savings associated with future cancers because states are unlikely to cover these costs directly. We compared data on 3 interventions with sufficient data on both intervention cost and effectiveness. Additional evidence on other interventions, including multilevel interventions, is needed.

Our analysis provides a rare comparison of cancer control interventions from a state perspective and presents decision-makers with evidence on cost-effectiveness for both short- and long-term outcomes. In future work, researchers may also consider that each intervention has the potential to improve receipt of other adolescent vaccines in addition to the HPV vaccine and that the HPV vaccine also prevents genital warts, benefits that would improve cost-effectiveness estimations.

CONCLUSIONS
Scaling up interventions to increase HPV vaccination could prevent
thousands of cancers nationally over the next 50 years, providing a high-value use of state prevention funding. Although most states support efforts to increase HPV vaccine uptake, they are of varying quality and intensity. State health departments should strengthen and scale-up existing QI visit programs because they have a high benefit relative to their cost. In addition, policy makers and advocates should consider devoting resources to more intensive interventions, including reminder and recall or school-located vaccination, which could prevent thousands of HPV cancers in the United States in the coming decades.

**REFERENCES**


**ABBREVIATIONS**

CDC: Centers for Disease Control and Prevention
HPV: human papillomavirus
ICER: incremental cost-effectiveness ratio
QALY: quality-adjusted life-year
QI: quality improvement

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