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Research

Estimating the effect of timetabling decisions on the spread of SARS-CoV-2 in medium-to-large engineering schools in Canada: an agent-based modelling study

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Abstract

Background: During the COVID-19 pandemic, universities transitioned to primarily online delivery, and it is important to understand what implications the transition back to in-person activities may have on spread of SARS-CoV-2 in the student population. The specific aim of our study was to provide insights into the effect of timetabling decisions on the spread of SARS-CoV-2 in a population of undergraduate engineering students.

Methods: We developed an agent-based modelling simulation that used a Canadian first-year undergraduate engineering program with an enrolment of 180 students in 5 courses of 12.7 weeks in length. Each course involved 150 minutes of lectures and 110 minutes of tutorials or laboratories per week. We considered several online and in-person timetabling scenarios with different scheduling frequencies and section sizes, in combination with surveillance and testing interventions. The study was conducted from May 1 to Aug. 31, 2021.

Results: When timetabling interventions were applied, we found a reduction in the mean number of students who were infected and that a containment of widespread outbreaks could be achieved. Timetables with online lectures and small (1/6 class capacity) tutorial or laboratory sections reduced the mean number of students who were infected by 83% and reduced the risk of large outbreaks that occurred with in-person lectures. We also found that spread of SARS-CoV-2 was less sensitive to class size than to contact frequency when a biweekly timetable was implemented (i.e., alternating online and in-person sections on a biweekly basis). Including a contact-tracing policy and randomized testing to the timetabling interventions helped to contain the spread of SARS-CoV-2 further. Vaccination coverage had the largest effect on reducing the number of students who were infected.

Interpretation: Our modelling showed that by taking advantage of timetabling opportunities and applying appropriate interventions (contact tracing, randomized testing and vaccination), SARS-CoV-2 infections may be averted and disruptions (case isolations) reduced. However, given the emergence of SARS-CoV-2 variants, transitions from online to in-person classes should proceed cautiously from small biweekly classes, for example, to manage risk.

In mid-March 2020, higher education institutions across Canada stopped in-person classes in response to provincial and national directives concerning the COVID-19 pandemic and shifted to emergency remote teaching. In the months that followed, faculty and students were required to adapt quickly to a new mode of course delivery, while institutions struggled to provide the necessary supports for remote instruction and assessment. Given that less than 10% of all course enrolments in credit programs at Canadian higher education institutions were fully online before the pandemic,[1] this resulted in a major shift for most of these institutions. The fall 2020 and winter 2021 terms proceeded predominantly online as expected; entering the fall 2021 term, it was understandable that there was a growing desire among students, faculty, staff and administration to transition back to "normal" operations.

We report on the use of an agent-based modelling (ABM) simulation to explore various strategies for transitioning an undergraduate engineering program to in-person instruction. We aimed to provide insights into the effect of timetabling decisions, combined with public health interventions (testing and vaccination), on the spread of SARS-CoV-2 in a population of undergraduate students.

Competing interests: Robert Brennan is a past president of the Canadian Engineering Education Association. No other competing interests were declared.

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Methods

Study design and setting

We used an ABM simulation to explore the effects of different timetables on the potential spread of an infectious disease (COVID-19). To reduce the risk of SARS-CoV-2 transmission, postsecondary institutions have considered a mixture of online and in-person class components, in which a "class component" is a timetabled component of the class such as a lecture, tutorial or laboratory. Our model focused specifically on the logistics of the transition from online to in-person delivery of classes for an undergraduate student cohort and was designed to explore a range of timetabling options at a medium-to-large engineering school in Canada (i.e., total undergraduate enrolment of 3000–5000 students).[2] We conducted our study from May 1 to Aug. 31, 2021, during the planning period for fall 2021 classes.

Our specific focus on Canadian engineering programs stemmed from the specific challenges and opportunities associated with offering a professional undergraduate program that is constrained by accreditation requirements. The Canadian Engineering Accreditation Board (CEAB) requires institutions to show that the graduates of their programs possess attributes in 12 specific areas.[3] Although many of these graduate attributes can be accomplished through online or remote delivery (e.g., "a knowledge based for engineering" and "problem analysis"), key graduate attributes such as "design," "investigation," and "individual and team work" are facilitated by in-person activities and access to facilities such as laboratories and makerspaces (i.e., collaborative student project spaces).

Given the requirements of accreditation and the nature of professional programs, engineering undergraduate curricula tend to be prescribed and, as a result, are typically offered in a cohort-based manner. For example, most Canadian engineering programs follow a sequence of core courses, with a limited number of elective courses that students typically take in the final year of study. Classes are timetabled in year-by-year and program-by-program cohorts that present opportunities for the transition back to in-person delivery if properly implemented.

Model overview

We intended to complement work by Weeden and Cornwell[4] on the small-world network of college classes, by Cipriano and colleagues[5] about the effect of reopening universities on the broader community, and by Gressman and Peck[6] on COVID-19 in a residential university setting. These studies focused on the entire population of a university. The work of these authors showed that there is a high degree of interconnectedness between students in classroom settings, which increases their susceptibility to virus transmission.[4,6] Cipriano and colleagues[5] showed that screening student populations is key to averting infections and protecting the general population. Gressman and Peck[6] suggested that universities have a "robust portfolio of interventions" and, in particular, that large classes should be moved online.

We developed a stochastic, agent-based model to explore questions around the effects of various class schedules on the potential spread of SARS-CoV-2 by student-to-student transmission and simulated a closed population (a typical undergraduate cohort of 180 students) over a period of 12.7 weeks. The model follows a modified "susceptible–exposed–infectious–recovered"[7] process (Figure 1). The model was written in Netlogo 6.1.1[8] and is described using the overview, design concepts and details protocol[9] in Appendix 1A, available at www.cmajopen.ca/content/9/4/E1252/suppl/DC1.

We performed multiple replications of the ABM and collected data on key measures such as cumulative number of students infected and number of students isolated over a simulated 12.7-week term. We fixed all the model parameters for SARS-CoV-2 transmission for the simulations, whereas we varied the parameters relating to interventions. We first investigated 12 timetabling options: 2 lecture options (in-person or online) and 6 tutorial or laboratory options (all in-person). For the tutorial or laboratory options, we considered 3 weekly timetables (a single section per course, 2 sections per course and 3 sections per course) and 3 biweekly sections (2 sections per course, 4 sections per course and 6 sections per course). We divided the full cohort of students evenly through tutorial or laboratory sections (e.g., the weekly tutorial or laboratory timetables resulted in 1 section of 180 students per course [1 × 180], 2 sections of 90 students per course [2 × 90] and 3 sections of 60 students per course [3 × 60]). Next, we investigated additional interventions (i.e., contact tracing, randomized testing and vaccination) that could supplement the timetabling interventions.

Our model's health-related parameters and data sources are summarized in Table 1. These parameters were fixed within each simulated sample (experiment) but varied across samples during each simulation run. Each simulation run used a new random number seed for random number

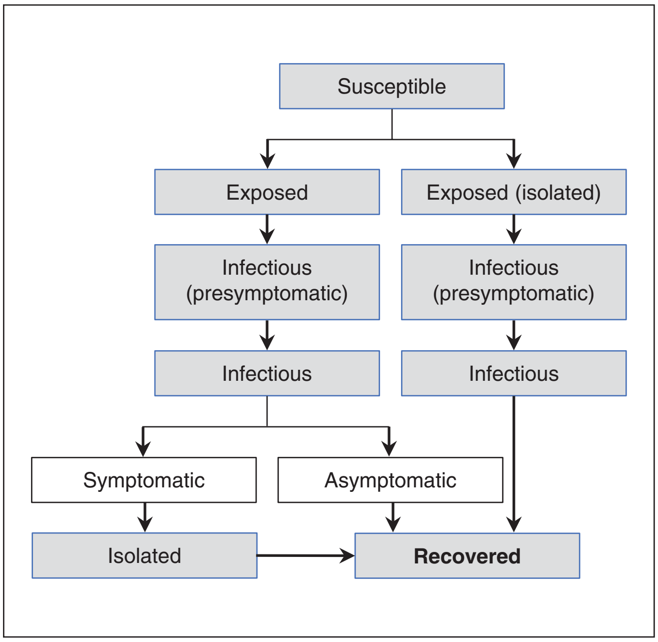

Figure 1: Transmission model structure. The boxes represent the health states of students. The arrows represent transitions between health states. Exposed cases can be either isolated or not; isolated cases (right side) represent students who were identified via contact tracing or randomized testing.

generation. As time advanced, the ABM followed the standard process of generating uniform random numbers and then converting the random number to a sample from the desired distribution. For example, the incubation period for a student who was exposed to SARS-CoV-2 was sampled from a Gaussian distribution specified by the parameter estimates from Table 1.

We obtained the 95% confidence intervals (CIs) for the parameter estimates from the sources noted in Table 1. We converted these estimates of mean and 95% CIs to mean and standard deviations (SDs) for use by the ABM; details on the representation of these variables are provided in Appendix 1A.

Interventions

The main intervention to reduce the spread of COVID-19 in a student population considered in our study was cohort-based timetabling. We investigated alternative mixtures of online and in-person timetabling components for a typical undergraduate cohort. For the timetabling scenarios, we assumed that all students were registered in the same 5 courses, which is typical of most Canadian engineering programs. Each course was assigned 150 minutes/week of lecture time and 110 minutes/week of tutorial or laboratory time.

The alternative timetabling approach we used is similar to the "modified tutorial model" proposed by Maloney and

Table 1: Model parameters for SARS-CoV-2 transmission

Parameter	Mean (95% CI)	Model	Source and notes
Incubation period, d	5.08 (4.77–5.39)	Sampled	He et al.;[10] meta-analysis estimate of the mean incubation time
Latent period, d	2.50	Fixed	Tuite et al.;[11] retrospective cohort study estimate of the mean time to exposure to onset of infectiousness
Time to isolation			
Symptom-based, d	4.60 (4.10–5.00)	Sampled	Bi et al.;[12] retrospective cohort study estimate of the mean time to isolation
Contact-based, d	1.90 (1.10–2.70)	Sampled	
Recovery time, d	20.80 (20.10–21.50)	Sampled	Bi et al.;[12] retrospective cohort study estimate of the mean recovery time
Asymptomatic infection rate, %	46.00 (18.40–73.60)	Sampled	He et al.;[10] Meta-analysis estimate of the mean asymptomatic infection rate[10]
Attack rate, %	6.10 (3.00–12.10)	Sampled	Koh et al.;[13] retrospective cohort study estimate of the mean attack rate. We used the estimate for 20–29 years of age.
Secondary attack rate, %	4.00 (2.80–5.20)	Fixed	Koh et al.;[13] meta-analysis estimate of the mean secondary attack rate (SAR). We used the nonhousehold SAR and the ratio of symptomatic versus asymptomatic SAR to calculate the probability of virus spread for symptomatic and nonsymptomatic contacts, respectively.
Outside transmission, cases/100 000/wk	153	Fixed	We performed the calculation of the probability of outside transmission on a daily basis based on the incident rate reported by the Government of Alberta;[14] population statistics were taken from Statistics Canada.[15]
Test duration, d	2	Fixed	Government of Alberta;[14] less than 2 days from swab collection to test result (1 d for the laboratory to receive the swab and 13 h for the result)
Isolation period, d	14	Fixed	Government of Alberta[16] mandatory isolation guideline
Vaccine effectiveness (1 dose), %	30.70 (25.20–35.70)	Fixed (mean)	Lopez Bernal et al.[17] Effectiveness of BNT162b2 (Pfizer-BioNTech) and ChAdOx1 nCoV-19 (AstraZeneca) vaccination against symptomatic disease caused by the B.1.617.2 (delta) variant.
Vaccine effectiveness (2 doses), %	79.60 (76.70–82.10)	Fixed (mean)	Lopez Bernal et al.[17] Effectiveness of BNT162b2 (Pfizer-BioNTech) and ChAdOx1 nCoV-19 (AstraZeneca) vaccination against symptomatic disease caused by the B.1.617.2 (Delta) variant.
Initial seeding	1 student	Fixed	We assumed an initial outbreak of 1 student who acquired SARS-CoV-2 infection.

Note: CI = confidence interval. The "model" column indicates whether a sampled or a fixed value was used in the model. We took all samples from the Gaussian distribution. Descriptions of the distribution parameters are provided in Appendix 1A, available at www.cmajopen.ca/content/9/4/E1252/suppl/DC1.

Kim,[18] in which students take common online lectures and then meet in smaller groups for tutorials or laboratories. The rationale is that small groups of students in tutorials or laboratories allows social distancing to be employed and limits the numbers of contacts between students.[18] This approach is well-suited to undergraduate engineering; most core courses have relatively large lecture sections that are not conducive to social distancing but also include lower-enrolment tutorial or laboratory components. There is the strong motivation to offer laboratories in person given the engineering accreditation requirements noted previously.

The timetabling scenarios involved 2 main variations. First, we compared timetables with in-person lectures and online lectures. The in-person lecture scenarios allowed for a comparison with prepandemic operation. Second, we looked at variations in the cohort size of tutorials or laboratories within the scenarios for in-person and online lectures. To reduce the cohort sizes sufficiently for tutorials or laboratories while staying within an 8:00–18:00 timetable, we considered both weekly and biweekly sections. In addition to classroom contacts, we also built hallway transitions into the timetables. Appendix 1B details the timetabling scenarios that we used.

As a supplement to timetabling alternatives, we also investigated the effect of different strategies for surveillance and testing for the spread of SARS-CoV-2. As noted in the Centers for Disease Control and Prevention (CDC) SARS guidance, "surveillance of contacts of SARS cases is essential to control efforts."[19] We considered both symptom- and contact-based surveillance in our model. We defined symptom-based surveillance as symptomatic screening at the university and self-reporting by students. Contact-based surveillance involved identification of cases through monitoring and testing of close contacts of confirmed cases, independent of their symptom presentation. In our model, symptoms-based surveillance involved immediate case notification: when a student became symptomatic, they self-isolated. For contact tracing, we followed a contact list policy in which infected students who were infected were asked to identify all their recent contacts, and those students were isolated.

As of late August 2021, 72% people aged 18–29 years in Canada had received a SARS-CoV-2 vaccine (14% partially vaccinated and 58% fully vaccinated).[20] For the fall 2021 term, many Canadian universities required proof of vaccination or regular rapid testing for participation in in-person activities.[21] Our model also provided the option for daily testing of students by selecting the number of tests per day and the effect of various vaccination rates.

Statistical analysis

The outputs from the model are intended to provide information on the efficacy of the various interventions noted previously. The main output that we considered was the number of students who were infected with SARS-CoV-2 over 1 academic term from an initial outbreak size of 1 student and the possibility of outside infections. This measure included all students who were infected (i.e., presymptomatic, symptomatic and asymptomatic), which will differ from actual reporting where presymptomatic and asymptomatic cases may be missed.

To provide information on alternative surveillance and testing policies, we also collected data on the number of students in isolation and the number of positive tests during the academic term.

We performed 250 replications for each experiment. All samples were taken from the Gaussian distribution. We then analyzed the output data using R, and the results were rendered using R's ggplot2 library functions.

Ethics approval

Because this was a modelling study, no ethics approval was needed.

Results

Figure 2 provides the ABM results for all 12 timetable combinations. The boxplots are arranged by timetabling option. Corresponding tutorial or laboratory scheduling for each timetable is characterized by number and size of the sections as described in Figure 2. A detailed description of the timetables is provided in Appendix 1B.

With respect to the first timetabling intervention, we found that the in-person lecture scenarios (orange boxplots) resulted in significantly higher numbers of students who acquired SARS-CoV-2 infection than the online lecture scenarios (teal green boxplots). For example, the worst-case single, weekly section scenario (1 × 180) with in-person lectures resulted in a median of 180 (interquartile range [IQR] 180–180) students acquiring infection compared with a median of 155.5 (IQR 129.0–170.8) students in online lectures.

The number of students who were infected decreased with decreasing size of tutorial or laboratory sections for both the in-person and online lecture scenarios. We found that the benefit of smaller section classes was most prominent for the online lecture scenarios: there was an 86% decrease in the mean number of students infected: there was an 86% decrease in the mean number of students infected using the 6 × 30 scenario (22.0 students infected) compared with the 1 × 180 scenario (155.5 students infected) (Figure 2). The same comparison resulted in a 54% decrease in the mean number of students infected for the in-person lecture scenarios (180 v. 82.5 students infected).

Comparing the weekly and biweekly findings, we found that the second timetabling intervention (biweekly tutorial or laboratory sections) resulted in an overall decrease in the number of students infected (Figure 2). In the case of online lectures with biweekly tutorial or laboratory sections, the reduction in contact hours per week gained by alternating the tutorial or laboratory sections had a larger effect than decreases in section size (i.e., the differences between the 2 × 90, 4 × 45 and 6 × 30 scenarios were negligible (Figure 2).

Surveillance

We evaluated two forms of surveillance: symptom based and contact tracing. Table 2 shows the results of the modelling for weekly and biweekly tutorial or laboratory sections. We found that contact tracing resulted in a significant decrease in the mean number of students who were infected in the models for both section types.

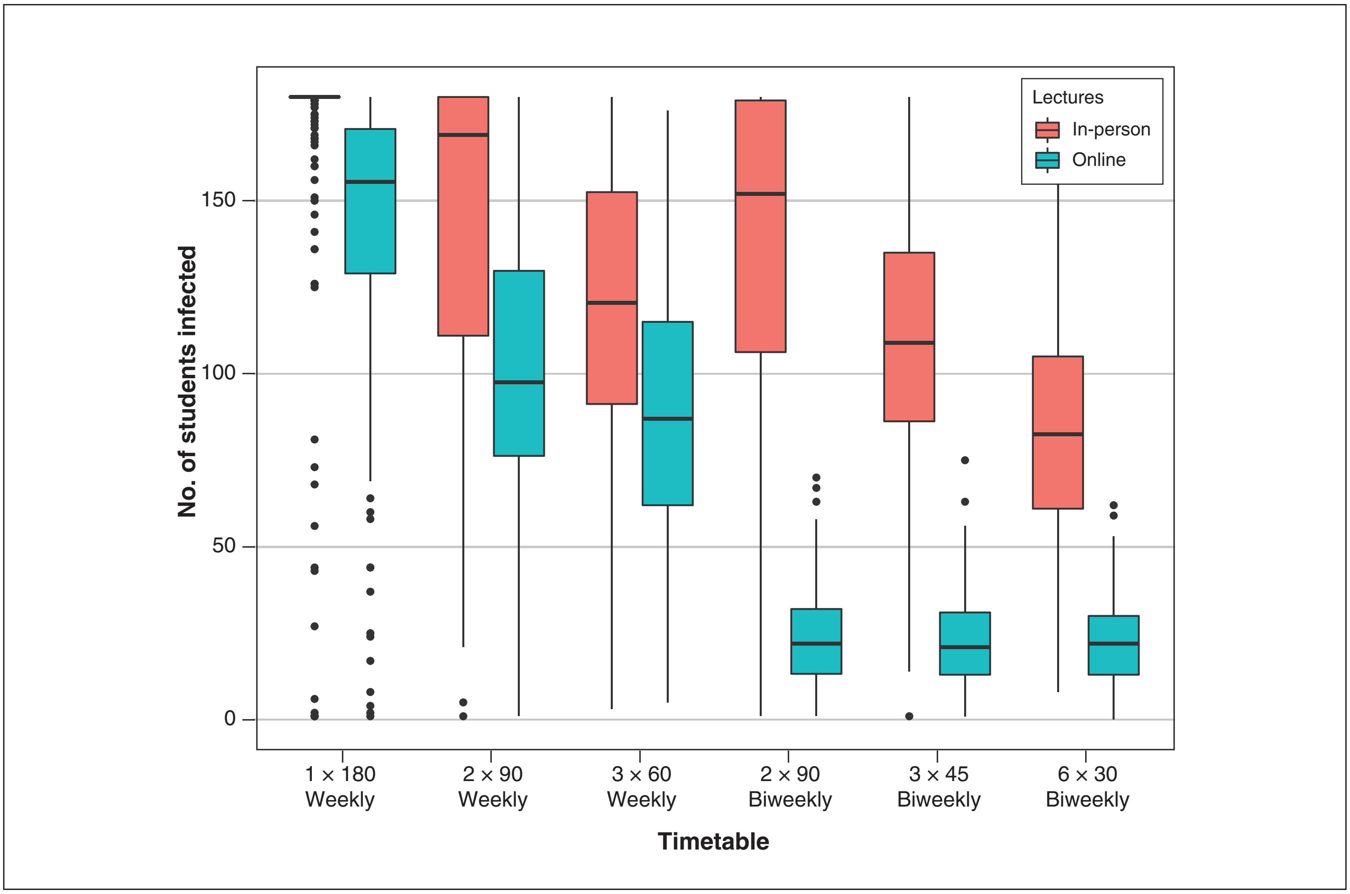

Figure 2: Box plots of the number of students who were infected over a 12.7-week term for different timetabling scenarios (no. of replications = 250). The tutorial or laboratory timetables are represented by no. of sections × size of sections. For example, 2 × 90 weekly represents the timetabling scenario of 2 tutorial or laboratory sections of 90 students each week. We used a population of 180 students for all scenarios. The coloured box represents median and interquartile range (IQR); whiskers the most extreme values within 1.5 times of the IQR beyond the 25th and 75th percentiles; and dots outliers.

We found no significant difference in the number of students infected between the contact-tracing groups (i.e., when contact tracing was implemented, the choice of tutorial or laboratory timetable did not affect the mean number of students infected).

Testing

For this set of simulations, we focused on online lectures with 6 × 30 biweekly tutorial or laboratory sections to explore the effect of randomized daily testing of students with contact-based surveillance. The randomized testing approach involved randomly selecting students from the set of students with the longest time since their last test. We divided the number of tests per day equally among the timetabling cohorts (e.g., if there were 3 timetabling cohorts and 18 tests/d, 6 students from each timetabling cohort were tested each day).

Our findings for these simulations are shown in Figure 3. As expected, the mean number of students infected decreased with increasing testing frequency. We also found a corresponding decrease in the mean number of students who were isolated.

Vaccination

For this set of simulations, we focused on online lectures with 6 × 30 biweekly tutorial or laboratory sections to evaluate the effect of various rates of vaccination. We investigated 5 levels of vaccination (0%, 25%, 50%, 75% and 100%) for both partial (1 dose) and full (2 doses) vaccination, as well as for full vaccination with weekly testing of students who were not vaccinated.

Our findings for these simulations are shown in Figure 4. Although regular testing had a positive effect, we found that vaccination coverage had the largest effect on reducing the number of students who were infected.

Interpretation

Our agent-based model provided several important insights about the transition from online to in-person delivery of classes at higher-education institutions. When we applied timetabling interventions, we found a reduction in the mean number of students who were infected and containment of widespread outbreaks could be achieved. Our analysis of alternative timetabling scenarios supported moving large classes online.[4–6] We found that timetables with online lectures and

Table 2: Number of students infected, using alternative surveillance policies with online lectures in the model			
Timetable	Surveillance type	Mean ± SD	95% CI
Weekly tutorial or laboratory section			
1 × 180	Symptom	143.97 ± 38.01	139.23–148.46
2 × 90	Symptom	101.68 ± 38.38	96.90–106.46
3 × 60	Symptom	88.40 ± 34.73	84.07–92.72
1 × 180	Contact	18.41 ± 11.17	17.02–19.80
2 × 90	Contact	16.81 ± 10.21	15.54–18.08
3 × 60	Contact	17.70 ± 10.54	16.39–19.02
Biweekly tutorial or laboratory section			
2 × 90	Symptom	23.62 ± 13.34	21.96–25.29
4 × 45	Symptom	22.78 ± 13.36	21.12–24.45
6 × 30	Symptom	22.50 ± 12.52	20.83–24.16
2 × 90	Contact	11.96 ± 6.76	11.11–12.80
4 × 45	Contact	11.70 ± 6.53	10.89–12.52
6 × 30	Contact	12.12 ± 6.20	11.34–12.89

Note: CI = confidence interval, SD = standard deviation. Tutorial or laboratory timetables are represented by no. of sections × size of sections. For example, 2 × 90 weekly represents the timetabling scenario with 2 tutorial or laboratory sections of 90 students each week.

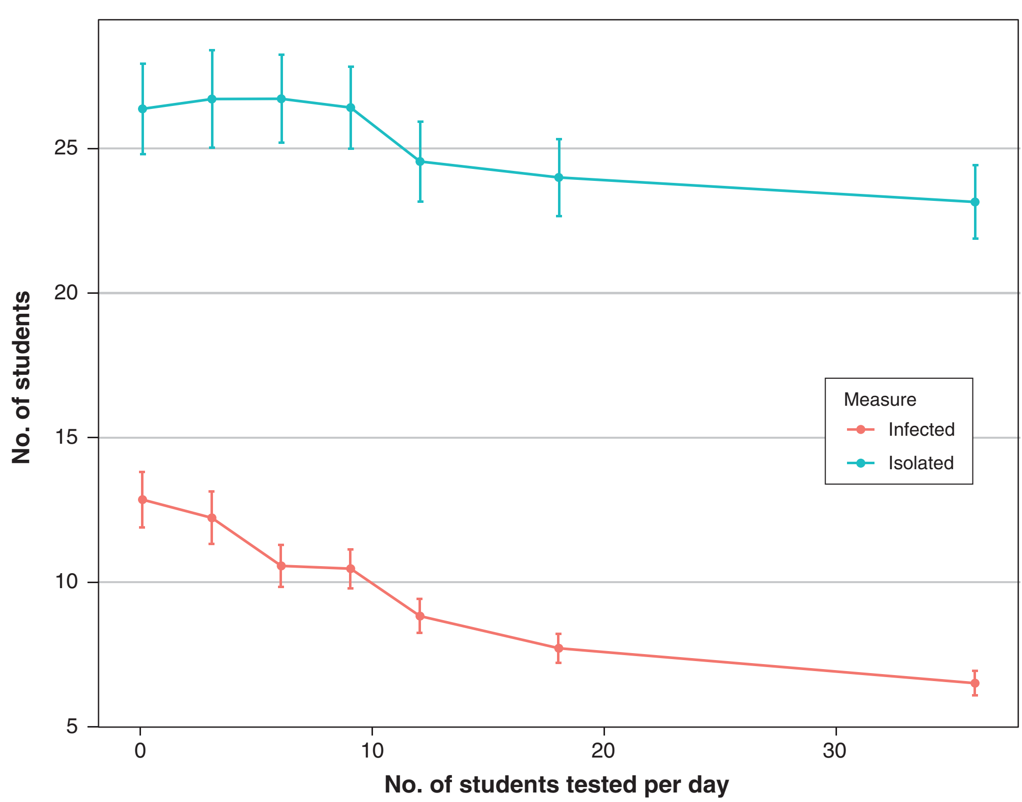

Figure 3: Number of students who were infected and number of students isolated for the 6 × 30 biweekly timetable with contact tracing and testing (means with 95% confidence intervals). Simulations were performed at testing frequencies ranging from 3 students tested per day to 36 students tested per day. From an individual student perspective, this corresponds to 1 test per student per 12-week term to 1 test per student per week, respectively. We also performed a base case of 0 students tested per day.

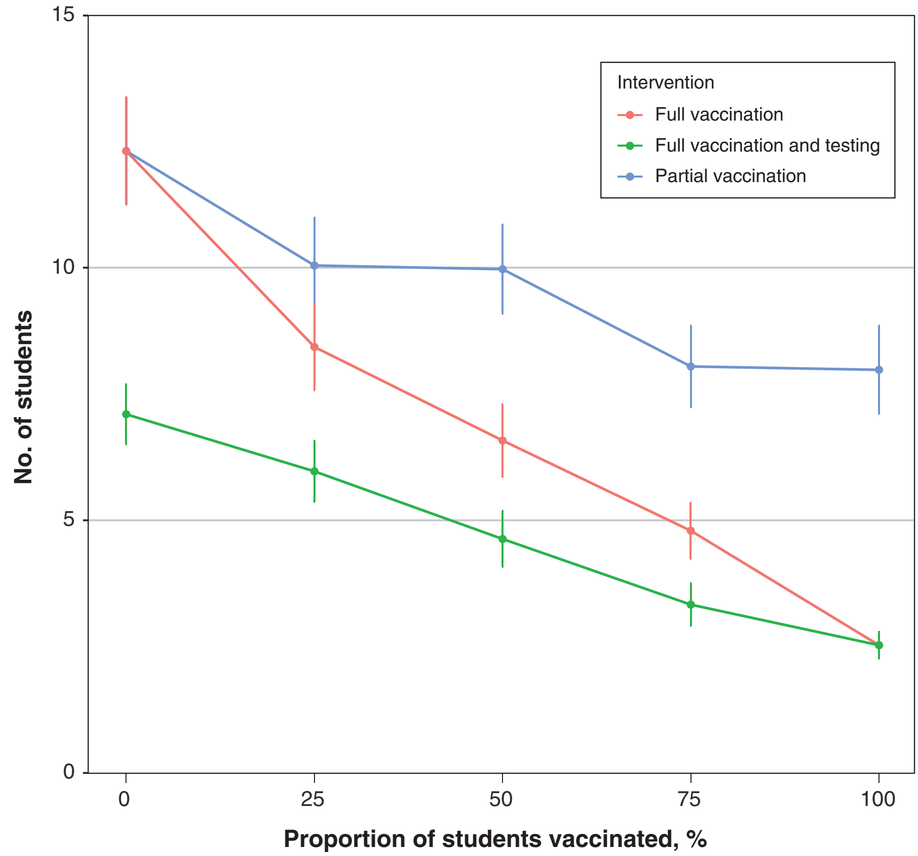

Figure 4: Number of students who were infected in the 6 × 30 biweekly timetable with vaccination scenario (partial = 1 dose, full = 2 doses) and weekly testing of nonvaccinated students (means with 95% confidence intervals). The effectiveness was based on a study of 2 SARS-CoV-2 vaccines, BNT162b2 (Pfizer-BioNTech) and ChAdOx1 nCoV-19 (AstraZeneca), against symptomatic disease caused by the B.1.617.2 (Delta) variant.[17]

small tutorial or laboratory sections not only reduced the mean number of students who were infected but also reduced the risk of large outbreaks that could occur with in-person lectures. The largest change was associated with a switch to biweekly classes (i.e., held online and in-person on alternating weeks). Biweekly classes had the benefit of both smaller class sizes and reduced hallway contacts (i.e., by alternating cohort timetables). Our results also showed that spread of SARS-CoV-2 appeared to be less sensitive to class size than to contact frequency with biweekly timetables. For example, a biweekly timetabling policy allowed class sizes to range from 1/6 to 1/2 of the cohort size with no significant increase in the mean number of students who were infected. This presents an opportunity for the transition from online to in-person delivery of classes (i.e., a gradual transition from small to larger biweekly sections).

Any transition to in-person classes should also be supported by surveillance. We found that including a contact-tracing policy with the timetabling interventions helped to contain the spread of SARS-CoV-2 further. Although the timetabling policies provided the opportunity to isolate entire cohorts of students, the potential improvement over a regular contact list isolation policy may be considered too small to justify the disruption caused by isolating entire student cohorts. For the biweekly timetabling scenarios, we found that contact tracing further reduced the effect of class size as noted previously. These combined interventions support the importance of a robust portfolio of interventions.[5]

When combined with randomized testing, we saw a further decrease in the mean number of students who were infected. Our investigation showed that both the mean number of infections and the mean number of students who were isolated decreased with increased frequency of testing. These are aligned with those of Cipriano and colleagues,[5] who noted the public health benefits of screening to the community through averted infections. Although an effective testing policy should lead to more cases being identified, and consequently, more students being isolated, the overall effect of this intervention on the containment of virus spread led to a reduction in both of these measures.

Finally, vaccination coverage appears to show the most promise for the transition back to in-person classes. This intervention is of key importance given the possibility of breakthrough infections increasing over time with waning immunity and emerging variants.

Limitations

Our study has several limitations. We considered a single cohort of students with a shared set of 5 courses as described in Appendix 1A. Although this form of timetabling is common in undergraduate engineering programs, there are often exceptions where students take 1 or 2 courses outside the regular set of courses for their cohort. For example, students may select optional courses from outside their program or be required to repeat courses that were not completed in previous terms, which results in a mixing with the broader student population. We based our parameters for the SARS-CoV-2 transmission models on extant meta-analyses, retrospective cohort studies and Governments of Alberta and Canada reports as summarized in Table 1.[10–17] Although the stochastic nature of the model allowed us to account for parameter uncertainty, it can only model our understanding of the virus transmission model at the time of these reports. For example, our attack rates are based on pre-Delta variant rates.[13] Given that people who are exposed to the Delta variant have an increased risk of SARS-CoV-2 acquisition compared with those exposed to other variants,[22] we would expect to see higher overall numbers of students infected, but no change in the relative number of students infected for different timetabling strategies. We based the probability of outside transmission on the incident rate reported by the Government of Alberta.[14] This does not capture instances of students gathering outside of classes in residences and at social gatherings, which have been reported to lead to isolated outbreaks in student populations.[5]

These limitations (i.e., the continually changing model parameters and the authors' choice to use a generic undergraduate engineering student timetable) affect the external validation of the model. As noted, our goal was not to provide accurate estimates of infection rates among university students in a specific setting but to provide insights into the effect of timetabling decisions on the spread of SARS-CoV-2 in a population of undergraduate students. Our simulation compares infection rates across various timetabling strategies with and without additional interventions (testing, surveillance and vaccination) under a specific empirically informed (but likely inaccurate) model.

Conclusion

We have shown that interventions that are within the control of colleges and universities can reduce the risk of the spread of the SARS-CoV-2 virus in the student population and inform decisions around this transition. However, the transition back to "normal" from the current emergency online teaching mode during the COVID-19 pandemic must be handled with care by higher-education institutions.

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Supplemental information: For reviewer comments and the original submission of this manuscript, please see www.cmajopen.ca/content/9/4/E1252/suppl/DC1.