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Widespread testing, case isolation and contact tracing may allow safe school reopening with continued moderate physical distancing: A modeling analysis of King County, WA data

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A R T I C L E I N F O

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A B S T R A C T

Background: In late March 2020, a “Stay Home, Stay Healthy” order was issued in Washington State in response to the COVID-19 pandemic. On May 1, a 4-phase reopening plan began. We investigated whether adjunctive prevention strategies would allow less restrictive physical distancing to avoid second epidemic waves and secure safe school reopening.

Methods: We developed a mathematical model, stratifying the population by age, infection status and treatment status to project SARS-CoV-2 transmission during and after the reopening period. The model was parameterized with demographic and contact data from King County, WA and calibrated to confirmed cases, deaths and epidemic peak timing. Adjunctive prevention interventions were simulated assuming different levels of pre-COVID physical interactions (pC_PI) restored.

Results: The best model fit estimated ~35% pC_PI under the lockdown which prevented ~17,000 deaths by May 15. Gradually restoring 75% pC_PI for all age groups between May 15-July 15 would have resulted in ~350 daily deaths by early September 2020. Maintaining <45% pC_PI was required with current testing practices to ensure low levels of daily infections and deaths. Increased testing, isolation of symptomatic infections, and contact tracing permitted 60% pC_PI without significant increases in daily deaths before November and allowed opening of schools with <15 daily deaths. Inpatient antiviral treatment was predicted to reduce deaths significantly without lowering cases or hospitalizations.

Conclusions: We predict that widespread testing, contact tracing and case isolation would allow relaxation of physical distancing, as well as opening of schools, without a surge in local cases and deaths.

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Introduction

The current COVID-19 pandemic started in Wuhan China in late December 2019. It rapidly spread across the globe soon thereafter and has disrupted normal life in virtually every country in the world ever since. As of Oct 19, 2020 more than 40 million confirmed cases had been reported around the world resulting in more than 1,100, 000 deaths. (D-19 Dashboard by the) While the scientific community has been is focused its full attention on developing effective treatments and vaccines, physical distancing – in many cases including quarantine of suspected and confirmed cases and contact tracing – has been the only effective prevention approach to reduce local attack rates.

In May, in the United States (US), many local and national governments developed plans to relax lockdowns and restore the sense of normalcy in their communities. These plans sought to delicately balance public health with economic and societal health. Vital societal institutions like workplaces and schools, were deemed worthy of reopening with measures designed to prevent rapid resurgence of infections and deaths. Unfortunately, results from many states where cases are mounting suggest that this process was too abrupt (Coronavirus in the:, 2020). Other countries in Europe and Asia, as well as the Northeastern United States, have demonstrated the possibility of careful, safe reopening, including schools, bars, and restaurants, without a massive surge in cases (Coronavirus in the:, 2020; Birnbaum, 2020; Han, 2020; Zhang et al., 2020). However, in mid-October many European counties, including France, Spain, Netherlands and Belgium are reinstating some restrictive measures after a new wave of cases (ews. Covid: What are, 2020).

Washington State (WA) holds a special place in the history of the COVID epidemic with both the first US case of COVID-19 (Jan 20) and the first death due to COVID-19 (Feb 29) (Holshue et al., 2020). Shortly thereafter, state authorities began imposing travel and gathering restrictions and many local businesses started implementing “work from home” policies. The process culminated with the “Stay Home, Stay Healthy” order of the Governor issued on March 23. (Washington Governor Jay Inslee,) On May 1, a plan for reopening in 4 phases was announced which, if implemented without interruptions would have resumed all public interactions with physical distancing by July 15. (O'Sullivan) This plan was consequently updated multiple times with the majority of WA counties (including King County, home to the Seattle metro area) not progressing beyond phase 2 as of Oct 19 due to ongoing widespread incident infection. (Washington Department of Health,).

Mathematical models have been employed to project the course of COVID-19 outbreaks in different settings and to inform policymaking at the local and national level (Chinazzi et al., 2020; Kissler et al., 2020; Kucharski et al., 2020; Lourenco et al., 2020; Pei & Shaman, 2020; Ferguson et al.). However, models require specific parameterization, depending on the geographic and political context. This procedure unavoidably makes critical assumptions that cannot be informed by local data. For instance, wide parameter ranges associated with asymptomatic infections (both prevalence and infectiousness) help fit models to cumulative case and death counts. However, varying these parameter values leads to significantly different estimates of the seroprevalence in the population at the end of the outbreak (final size), an essential prediction for those planning reopening strategies. The large uncertainties related to asymptomatic infections is recognized by Centers of Disease Control (CDC) and currently incorporated into the COVID-19 pandemic scenarios designed to help inform ongoing modeling studies (Centers for Disease Contr, 2019).

While the majority of early studies focused on estimating the effects of physical distancing and projecting the burden on healthcare systems during the initial outbreak, the focus has switched to evaluation of potential reopening scenarios in different settings. In this study, we use a mathematical model, specifically calibrated to King County, to project SARS-CoV-2 transmission during and after various reopening scenarios. We quantitatively investigate adjunctive interventions such as early test and isolate, early test and treat, and post exposure prophylaxis. Our primary goal is to understand how adjunctive interventions and physical distancing, may be used to help society return to “normalcy” and endure potential subsequent epidemic waves. We also address the critical question of school reopening in fall 2020 and its potential impact on the epidemic situation in King County.

Methods

Model description

We use a deterministic compartment model to describe epidemic dynamics. Our model (Fig. 1 and Fig. S1) stratifies the population by age (0–19 years, 20–49 years, 50–69 years, and 70+ years), infection status (susceptible (S), exposed non-infectious (E), asymptomatic (A), pre-symptomatic (P), symptomatic (I), recovered (R)) and treatment status (undiagnosed, diagnosed (D), hospitalized (H)). The model is described by a set of differential equations for each age group ($i = 1$ for age 0–19 years, $i = 2$ for age 20–49 years, $i = 3$ for age 50–69 years, and $i = 4$ for age 70+ years):

$$\frac{dS_i}{dt} = -\lambda_i S_i$$

$$\frac{dE_i}{dt} = \lambda_i S_i - \gamma_1 E_i$$

$$\frac{dA_i}{dt} = (1-p_i)\gamma_1 E_i - (r_1 + d_A)A_i$$

$$\frac{dD_{A,i}}{dt} = d_A A_i - r_1 D_{A,i}$$

$$\frac{dP_i}{dt} = p_i \gamma_1 E_i - (\gamma_2 + d_P)P_i$$

$$\frac{dI_i}{dt} = \gamma_2 P_i - d_i(t) I_i - h_i^* I_i - r_i^* I_i$$

$$\frac{dD_i}{dt} = d_P P_i + d_i(t) I_i - h_i^* D_i - r_i^* D_i$$

$$\frac{dH_i}{dt} = h_i^* I_i + h_i^* D_i - r_3 H_i - f_i H_i$$

$$\frac{dF_i}{dt} = f_i H_i$$

$$\frac{dR_i}{dt} = r_1 A_i + r_1 D_{A,i} + r_i^* I_i + r_i^* D_i + r_3 H_i$$

where p_i is the proportion of the infections which become symptomatic by age, γ_1 and γ_2 are progression rates from exposed (E) to infectious non-symptomatic (A and P) and symptomatic (I) classes, h_i^* are hospitalization rate among diagnosed by age, r_{1-3} is the recovery rate of the asymptomatic, mild symptomatic and hospitalized cases , r_i^* is the recovery rate of the diagnosed symptomatic cases by age and f_i is fatality rate among hospitalized by age.

The force of infection ($\boldsymbol{\lambda_i}$), representing the risk of the susceptible individuals in age group i to acquire infection (transition from susceptible to exposed class), depends on the contact matrix c_{ij} (proportion of contacts with each age group), infection

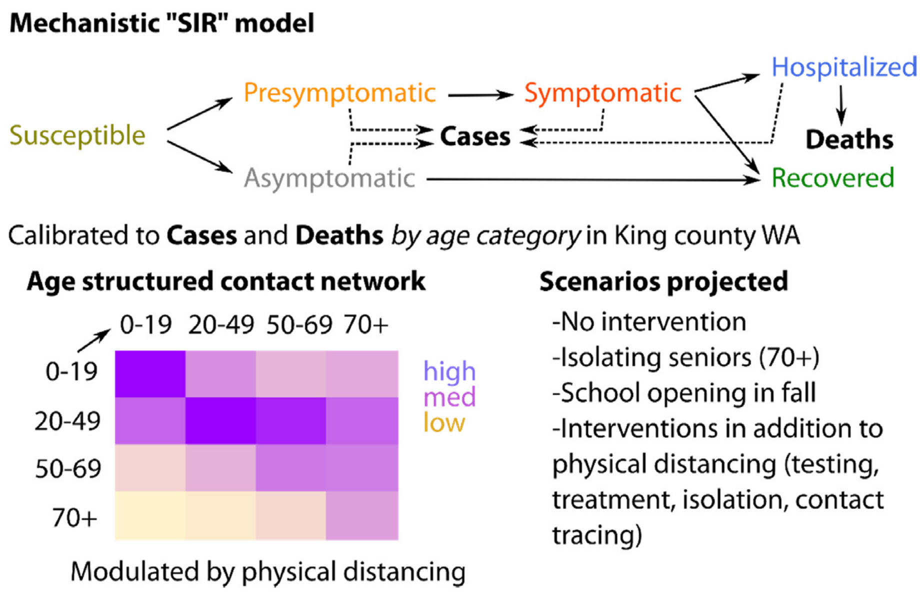

Fig. 1. Simplified diagram of the modeling analysis.

and treatment status (asymptomatic, pre-symptomatic, symptomatic, diagnosed and hospitalized cases) of the infected contacts, and the time-dependent reduction of transmission due to physical distancing measures (work from home, closing non-essential businesses, banning large gathering, etc.) applied in the area. It is given by:

$$\lambda_i = \sum_{j=1}^{4} c_{ij}\,(1 - R_{sd}(t))\left(\beta_a A_j + \beta_p P_j + \beta_s I_j + \beta_d D_j + \beta_{da} DA_j\right)\Big/N_j + c_{ij}\beta_h H_j\Big/N_j$$

where β_a, β_p, β_s, β_d, β_h are the transmission rates from contacts with asymptomatic, pre-symptomatic, symptomatic, diagnosed and hospitalized infections before the start of COVID mitigation measures at $t = \delta_1$, N_i is the population size by age. The reduction of transmission due to physical distancing R_{sd} (t) is applied uniformly to all age groups and scaled up linearly from 0 to R_{sd}^{max} by the start of the lockdown (between $t = \delta_1$ and $t = \delta_2$). Later it is decreased for all age groups (in the baseline scenario) or only age groups 1–3 (in the Protect Seniors scenario) from R_{sd}^{max} to some pre-defined value during reopening period (between $t = \delta_3$ and $t = \delta_4$), It is further reduced to 20% for the youngest group at school reopening (after $t = \delta_5$).

A full description of the model can be found in the Supplement.

Parameterization, calibration and validation

The model is parameterized with local demographic and contact data from King County, WA and calibrated to local case and mortality data using transmission parameters ranges informed from published sources (Fig. 2). (Ferguson et al.; Public Health - Seattle &, 2020; nline Portal for, 2020; Ferretti et al., 2020) We used a genetic algorithm (NSGA-II multivariate optimization algorithm in the mco R package) and Monte Carlo filtering to select the best fit and 100 parameter sets which reproduce the data within pre-specified tolerances.

We validate our population model by predicting independent data not used for calibration (cases and deaths after the calibration period, hospitalizations), and comparison to expert predictions and independent region-specific modeling projections (Bedford, 2020; Thakkar & Famulare, 2020). More details on the calibration scheme are in the Supplement.

Reopening plans and intervention scenarios

Given the impact of the COVID epidemic on daily life and recommendations from the CDC aiming to prevent new infections with continued physical distancing, hand washing, and masking, it is reasonable to expect that even after a fully implemented reopening plan, transmission reduction measures will remain in place. We explore reopening scenarios assuming gradually restoration of up to 75% of the pre-COVID physical interactions (pC_PI) for all age groups between May 15-July 15 (see Fig. 3) with baseline scenario assuming 60% pC_PI. We also simulate an alternative scenario (Protect seniors) in which the oldest age group (70+ year-old) remain under strict physical distancing with pC-PI at lockdown levels. Finally, we evaluate the impact of school reopening on September 1 under baseline or “Protect seniors” reopening plans.

Several adjunctive prevention interventions listed in Table 1 were simulated assuming different levels of pC_PI restored during reopening. These include non-pharmaceutical interventions which are currently available such as rapid targeted or mass testing, isolation and contact tracing; as well as hypothetical treatment options for exposed individuals (post-exposure prophylaxis), mild cases (outpatient treatment) and severe cases (inpatient treatment). We assume that: i) enhanced early testing will increase the daily probability that symptomatic individuals get tested to 10% in the main scenario which will ensure that more than 50% of the symptomatic infections (more than 40% of all infections) are diagnosed. Estimates based on serological data from late March suggest that less than 10% of all infections are reported (Havers et al., 2020). Even more aggressive programs of early testing assuming symptomatic diagnostic rates up to 50% daily are also evaluated; ii) contact tracing allows for testing 5% of the asymptomatic and pre-symptomatic cases in the main scenario assuming that 50% of the contacts of the diagnosed cases will be traced; iii) random mass testing will add 0.5 percentage points to the diagnostic rates among asymptomatic, pre-symptomatic and symptomatic cases which implies that at least 10,000 random tests are performed daily. Mass testing of up to 4.5% of the total population was explored which at the upper bound would mean that the entire population is tested monthly. We also assume that imperfect isolation will halve the transmission from diagnosed cases from its lowest level during lockdown while effective early treatment will halve it again and reduce hospitalization rates among diagnosed by 50%. Finally, effective inpatient treatment is assumed to improve the recovery rate by 20% and reduce mortality rates by 50% similar to reported data from a clinical trial of remdesivir (Beigel, 2020).

Metrics of interest

We evaluate the course of the epidemic and effectiveness of interventions by tracking several key metrics including cumulative and daily number of deaths, number of new and current hospitalizations and effective reproductive number (Rt). Point estimates based on the “best fit” (annotated by BF) are presented in addition to 80% uncertainty interval (UI) based on 100 acceptable trajectories simulated per scenario.

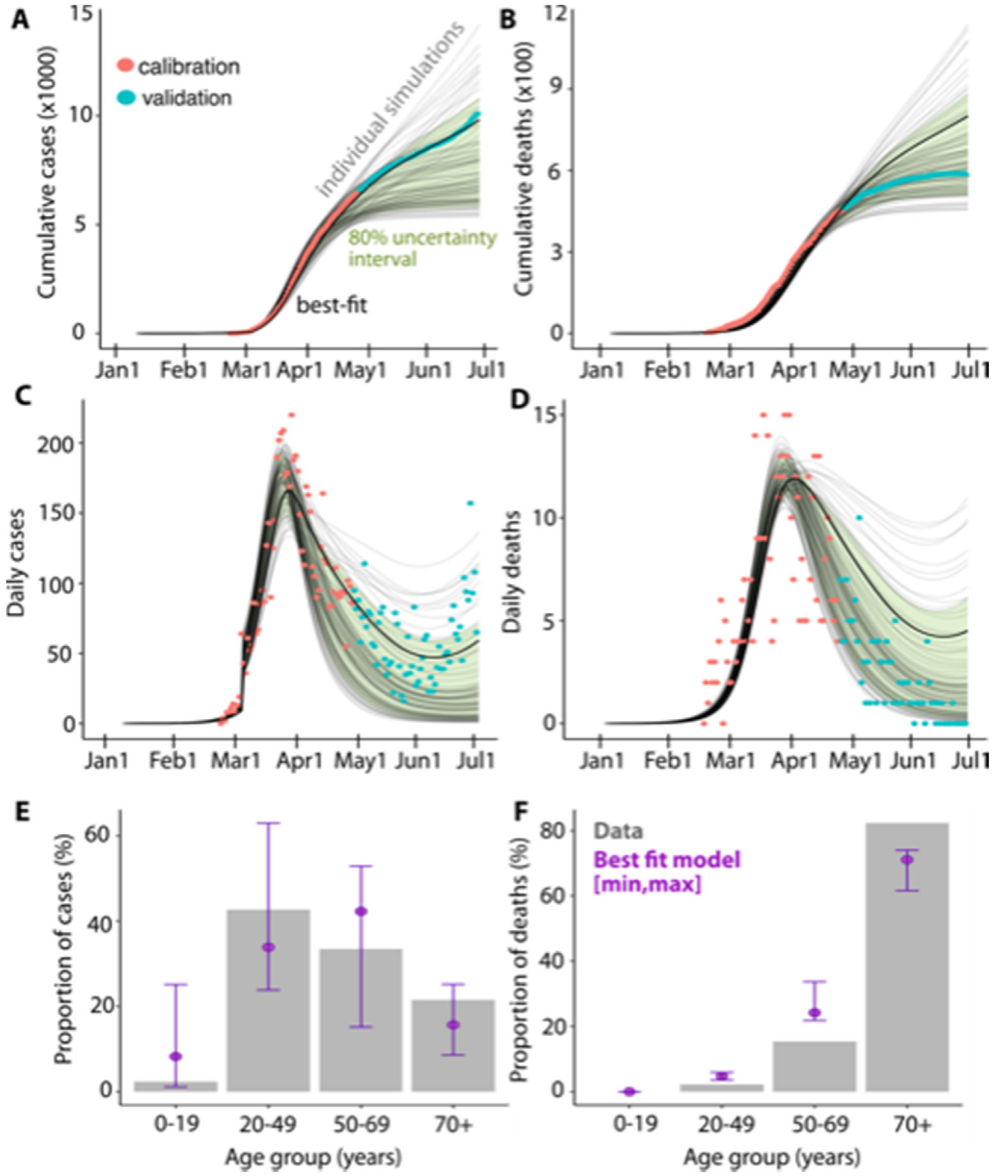

Fig. 2. Model calibration and validation. Model fitting to 5 sources of King County data assuming gradual scale up of social distancing between March 8 and March 29: A)-B) Cumulative and daily cases and deaths. Red dots represent data up to April 30, thick lines represent the best model fit while other acceptable trajectories are shown in grey. Green bands show 80% range from acceptable trajectories. C)-D) Age distributions of cases and deaths as of April 15. Bars represent data, green dots and ranges represent the best fit and other acceptable trajectories included in the analysis. Reopening plan is implemented between May 15 and July 15 by restoring 60% of pC_PI in all age groups.

Sensitivity analysis

Some of the key unresolved uncertainties related to SARS-CoV-2 transmission concern the prevalence and infectiousness of the asymptomatic infections. Our literature review has shown that proportion of infections which progress without symptoms is estimated from 10% to 70% by different empirical and modeling studies (Byambasuren, 2020; Poletti et al., 2020; Mizumoto et al., 2020; Lavezzo et al., 1038). Asymptomatic transmission was qualified as “very rare” by one WHO official who later clarified that “the actual rates of asymptomatic transmission aren’t yet known (Howard, 2020). Recently published review estimated that 20% of people who become infected with SARS CoV-2 remain asymptomatic throughout infection with a prediction interval of 3%–67% based on the results from 79 studies (Buitrago-Garcia et al., 2020). Previous studies demonstrated that asymptomatic infections have periods of viral shedding allowing for transmission. However, these individuals often have lower viral loads, so it is unclear if transmissibility is identical to symptomatic shedders (Lee, 2020; Zhou

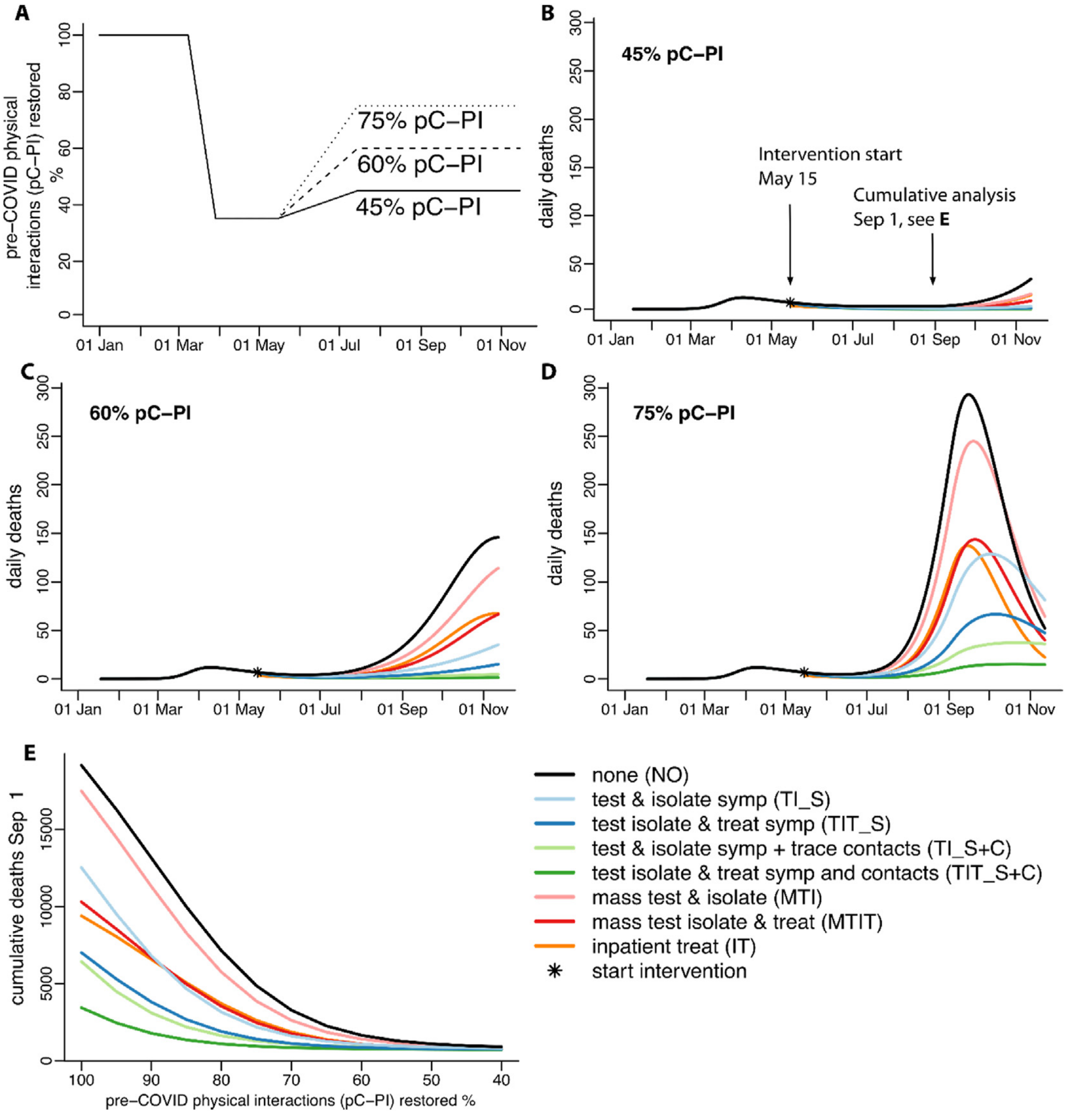

Fig. 3. Model best fit p**rojections under different intervention scenarios. A)** Time variation of the physical interactions for specific levels of pC_PI restored B-D) Daily deaths for specific levels of pC_PI restored; E) Cumulative deaths from the beginning of the outbreak to Sep 1. Reopening plan is implemented from May 15 to July 15 by restoring different levels of pC_PI as shown in the upper left corner of each panel.

et al., 2020). More importantly, very few infected people, symptomatic or asymptomatic, have been sampled during the earliest phase of infection when contagiousness is likely to be highest. In our main scenario we assume that 20% of the infections are asymptomatic and that they are as infectious as the symptomatic infections (100% relative infectivity). In sensitivity analyses we vary the prevalence of asymptomatic infections between 10% and 50% and relative infectivity of asymptomatic infections between 50% and 100% in unison with the CDC recommendations (Centers for Disease Contr, 2019).

Results

Effectiveness of physical distancing during the early King County outbreak. Our best fit (BF) suggests that physical distancing reduced SARS-CoV-2 transmission by 65% when fully implemented in King County with an uncertainty range (UI) of 54%–83% from the sampled parameter sets.

Had transmission not been reduced by physical distancing, we estimate that by May 15, more than three quarters of King County residents would have been infected with 17300 additional excess deaths (BF). Our model suggests that the virus was likely introduced into King County around Jan 15 and projects approximately 2% (BF, range 1–2% UI) cumulative incidence among the population in King County by May 15 including those infected and recovered with only 21% (BF, range 18–34% UI) of the symptomatic infections diagnosed. We estimated that the effective reproductive number (Rt) decreased from 2.43 (BF,

Table 1
Reopening and intervention scenarios.

Scenario (NAME)	Simulated effects in the model
Reopening plans:	•Gradually increase physical interactions to predefined post-reopening levels over 2-month period (May 15-July 15) for all age groups assuming that diagnostic rates remain unchanged.
No intervention, uniform expansion of physical contacts across age groups (**Baseline**)	
Extended physical distancing for seniors (**Protect seniors**)	•Gradually increase physical interactions to predefined post-reopening levels over 2-month period (May 15-July 15) for age groups 1,2 and 3 only. All diagnostic rates remain unchanged.
Schools reopening in fall (**Reopen schools**)	•Additional increase of the physical interactions of the youngest group to 80% of the pre-COVID on Sept.1
Interventions:	•Reduce mortality rate among hospitalized by 50%
Effective inpatient treatment (**IT**)	•Improve recovery rate among hospitalized by 20%
Rapid test and isolate symptomatic (**TI_S**)	•Increase diagnostic rates among symptomatic to 10% daily (Rates up to 50% explored) •Reduce transmission from diagnosed by 50%
Rapid test, isolate and treat symptomatic (**TIT_S**)	•Increase diagnostic rates among symptomatic to 10% daily (Rates up to 50% explored) •Reduce transmission from diagnosed by 75% •Reduce hospitalization rate from diagnosed by 50%
Rapid test and isolate symptomatic + trace, test and isolate contacts (**TI_S + C**)	•Increase diagnostic rates among symptomatic to 10% daily (Rates up to 50% explored) •Reduce transmission from diagnosed by 50% •Increases diagnostic rates among asymptomatic and pre-symptomatic to 5% daily
Rapid test, isolate and treat symptomatic + trace, test and treat contacts (**TIT_S + C**)	•Increase diagnostic rates among symptomatic to 10% daily (Rates up to 50% explored) •Reduce transmission from diagnosed by 75% •Reduce hospitalization rate from diagnosed by 50% •Increases diagnostic rates among asymptomatic and pre-symptomatic to 5% daily
Mass testing and isolate (**MTI**)	•Increase diagnostic rates among asymptomatic, pre-symptomatic and symptomatic by 0.5 percentage points daily (Increase up to 4.5 percentage points explored) •Reduce transmission from diagnosed by 50%
Mass testing, isolate and treat (**MTIT**)	•Increase diagnostic rates among asymptomatic, pre-symptomatic and symptomatic by 0.5% percentage points daily (Increase up to 4.5 percentage points explored) •Reduce transmission from diagnosed by 75% •Reduce hospitalization rate from diagnosed by 50%

range 2.19–2.55 UI) at the start of the epidemic to 0.81 (BF, range 0.40–0.93 UI) by the end of April and remained below 1 at the time when reopening started for all parameterizations.

Projections of reopening plans with no added interventions. Degree of restoration of pre-contact physical interactions (Fig. 3A) is the key determinant of severity of local outbreaks in the absence of adjunctive interventions. Our model suggests that daily deaths and cases would remain low without additional interventions if physical interaction is kept at 45% of the pre-COVID level even without additional interventions (Fig. 3B).

With gradual progression towards 60% pC-PI, cases are predicted to surge starting in mid-July, which is consistent with current observations (Fig. 2B). At 60% pC-PI, the cumulative number of deaths in the absence of intervention is expected to be ~2000 by November 1 (Fig. 4A) with a peak of deaths per day far exceeding the peak of 15 deaths per day observed in April (Figs. 3C and 4B). In half of the simulations, the number of current COVID-19 hospitalizations is expected to surpass 1700 (Table S5) exceeding more than three times the state mandated maximum of 10% occupancy. We predict that the threshold of 15 deaths per day would likely be met in October but possibly as early as August under these conditions (Fig. 4C, black).

A peak of ~300 daily deaths per day in September is projected for 75% pC_PI (Fig. 3D). Therefore, resumption of lockdown levels of physical distancing would have been necessary in mid to late July under these conditions.

Predicted failure of all adjunctive interventions with restoration of 75% pre-contact physical interactions. With restoration of 75% of pC-PI, only the implementation of the most comprehensive strategy (TIT_S + C) including early testing, contact tracing, isolation and COVID-19 treatment of cases and contacts (Fig. 3D, dark green) may prevent unacceptable levels of excess deaths with notable improvements relative to testing and treatment of symptomatic cases (TIT_S) and testing and tracing (TI_S + C) in the absence of treatment (Fig. 3D, dark blue and light green). However, even in this scenario the number of current COVID-19 hospitalizations is expected to surpass 2000 (Fig. S4) by Nov. 1 which corresponds to almost 40% occupancy. Therefore, if 75% pC_PI is restored, adjunctive strategies are likely to be insufficient without reimplementing greater restrictions of physical interactions.

Adjunctive interventions could be effective if only 60% pre-COVID physical interactions are restored. A slowly escalating number of daily deaths is predicted in mid-September if test and isolate strategy (TI_S) is added to 60% pC_PI with ~35 deaths per day (BF) by November (Fig. 3C, light blue). with more than 75% of the acceptable parameterizations predicting fewer than 10 deaths per day under the baseline reopening plan (Fig. 4B). Adding contact tracing (TI_S + C) will likely prevent 300–600 deaths by November 1 with no more than 7 deaths (BF, UI range 2–8) expected daily (Table S5).

Adding treatment to isolated cases and contacts (TIT_S + C) would reduce mortality and hospitalizations by 25% (BF and UI) compared to TI_S + C (Fig. 4A, Table S5) with daily deaths remaining below 8 by November 1. Current COVID-19 hospitalizations are expected to remain significantly lower than state mandated goal of 10% occupancy (Fig. S5, dark green).

Inpatient treatment is unlikely to prevent virus resurgence even at 60% pC-PI with 65 daily deaths (BF) expected at the peak by November 1 in the baseline scenario and the threshold of 15 deaths being reached by early October (UI range, mid-

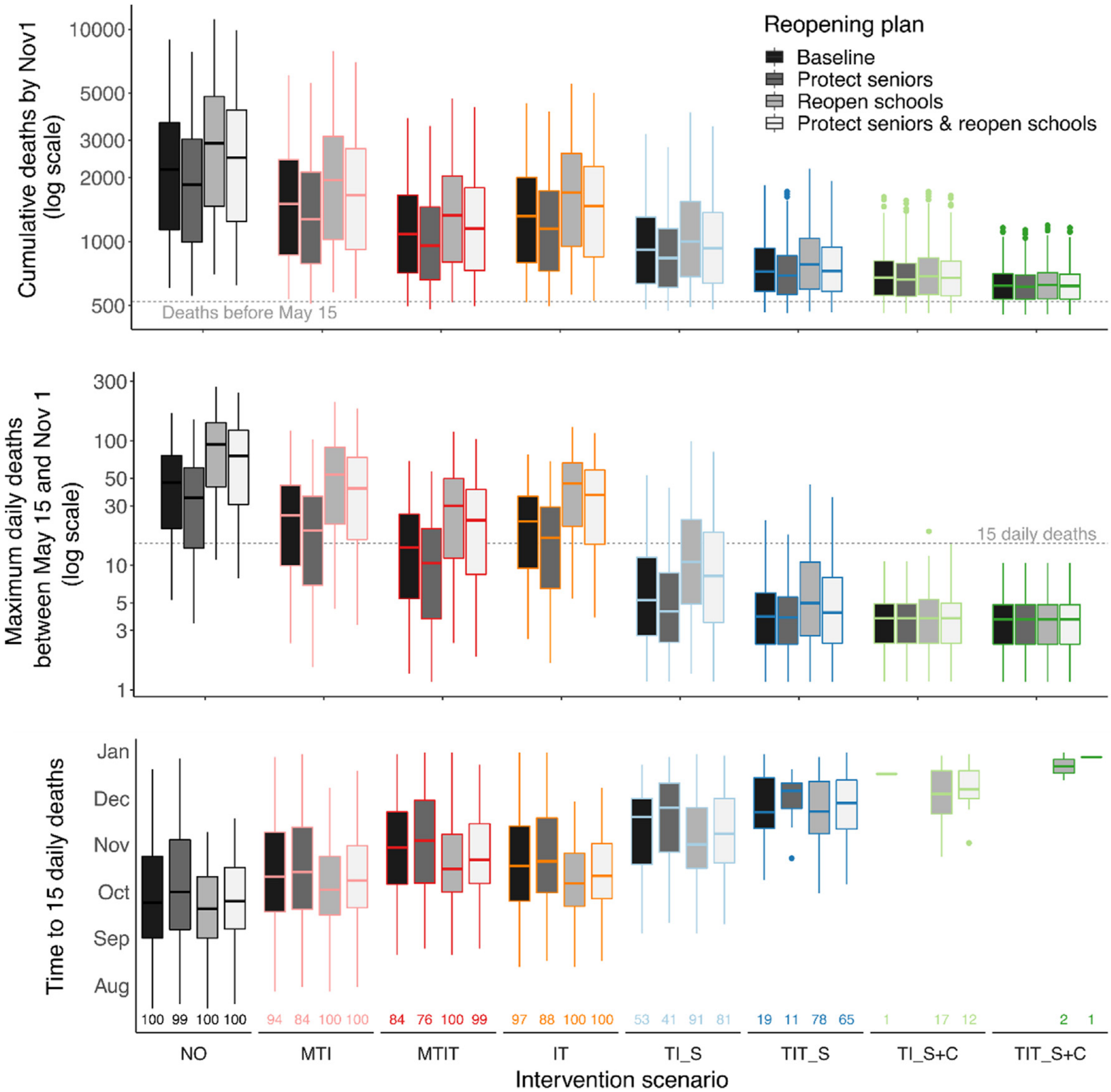

Fig. 4. Model p**rojections under different combinations of reopening scenarios and adjunctive interventions in terms of:** A) Cumulative deaths by Nov 1. B) Maximum daily deaths by Nov 1; C) Time from the start of reopening to reach 15 deaths daily. Reopening plan is implemented between May 15 and July 15 by restoring 60% of pC_PI in all age groups (Baseline) or age groups 1–3 only (Protect seniors). Schools reopen on Sept.1.

August to not reached by the end of December). Interval mass testing of the population at levels feasible to date (0.5% daily) with isolation of cases would have a limited impact on the trajectory of deaths relative to no intervention at 60% pC-PI (Fig. 3C, pink).

Feasibility of expanded testing strategies. A reasonable goal for any intervention is to keep the death rate below peak death rate in April (~15/day) through November. Our analysis suggests that for safe restoration of 60% pC_PI, at least 2.5% of the population would need to be tested daily (roughly 55, 000 tests per day) to keep daily deaths below 15 (i.e., 80% of parameterizations below threshold, Fig. 5A). Required testing proportion increases further if larger fraction of pC_PI is allowed during reopening and even 4.5% daily testing is insufficient at 70% pC_PI. At 70% pC_PI, diagnosing 20% of symptomatic cases daily will achieve a similar level of mortality reduction (i.e., 80% of parameterizations below threshold) without contact tracing (Fig. 5B) as diagnosing only 10% of symptomatic cases daily if effective contact tracing is assumed (Fig. 5C).

Impact of isolating elderly populations. Our analysis suggests that protecting seniors above age of 70, by keeping them under the physical distancing achieved during the lockdown, would have a small positive impact on epidemic trajectories (Fig. 4). For instance, the cumulative death count by Nov. 1 under the test and isolate systematic cases (TI_S) intervention is 12% lower (BF, range 1–14% UI) if seniors' interactions are restricted compared to the baseline scenario (Fig. 4A), with fewer slightly maximum daily deaths projected (Fig. 4B). Twelve percent of the parameterizations (UI) exceed 15 deaths daily compared to 17% in the baseline scenario.

Impact of school reopening on the epidemic projections. Simulations of schools reopening reiterate further the need to maintain pC_PI below 60% and to include effective contact tracing to the intervention strategies against COVID-19. Our analysis demonstrates that opening schools is likely to more rapidly increase the death count to more than 15 per day if the only existing policy is diagnosing and isolating symptomatic cases (TI_S) with the BF parametrization crossing that threshold on Sept. 22 and 46% of the parameterizations (UI) exceeding that threshold compared to only 17% in the baseline scenario. In comparison, school reopening shows little impact if early infections are identified through contact tracing (TI_S + C) with only 1% of the parameterizations (UI) reaching 15 daily deaths by the end of 2020 (Fig. 4C).

Sensitivity analysis. We detected only slight sensitivity of cumulative deaths to the percentage of asymptomatic infections (parameter p) and the level of infectivity of those infections (parameter β_a) after the end of the calibration period (Fig. 6A) and also after the reopening plan is completed (Fig. 6B). This suggests that our mortality projections are not influenced by the uncertainty in the asymptomatic assumptions. Similarly, the assumed asymptomatic infectivity does not impact the projected cumulative incidence over time (Fig. 6C and D). Conversely, there is a clear association of increasing cumulative incidence with the increase of the fraction of asymptomatic infections with 2.1% (median, range 1.0–10.2% UI), 2.7% (median, range 1.2–11.1% UI) and 5.0% (median, range 2.0–18.3% UI) of the population expected to be infected with SARS CoV-2 by Sept. 15 (assuming $\beta_a = 1$) if 10%, 20% and 50% of the infections are asymptomatic, respectively.

Discussion

Safely resuming economic and educational activities while avoiding a significant SARS-CoV-2 resurgence will require precisely tuning the amount of physical interactions and will also be contingent upon adjunctive interventions such as improved testing and contact tracing. In this study, we used a mathematical model, specifically parameterized to King County, WA to assess the future trajectory of cases and deaths under a variety of reopening scenarios. We demonstrate that the prevention policies culminating with the “Stay Home, Stay Healthy” order were able to successfully reduce SARS-CoV-2 transmission by 65% and bring the effective reproductive number, which measures the average number of new infections transmitted from one infected individual at any specific time to a value below one, corresponding to a contracting epidemic. However, we predict that unless transmission is kept at or below 45% of pre-lockdown levels, the epidemic will continue its rapid rebound as has been observed in recent weeks. The increasing case count, after some local and state restrictions were lifted, combined with the lack of effective vaccine and other therapeutic products clearly suggest that it is necessary to prepare for a prolonged period of new sustainable endemic “normalcy”.

One of the most consistent findings from this modeling is that the effectiveness of individual interventions hinges on maintaining a certain degree of physical distancing which in our analysis is a cumulative metric of reduced physical contacts, improved personal hygiene, disinfection and the use of personal protection such as face masks. Rapid testing and isolation alone may significantly curb transmission, but only if contacts are maintained at levels <60% pre-pandemic levels, or if testing is very widely implemented. We estimated that by May 15, more than 80% of symptomatically infected individuals remained undiagnosed and demonstrated that close to 100% of symptomatically infected need to be tested and isolated to allow restoration of 70% pre-pandemic contacts levels without a surge in deaths.

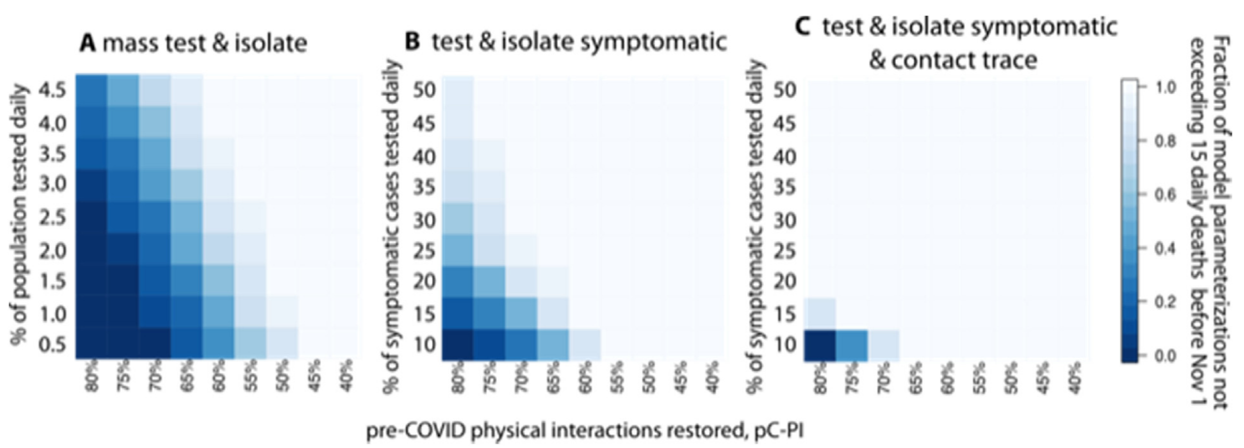

Fig. 5. Model p**rojections under different levels of diagnostic rates among**: A) asymptomatic, pre-symptomatic and symptomatic cases due to mass testing programs; B)–C) symptomatic cases due to test & isolate programs. Reopening plan is implemented between May 15 and July 15 by restoring different levels of pC_PI in all age groups on the x-axis. Heatmap represent the proportion of parameter sets (UI) (from 0 to 1) for which daily deaths remain at or below 15 through November 1.

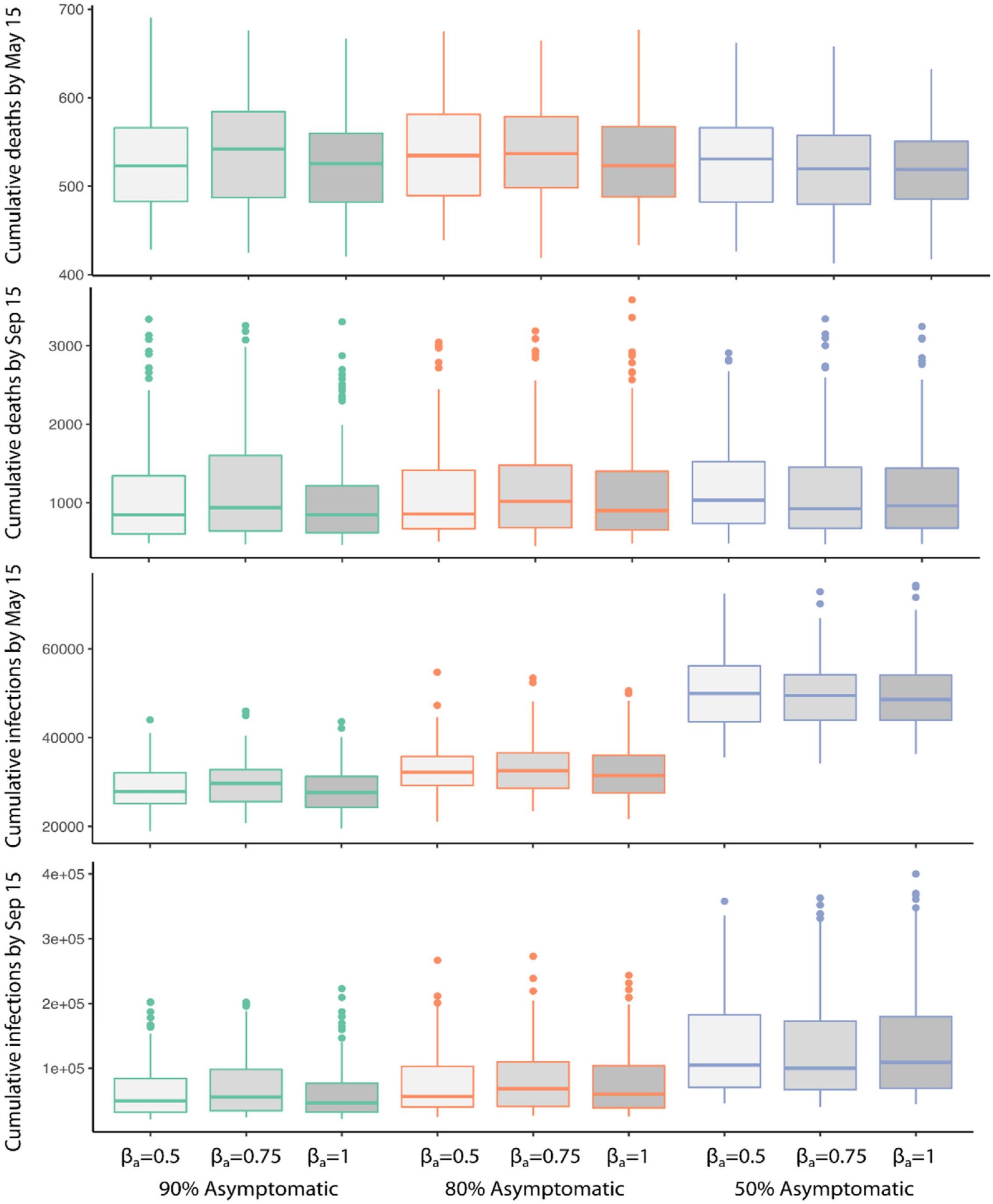

Fig. 6. Model p**rojections with different asymptomatic assumptions**: A)- B) cumulative deaths by May 15 and Sept.15; C)-D) cumulative incidence at May 15 and Sept 15. Reopening plan is implemented between May 15 and July 15 by restoring 60% of pC_PI in all age groups on the x-axis. Boxplots show median and interquartile range (IQR) with whiskers extending to the smallest/largest value no further than 1.5 * IQR based on 100 accepted parameter sets per scenario.

However, implementation of test, isolate and trace strategies would allow restoration to more than 60% of pre-COVID physical interactions, a scenario which may be feasible with stricter mask wearing policies (Chu et al., 2020; Reintjes, 2020).

While outpatient therapies and post exposure prophylaxis measures are not yet licensed, these methods could further reduce the number of cases and deaths, and slightly increase the percentage of pre-pandemic contacts permitted before exponential growth in cases and deaths resume. Currently available inpatient treatments, such as remdesivir and dexamethasone are unlikely to control death because minimal SARS-CoV-2 transmission is generated by hospitalized patients (Beigel, 2020; Horby, 2020). This is unlikely to change even as more potent and effective products become available.

As in other models (Imperial CollegeD-19, 2020), we predict that mass testing interventions are also unlikely to be useful. We estimate that >40,000 daily tests would be needed, which is infeasible at the moment. This method is impractical mostly because of the low prevalence of the virus in any given time but also of poor detection of newly infected people who are not yet shedding virus and many new infections occurring between phased testing.

Another proposed strategy is to protect the highest risk members of society. However, we demonstrate that continuous restriction of seniors' interactions at lockdown levels has a relatively small positive impact on the projected death rates. This finding serves as a warning that increased number of cases in younger demographics observed after reopening, puts the elderly at very high risk. Unfortunately, this risk has been realized in multiple states where the prediction of our model of transmission diffusing into the older age groups has already occurred. It has also been demonstrated with transmissions from universities to skilled nursing facilities (Richmond et al., 2020).

While there is concern for the negative impacts on children from prolonged school closures (Sheikh et al., 2020), reducing community transmission will be even more challenging if schools reopen, potentially fueling new viral circulation. Therefore, we analyzed the rates of testing, case isolation and contact tracing which will allow for safe schools reopening in King County. Importantly, these rates are achievable only while the SARS-CoV-2 incidence remain low enough for testing centers and contact tracers to handle the demand in timely manner. Under certain scenarios including 60% pre-pandemic contact rate with active test and tracing school opening unfortunately tips the balance of transmission and causes death rates to increase dramatically. Together, our analysis argues for urgent case reductions, high levels of physical distancing in the population at large, aggressive test and trace strategies, and careful evaluation of testing demand in order to make school openings safe enough to prevent new epidemic outbreaks (Stein-Zamir et al., 2020). There have been apparent successes with these strategies with Taiwanese universities (Cheng et al., 2020), and research confirms that reducing community transmission is essential to reopening schools without increasing transmission rates (Keeling et al., 2020; Lordan et al., 2020; Stage et al., 2020).

Our study has several limitations. As in most epidemics, SARS-CoV-2 transmission and acquisition risk is not distributed homogeneously. Individuals with more daily contacts, due to workplace or household size are at greater risk of infection (Goyal et al., 2020). Those deemed to be essential workers who cannot physically distance will also be less responsive to state stay-at-home orders. Our model projections capture the heterogeneity in transmission by age but assume homogeneous risk of transmission and outcomes within age groups. Importantly for policy, this assumption means our current predictions are pessimistic. Another limitation of our analysis is that we apply uniform reduction of transmission across age groups due to social distancing. Contact rates of different age groups are surely affected differentially by the restrictions imposed to prevent the spread of SARS-CoV-2 (school closures, work-from-home policy, etc.). However, lack of local data prevented more detailed analysis. Implementing separate contact matrices for each transmission venue (home, school, work, etc.) in the future will allow more precision. Diagnostic rates are similarly simplified here. Some recent data suggest that time-varying age-specific diagnostic rate are more appropriate and will be included and informed by the number of tests and the fraction positive reported daily in the next model iteration.

Our analysis gives hope that widespread testing, case isolation and contact tracing may allow for coexistence with SARS-CoV-2 including safe schools reopening in King County without a virus resurgence which will overburden the health system and require further lockdowns. However, this will require continued physical distancing and a disciplined and coordinated effort to interrupt transmission prior to school opening followed by vigilant monitoring with broadly implemented contact tracing after the students return to school.

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Declaration of competing interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2020.11.003.

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