IMPORTANCE In addition to illness, the COVID-19 pandemic has led to historic educational disruptions. In March 2021, the federal government allocated $10 billion for COVID-19 testing in US schools.

OBJECTIVE Costs and benefits of COVID-19 testing strategies were evaluated in the context of full-time, in-person kindergarten through eighth grade (K-8) education at different community incidence levels.

DESIGN, SETTING, AND PARTICIPANTS An updated version of a previously published agent-based network model was used to simulate transmission in elementary and middle school communities in the United States. Assuming dominance of the delta SARS-CoV-2 variant, the model simulated an elementary school (638 students in grades K-5, 60 staff) and middle school (460 students grades 6-8, 51 staff).

EXPOSURES Multiple strategies for testing students and faculty/staff, including expanded diagnostic testing (test to stay) designed to avoid symptom-based isolation and contact quarantine, screening (routinely testing asymptomatic individuals to identify infections and contain transmission), and surveillance (testing a random sample of students to identify undetected transmission and trigger additional investigation or interventions).

MAIN OUTCOMES AND MEASURES Projections included 30-day cumulative incidence of SARS-CoV-2 infection, proportion of cases detected, proportion of planned and unplanned days out of school, cost of testing programs, and childcare costs associated with different strategies. For screening policies, the cost per SARS-CoV-2 infection averted in students and staff was estimated, and for surveillance, the probability of correctly or falsely triggering an outbreak response was estimated at different incidence and attack rates.

RESULTS Compared with quarantine policies, test-to-stay policies are associated with similar model-projected transmission, with a mean of less than 0.25 student days per month of quarantine or isolation. Weekly universal screening is associated with approximately 50% less in-school transmission at one-seventh to one-half the societal cost of hybrid or remote schooling. The cost per infection averted in students and staff by weekly screening is lowest for schools with less vaccination, fewer other mitigation measures, and higher levels of community transmission. In settings where local student incidence is unknown or rapidly changing, surveillance testing may detect moderate to large in-school outbreaks with fewer resources compared with schoolwide screening.

CONCLUSIONS AND RELEVANCE In this modeling study of a simulated population of primary school students and simulated transmission of COVID-19, test-to-stay policies and/or screening tests facilitated consistent in-person school attendance with low transmission risk across a range of community incidence. Surveillance was a useful reduced-cost option for detecting outbreaks and identifying school environments that would benefit from increased mitigation.
In kindergarten through 12th grade education, COVID-19 has posed risks to student, teacher, and family health; school operations; and local communities. As of May 2021, about a third of US students were not offered the option of full-time in-person attendance,\(^1\) and virtual and hybrid models imposed substantial burdens during the 2020-2021 school year.\(^2\)-\(^8\) Districts are seeking to maintain safe in-person education for the 2021-2022 school year, despite high transmissibility of newer variants, record hospitalizations among children during the latter half of 2021,\(^9\) and the potential for seasonal increases in transmission.\(^10\)-\(^15\)

Frequent, widespread SARS-CoV-2 testing is now a viable option,\(^14\),\(^15\) and the federal government has allocated $10 billion for diagnostic and screening tests in US schools.\(^16\) A key question is how to best allocate this funding to maximize in-person educational time while both controlling COVID-19 transmission and managing financial and operational costs. Centers for Disease Control and Prevention (CDC) guidelines for school reopening divide testing into 3 categories.\(^17\) Diagnostic testing targets individuals showing symptoms of COVID-19 as well as close contacts of someone with diagnosed infection. Screening entails routine asymptomatic testing of the full school population to identify active cases and prevent onward transmission. By contrast, surveillance testing involves sampling a fraction of the population to identify potential outbreaks and trigger a public health response (eg, schoolwide screening or classroom closures). Schools require guidance on how to best allocate resources toward different testing objectives.

Previous modeling analyses have projected transmission-related outcomes associated with school attendance under a variety of mitigation measures but did not compare different testing strategies or explore their monetary or operational costs.\(^18\)-\(^21\) In this article, we address several questions regarding the role of testing in educational settings: first, to what extent can different testing strategies limit school-associated transmission of SARS-CoV-2 while sustaining in-person learning? How frequent are quarantines arising from different strategies? and, what extent can testing of contacts avert days out of school? How do testing costs compare with the financial costs associated with school absences or closures? How might these outcomes vary depending on local transmission risk? We focus on elementary and middle schools because of higher child-care costs and later vaccine rollout for these groups.\(^22\) We use an agent-based simulation of COVID-19 transmission to compare outcomes associated with different testing strategies, with a particular focus on infections, in-person educational days, and costs.

Methods

This study was deemed not human subjects research by the Mass General Brigham institutional review board (2021P002876). Reporting conforms to the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) guidance.\(^23\)

Key Points

**Question** What are the costs and benefits of COVID-19 testing in primary schools (students in kindergarten through eighth grade)?

**Findings** In this decision analytic model of COVID-19 transmission in simulated US elementary and middle schools, test-to-stay strategies were associated with reduced quarantine time but minimal increases in transmission across all levels of community incidence. Compared with no testing, weekly screening was associated with substantial reductions to in-school transmission when community incidence was high and had lower societal cost than remote instruction, while an adaptive surveillance strategy offered a more efficient option to detect outbreaks when local incidence was lower or poorly characterized.

**Meaning** With federal funding available, schools should use COVID-19 testing to facilitate in-person education, adapting their testing strategy to changes in local COVID-19 risk.

We used a previously validated agent-based simulation model (ie, a model that explicitly simulates individuals and their interactions) to estimate the effects of different testing strategies in elementary and middle schools in the United States (eMethods and eFigure 1 in the Supplement).\(^18\) When individuals interacted with an agent (ie, person) infected with SARS-CoV-2, transmission risk was proportional to duration and intensity of exposure. In schools, individuals had sustained daily contact with a classroom cohort as well as additional interactions with other members of the school community. Outside of schools, in addition to an exogenous community infection risk, individuals interacted with household members, and each day that students did not attend school, families mixed with another randomly chosen family to reflect learning pods or social interactions.

The model drew stochastic outcomes assuming an average latent period of 3 days before the onset of infectiousness, 2 days of presymptomatic transmission if symptoms develop,\(^24\),\(^25\) total infectious time of 5 days,\(^26\)-\(^29\) and overdispersion of infectivity in adolescents and adults\(^26\),\(^30\) (eTable 1 in the Supplement). We assumed that adults and adolescents with fully asymptomatic disease transmit COVID-19 at half the rate of those with any symptoms.\(^31\) In the absence of vaccination, children younger than 10 years were half as susceptible and half as infectious as asymptomatic adolescents and adults.\(^32\)-\(^36\)

We modeled circulation of the delta variant, assuming twice the transmissibility of wild-type virus,\(^37\),\(^38\) and, except in a sensitivity analysis, we assumed use of other mitigation measures (eg, masking and ventilation). We further assumed that 90% of teachers and staff and 50% of middle school students were vaccinated with an 80% efficacious vaccine.\(^39\)-\(^41\)

In the eMethods in the Supplement and previous work,\(^18\) we describe additional details of model structure, assumptions, and data sources.

Testing Strategies

**Scenarios Without Testing**

We first modeled 3 scenarios without school-based testing: (I) 5-day in-person attendance (the base case and the schedule...
assumed for all testing scenarios), (2) a hybrid model in which half of each class attends school on Monday/Tuesday and the other half on Thursday/Friday, and (3) fully remote learning. In these scenarios, we assumed that individuals with clinically identifiable symptoms isolated and underwent testing outside of school on the day symptoms appeared, that they received results within 48 hours of symptom onset, and that the classroom cohort of a diagnosed COVID-19 case quarantined for 10 days.42

Diagnostic Testing
The test-to-stay strategy altered both how the school managed the asymptomatic contacts of diagnosed COVID-19 cases and how students and staff with symptoms of potential COVID-19 were managed. After exposure to a confirmed case, rather than quarantining, contacts remained in school and received a rapid test each school day for 1 week, isolating only if they tested positive. (This resembles the Test and Stay program used in Massachusetts and elsewhere.43,44) In addition, individuals with symptoms of possible COVID-19 took a rapid test each day they had symptoms, isolating only after testing positive. We assumed 80% test sensitivity during the infectious period, and 100% specificity following a second confirmatory test.55,46 We present both quarantine and test-to-stay versions of each of the 5-day in-person scenarios modeled.

Screening and Surveillance
Screening entailed weekly polymerase chain reaction (PCR) screening (on Mondays) of all students and teachers, with 90% coverage, 90% sensitivity during infectiousness, and a 24-hour test turnaround time. Surveillance entailed random weekly PCR testing (90% sensitivity) of 10% to 20% of the school population. Because of the small proportion of the school tested, if 1 or more cases were detected during surveillance, 90% of the school was screened the following day, including vaccinated individuals, and if further cases were found, the school continued weekly schoolwide screening (90% coverage) rather than surveillance for the remainder of the month. (We discuss considerations for threshold selection further in the eMethods in the Supplement.)

Based on recent CDC guidance,13 we assumed that vaccinated individuals do not quarantine, but given recommendations to test vaccinated contacts,12 we included them in test-to-stay measures and schoolwide screening. To maximize power, surveillance sampled only unvaccinated individuals.

Costs
We based screening and surveillance costs on pooled PCR testing of 8 specimens (eMethods in the Supplement). Costs of PCR testing were estimated at $40 per assay (eTable 1 in the Supplement). Rapid testing for the test-to-stay scenario cost $6 per assay. For both scenarios, we assume an $8 per-person cost of labor and supplies for nasal swab collection. In a sensitivity analysis, we also considered rapid testing with confirmatory PCR for screening and surveillance.

In comparing the costs associated with remote learning and the costs of testing, we took a modified societal perspective that focused on childcare or parent productivity costs (eMethods and eTable 1 in the Supplement); to be conservative with respect to the benefits of testing programs, we did not include educational and other student costs (which are likely to accrue but difficult to estimate) nor the health care–related costs of COVID-19. For remote and hybrid education for all students and for middle school quarantine/isolation, we estimated the cost of a day of remote instruction based on the average cost of group childcare (eTable 1 in the Supplement). For unplanned days that elementary students stayed at home for quarantine/isolation, we estimated costs based on the average childcare worker’s wages over a 7-hour day to account for the higher costs of last-minute scheduling or inability to use group childcare (eTable 1 in the Supplement).47 Although parents may choose to supervise remote learning at home, we assumed that the average productivity loss of supervising at-home learning was comparable with childcare costs.

Outcome Estimation, Reporting, and Sensitivity Analysis
For each scenario, we ran the model 1000 times for 30 days each (with no temporal discounting) and estimated the following outcomes over a 30-day period: average cumulative true incidence of SARS-CoV-2 infection among staff and students, cumulative cases detected, detection fraction (the ratio between cases detected and true infections), and proportion of weekdays spent at home (for unplanned quarantine/isolation or for planned days at home dictated by the virtual/hybrid schedule). Sensitivity analyses for multiple parameters evaluated uncertainty in the infections prevented by different strategies. Model code is publicly available as an R package (implemented in version 4.0.2) at https://github.com/abilinski/BackToSchool2.

Results
Simulated Effects of In-Person School Attendance With COVID-19 Incidence
Figure 1 and eTable 2 in the Supplement show estimated 30-day incidence, case detection, and school attendance outcomes in different testing scenarios among 638 students and 60 staff in a simulated elementary school with no student vaccination or 460 students and 51 staff in a simulated middle school with 50% vaccine coverage. At the elementary school level, compared with fully remote instruction, 5-day in-person attendance with quarantine was associated with an estimated average of 2.3 additional infections per school per month at a community notification rate of 10 per 100 000 population per day (30% increase) and 9.4 additional infections at 50 community notifications per 100 000/d (25% increase) (Figure 1A). Under the test-to-stay strategy, slightly more transmission occurred; eg, an estimated mean of 11.6 infections rather than 9.4 infections over the remote instruction baseline at 50 community notifications per 100 000/d.

In the middle school with 50% vaccination, 5-day attendance with quarantine was associated with 4.9 additional infections per school per month on average (45% increase) at 10 community notifications per 100 000/d and 17.9 infections (33% increase) at 50 community notifications per 100 000/d.
Results are shown over a range of community COVID-19 notification rates for an elementary school of 638 students and a middle school of 460 students. For the infections and diagnoses, the outcomes do not include infections among others in the community that may result from school-associated transmission. The detection fraction as reported in the text reflects the absolute number of diagnosed cases divided by true cumulative incidence. EFigure 14 in the Supplement transforms panels A and E to show the differences between remote schooling and the other scenarios.
(Figure 1E). The test-to-stay strategy was associated with 20.4 infections, rather than 17.9 infections over remote instruction at 50 community notifications per 100 000/d.

**Simulated Effects of Transmission With Weekly Screening and Surveillance**

With weekly screening of all students and teachers, and with isolation of the identified cases and quarantine of their unvaccinated classroom contacts, the incremental increase in transmission associated with school attendance compared with remote learning decreased. In a community with 10 notifications per 100 000/d, when weekly screening was in place, the excess incidence associated with school attendance was an estimated 50% lower (1.1 fewer cases per school per month) in elementary school and 57% lower (2.8 fewer cases) in middle school. A slightly greater estimated proportion of school-associated transmission was prevented by screening at higher community incidence: for example, 71% (8.2 cases) in an elementary school at 50 community notifications per 100 000/d (Figure 1A and E and eTable 2 in the Supplement).

Weekly surveillance testing, at relatively low levels of community incidence (≤25 cases/100 000/d), was associated with a large projected transmission benefit relative to the number of students tested (Figure 1A and E and eTable 2 in the Supplement): for example, a 21% mean reduction in excess transmission with weekly surveillance of 20% of students in an elementary school at 10 community notifications per 100 000/d (ie, about half of the 49% reduction seen with weekly 90% screening); 36% of model runs obtained enough positive results to switch from 20% surveillance to schoolwide screening for the remainder of the month (eFigure 2 in the Supplement). At higher community incidence, surveillance was associated with nearly the same projected transmission benefit as universal screening, but this was attributable to a high probability of converting to universal screening (reaching 98.3% at 50 community notifications/100 000/d) (eFigure 2 in the Supplement).

As in the no-screening scenario, test to stay was associated with a slight reduction in the projected transmission benefits of screening or surveillance in both elementary and middle schools (Figure 1E and eTable 2 in the Supplement).

**Simulated Effects of Case Detection and In-Person Learning Days Lost With Screening and Surveillance**

Screening and surveillance were associated with fewer infections but with a greater number of cases detected (by more than a factor of 2 for weekly screening). Thus, without a test-to-stay policy, the days spent in quarantine or isolation also increased (Figure 1C and G). For example, weekly screening in an elementary school was associated with an estimated average of 1.0 quarantine/isolation days per student per month at 10 community notifications per 100 000/d and 3.9 at 50 community notifications per 100 000/d (Figure 1C). In middle school, quarantine of only unvaccinated students resulted in fewer days of quarantine or isolation per student despite similar incidence (Figure 1F and G).

Test to stay had the benefit of minimal quarantine and isolation, estimated at less than 0.25 days per student per month even in scenarios with high community transmission and maximal case detection through weekly screening.

**Costs**

The testing costs of weekly screening began at an estimated $69 per student per month at low community incidence (Figure 2); as incidence increased, the increased cost of deconvoluting positive pools was partially offset by quarantine-related reductions in the number of tests performed (eFigures 3 and 4 in the Supplement). Above community notification rates of 25 per 100 000/d, surveillance and screening had similar costs because positive surveillance test results regularly triggered schoolwide testing (Figure 2).

Accounting for childcare during quarantine and isolation, the estimated societal costs associated with weekly screening in an elementary school ranged from $109 per student per month at community notification rates of 5 or less per 100 000/d, to $368 per student/mo at a community notification rate of 50 per 100 000/d (eFigures 5 and 6 in the Supplement). A test-to-stay strategy was associated with greater diagnostic costs but lower combined costs of testing plus childcare at all community notification rates (Figure 2). The estimated costs of a rapid antigen screening strategy were similar to those of pooled PCR screening (eFigure 7 in the Supplement).

**Cost per Infection Averted**

In the elementary school, the estimated costs of weekly screening per infection directly averted among students and teachers/staff were less than $16 000 at community notification rates of 25 or more cases per 100 000/d; these increased to $40 000 to $60 000 per infection averted at 10 cases per 100 000/d and more than $300 000 per infection averted at 1 case per 100 000/d. In the middle school, greater risk of transmission offset the comparative inefficiency of screening vaccinated students, resulting in similar costs per infection averted as the elementary school had (Figure 3). Cost per infection averted was similar for rapid antigen screening and lower in a high-transmission or unmasked school setting (eFigures 8 and 9 in the Supplement).

**Sensitivity Analysis**

The estimated number of infections averted by screening, with or without test to stay, was approximately 3 times higher in schools without masking than in schools where screening was added to mask use, in both elementary and middle schools (eFigures 4-5, 9, and 11-12 and eTable 3 in the Supplement). Infections averted by screening were also highly sensitive to vaccine coverage and vaccine efficacy (Figure 4, Figure 5, and eFigures 10-12 and eTable 3 in the Supplement). The estimated number of infections averted was slightly lower if screening occurred later in the week or with a less sensitive test and was less than 25% higher if screening occurred twice weekly in schools with masking or other mitigation measures (Figure 4 and Figure 5).

The transmission increases associated with the test-to-stay strategy were largest in the elementary school if the rapid test had low sensitivity for detecting infectious individuals or...
if the community notification rate was high (Figure 4) and in the middle school if vaccination coverage was low or testing was only offered to unvaccinated individuals (Figure 5). For surveillance, reducing the weekly percentage tested to 10% (vs 20%) was associated with smaller reductions in transmission but still allowed a response to large outbreaks; surveillance was more beneficial with less in-school mitigation or more transmissible variants (eFigure 2 in the Supplement).

**Discussion**

This modeling study of a simulated population of primary school students and simulated transmission of COVID-19 highlights that well-designed COVID-19 testing can help maintain safe, 5-day in-person education despite a highly transmissible (delta) variant. In particular, we underscore the importance of considering multiple dimensions of cost in school reopening plans. While school-based testing increases expenditures, these costs may be offset societally by reducing the burden of COVID-19-related childcare costs currently borne by parents and caregivers and costs associated with lost educational time.

Gains are particularly pronounced for expanded diagnostic testing. We project that test to stay is associated with only minor increases in transmission, even at high community case rates. Such estimates are consistent with a 2021 randomized controlled trial of test-to-stay programs in the United Kingdom, which were layered on top of twice-weekly screening.48 We further estimate that test-to-stay strategies have lower societal costs than quarantine-based strategies and could maintain student absences to less than 0.25 school days per month. Additional benefits of test to stay include situational awareness of in-school transmission that can inform mitigation policies as well as the option to adopt a broad definition of close contact without associated loss of school time.

Our main test-to-stay specification allowed both close contacts and symptomatic individuals to attend school after a negative test. In practice, most schools set more conservative policies for symptomatic students, requiring them to remain home.
for certain significant symptoms (e.g., fever), regardless of etiology, or if they have symptoms strongly indicative of COVID-19 (e.g., loss of taste or smell). This renders our analysis conservative with respect to the simulated effect of test to stay with COVID-19 transmission; in sensitivity analyses, we show that offering test to stay only to contacts maintains most benefits with respect to learning days lost (eFigure 13 in the Supplement).

Likewise, for combined costs of testing plus childcare, we show the strategy of weekly screening with exposed contacts undergoing daily rapid tests to stay at school, which dominates at-home quarantine. For alternative scenarios with rapid tests and/or lower in-school mitigation, see eFigures 8 and 9 in the Supplement.
We also provide information about the benefits and costs of 2 additional testing strategies: screening and surveillance. While previous analyses have documented that weekly screening can help control transmission, this analysis adds the finding that under conservative assumptions, 5-day in-person learning with screening is expected to be cost-saving from a societal perspective, compared with the hybrid or remote models often used in 2020-2021.18,20,49 Cost savings persist across levels of community transmission up to 100 cases per 100,000 population per day, even when improved case detection from the screening program increases the time that students spend in quarantine. In addition, although limited data on implementation of various measures by state or county suggest that schools are likely to implement simpler measures such as masks before they adopt testing, our sensitivity analyses indicate that screening or surveillance could offer the greatest benefit in settings with low uptake of other mitigation measures.

In simulating the effect of testing with transmission, we did not include the downstream infections averted beyond students and staff, the medical costs associated with SARS-CoV-2 infection, or other dimensions of cost (eg, educational). Our estimates of cost per infection averted are therefore likely conservative, and when interpreting them, a school community’s willingness to pay per averted case should consider onward transmission risk. For example, setting the value per statistical life of $8 million,54 communities would be willing to invest $48 000 to avert a downstream infection in an unvaccinated person aged 50 to 64 years and $720 000 per infection averted in those older than 65 years.55 Other important planning inputs might include local hospital capacity and any increased pediatric risks that may be associated with new variants. However, the widespread availability of external fed-
eral funding may render the financial costs of testing less consequential for districts than logistical and practical considerations; smaller districts with fewer resources may require additional support to implement testing programs.\(^1\)^

For districts concerned about in-school transmission but without capacity to perform regular screening, weekly surveillance of 10% to 20% of the school population may offer a middle ground. Surveillance (with conversion to weekly screening when cases are identified) can reduce the risk of large outbreaks and may allow schools to reduce testing costs when local incidence is low. However, surveillance of a small portion of the school population is likely to miss early outbreaks and requires regularly adapting school procedures. Therefore, the benefit of surveillance is largest when local testing is sparse (making it difficult to know how community case notification maps to school incidence), local incidence is rapidly changing, or there is high uncertainty in the school attack rate. Beyond transmission effects, the real-time information provided by either screening or surveillance may have value even at low incidence levels, by providing reassurance to educators and parents.

**Limitations**

There are a number of limitations to this analysis. Like all models, this analysis relies on assumptions about transmission dynamics, test performance, and public health responses, which are uncertain and often in flux. Public health guidance continues to evolve, particularly in terms of defining close contacts in the context of new variants and recommended precautions for vaccinated individuals, which may affect costs and benefits of testing strategies. In addition, our model does not address the operational aspects of specimen collection, laboratory transport, and reporting of results, which some schools have navigated successfully but nevertheless may pose barriers to adoption.\(^1\)^ Nevertheless, this work highlights that flexible, strategic testing can help ensure stable 5-day in-person education throughout the 2021-2022 school year.

**Conclusions**

In this modeling study of transmission of COVID-19 in simulated US elementary and middle schools, screening tests facilitated in-person schooling with limited transmission risk across a range of community incidence, and test-to-stay policies were associated with increased school attendance but little incremental transmission. Surveillance was a useful, reduced-cost option for detecting outbreaks and identifying school environments that could benefit from increased mitigation.

**ARTICLE INFORMATION**

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**Author Contributions:** Drs Bilinski and Kendall had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

**Concept and design:** Bilinski, Ciaramello, Fitzpatrick, Giardina, Salomon, Kendall.

**Acquisition, analysis, or interpretation of data:** All authors.

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Research Original Investigation

SARS-CoV-2 Testing, Screening, and Surveillance Strategies Among Simulated School Populations


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