Infectious Disease Modelling 7 (2022) 83–93

Contents lists available at ScienceDirect

Infectious Disease Modelling

journal homepage: www.keaipublishing.com/idm

Projections of the transmission of the Omicron variant for Toronto, Ontario, and Canada using surveillance data following recent changes in testing policies

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A R T I C L E I N F O

Article history:
Received 4 March 2022
Received in revised form 21 March 2022
Accepted 22 March 2022
Available online 30 March 2022
Handling editor: Dr. J Wu

Keywords:
PCR testing
Self-testing
Booster dose
Social behavior
Mathematical model
COVID-19
Omicron
Exit strategy

A B S T R A C T

At the end of 2021, with the rapid escalation of COVID19 cases due to the Omicron variant, testing centers in Canada were overwhelmed. To alleviate the pressure on the PCR testing capacity, many provinces implemented new strategies that promote self testing and adjust the eligibility for PCR tests, making the count of new cases underreported. We designed a novel compartmental model which captures the new testing guidelines, social behaviours, booster vaccines campaign and features of the newest variant Omicron. To better describe the testing eligibility, we considered the population divided into high risk and non-high-risk settings. The model is calibrated using data from January 1 to February 9, 2022, on cases and severe outcomes in Canada, the province of Ontario and City of Toronto. We conduct analyses on the impact of PCR testing capacity, self testing, different levels of reopening and vaccination coverage on cases and severe outcomes. Our results show that the total number of cases in Canada, Ontario and Toronto are 2.34 (95%CI: 1.22–3.38), 2.20 (95%CI: 1.15–3.72), and 1.97(95%CI: 1.13–3.41), times larger than reported cases, respectively. The current testing strategy is efficient if partial restrictions, such as limited capacity in public spaces, are implemented. Allowing more people to have access to PCR reduces the daily cases and severe outcomes; however, if PCR test capacity is insufficient, then it is important to promote self testing. Also, we found that reopening to a pre-pandemic level will lead to a resurgence of the infections, peaking in late March or April 2022. Vaccination and adherence to isolation protocols are important supports to the testing policies to mitigate any possible spread of the virus.

1. Introduction

When the Omicron variant became the dominant strain in Canada, testing centers became overwhelmed and many provinces announced a targeted testing strategy strategy (British Columbia Centre for Disease Control, 2022; Government of Manitoba, 2022; Government of Ontario, 2021; Government of Quebec, 2022; British Columbia Centre for Disease Control,

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Peer review under responsibility of KeAi Communications Co., Ltd.

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https://doi.org/10.1016/j.idm.2022.03.004

2022). Tests for COVID-19 are typically divided into two types according to population priority. Individuals working or living in high-risk settings (hospitals or congregate living setting, such as shelters, group homes, jails, etc. …) are eligible for PCR testing if symptomatic. For non-high-risk populations, severe infected individuals are prioritized for PCR testing to support medical treatments in time. Mild infected non-high-risk people are recommended to conduct self-testing, and isolation. Consequently, the cases reporting criterium was changed, leading to an underestimation of the actual number of cases. To implement new reopening stages, it is important to understand what the real status of the epidemic is, by estimating, as much as possible and precise, the unreported cases.

The high accurate PCR test is a time-consuming process requiring specialized personnel and laboratory equipment. Although PCR tests can be returned within 24 h after the collection, if the system is overwhelmed, results might be returned after several days (ClevelandClinic medical professional, 2021). Given the role of testing and isolation in controlling the spread of the virus, returning the tests in a short period of time is extremely important (Larremore et al., 2021). In contrast, the rapid antigen tests can be a preferable surveillance resource in areas where there are long delays PCR returns, ensuring the implementation of subsequent isolation measures (Forde & Ciupe, 2021; Peeling et al., 2021; Holmdahl et al., 2021; Korenkov et al., 2021). The easy availability of cheap rapid test kits can help to maintain hospitalization caps under critical levels (Grundel et al., 2022). Studies have shown that antigen screening with sufficient frequency could reverse the epidemic, while PCR-based pooled screening may not stop the outbreak (Smith et al., 2022; Yu et al., 2021). However, all the available studies look at the implementation of a single type of test. The effect of the hybrid testing strategy on the mitigation of the outbreak in which both PCR and self-test are conducted is crucial for the transition to endemic, but still unknown.

Over the past months, the intense vaccination campaign helped mitigate the spread of the virus, and its variants, as well as possible severe outcomes (Centers for Disease Control and Prevention, 2022). However, given the waning of the first two doses of vaccine (Levin et al., 2021; Goldberg et al., 2021) and their low effectiveness against the Omicron variant (Swaminathan, 2022), a third dose campaign has been implemented across Canada starting mid-Fall 2021 to protect the population and prevent overwhelming public health resources. Studies have shown that the effectiveness of the booster dose against the Omicron variant is roughly 70%–90% (Swaminathan, 2022; Tartof et al., 2022; Del Rio et al., 2022; Mahase, 2021; Grannis et al., 2021).

The beneficial implementation of non-pharmaceutical interventions (NPIs) to mitigate the spread of SARS-COV-2 has been widely studied (Yuan et al., 2022; Ngonghala et al., 2020; Hellewell et al., 2020; Yuan et al., 2020), even in combination with vaccination (McCoy et al., 2020; Layton & Sadria, 2022; Brüssow & Zuber, 2022; Tong et al., 2022; Aruffo et al., 2021). After almost three years of restrictions and implementation of NPIs, people's adherence to following and respecting the rules has been changing over time, and this had a great impact on the actual mechanisms of virus transmission (Caldwell et al., 2021; Ejigu et al., 2021; Pedro et al., 2020; Lafzi et al., 2021). Social behavior also depends on the perception of severity that individuals have due to the change in number of deaths or infections, leading to a change of the infections' transmission (Weitz et al., 2020; Lin et al., 2020). It is therefore important to incorporate all these crucial factors when evaluating the new testing system for Omicron in Canada.

In this paper, we aim to determine an exit strategy under the prevalence of Omicron, using Toronto, Ontario, and Canada as cases studies. We build a comprehensive SEIR compartmental model that distinguishes populations depending on the risk of the settings (where PCR testing continues or not) they belong to. Based on this division, we can depict the new testing guidelines, including PCR testing and self-testing. We further include the third dose of the vaccine, people's awareness of the disease, and compliance with isolation requirements. The model is calibrated using Monte-Carlo-based Bayesian melding framework. We then assess different strategies in which various combinations of PCR testing and self-testing administration, different levels of restrictions lifting, PCR test turnaround times are considered. We also investigate how booster dose coverage and social behavior affect mitigation of epidemic, especially when restrictions are lifted.

2. Materials and methods

2.1. Modelling

A compartmental model is developed to capture the impact of the new targeted testing strategy and transmission of the Omicron variant in Toronto, Ontario, and Canada. To study how the recent changes in testing policies affect the transmission, based on the new PCR testing eligibility criteria, the population is divided into two groups: high-risk (HRS, including the hospitals and congregate living settings, elementary and secondary students and education staff) and non-high-risk (nHRS). The model follows the SEIR framework, extended to include asymptomatic, confirmed cases, those in hospital, ICU, deceased and vaccinated individuals (Fig. 1). A description of variables and parameters used are presented in Supplementary materials (Tables S2 and S4). The transmission in the population is defined using transmission risk parameters and a contact matrix describing contacts between and within subpopulations. The model captures the effect of population awareness of high daily reported cases on mitigation of epidemic. Population mixing and contacts are assumed to increase, or decrease, depending on the respective decrease or increase of reported cases. The maximum reduction of contact rates compared to the pre-pandemic level due to the awareness of high reported cases is assumed to be 79.9% (Brankston et al., 2021).

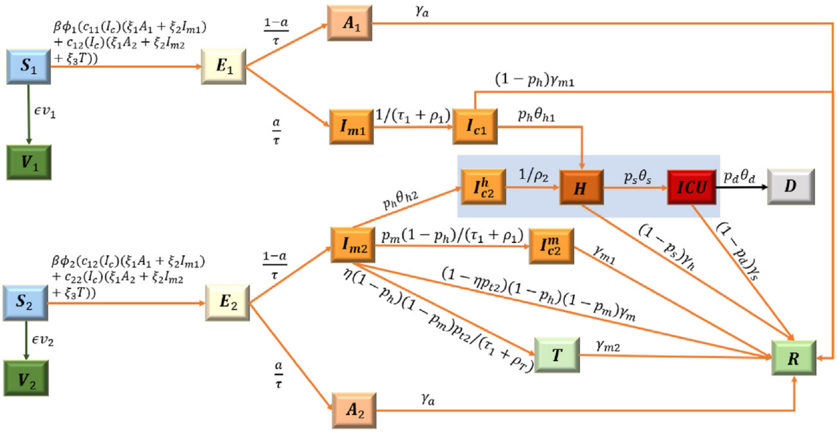

Fig. 1. Diagram for the transmission in high-risk settings (subscript 1) and non high-risk settings (subscript 2).

2.2. New testing policies and isolation

The model incorporates the new testing policies of both required PCR and self-testing. Following the government policy, it is assumed that symptomatic nHRS individuals self-test at home, but most of them are not confirmed by any PCR tests and consequently, will not be reported in the daily case count by the public health unit unless hospitalized. The turnaround time of PCR tests (from sampling to informing the patient of the result) is assumed to be 2 days on average (City of Toronto, 2022a, 2022b), and this is shorter for the self-test (1 day). Those with severe symptomatic infections in nHRS will be tested when admitted to the hospital, and it is assumed it takes 1 day to be included in the reported cases. The sensitivity of detection of infections of rapid test kits is assumed to be 64.2% (Prince-Guerra et al., 2021). It is assumed that 66.3% (Arora, 2021) of those with mild symptomatic infections in nHRS confirmed by self-testing, and 96.5% (Arora, 2021) of those with mild symptomatic infections confirmed by PCR testing will follow isolation policies.

2.3. Vaccination and waning immunity

Given the waning immunity of the first two doses (Levin et al., 2021; Goldberg et al., 2021) and their low efficacy against the newest Omicron variant (Tartof et al., 2022), we assume that all individuals in the population are susceptible to infection, except those protected by the second dose in the last three months and those who received the third dose. We include the rollout of booster doses in the model using daily doses, and we assume that booster dose provides 70% effectiveness against the Omicron infection (Swaminathan, 2022; Tartof et al., 2022). The count data of daily booster dose 3 is incorporated into the model and we assume a maximum vaccination coverage of 80% (or 60%) of the eligible population (12+), and use the average vaccination rate based on data of the latest week in the projections. Waning immunity of booster dose is not included due to uncertainty regarding such process at the time of writing.

2.4. Model calibration

The model is calibrated using publicly available surveillance data of daily new reported cases and deaths, daily hospitalized and ICU cases in Toronto, Ontario, and Canada from January 1 to February 9, 2022 (City of Toronto, 2022a, 2022b; Government of Canada, 2022; Public Health Ontario, 2022). The proportion of nHRS mild symptomatic infections conducting self-testing and PCR testing, the transmission risk, the proportion of hospitalized, ICU and deaths from ICU are estimated using a Monte-Carlo-based Bayesian melding framework (Newcomb et al., 2022) and are reported in Table S6. The estimations are based on a forwarding weekly time window to capture in a timely fashion the changes in transmission risk and severity.

We sample 200,000 parameter vectors from the uniform prior distribution (Table S6), then minimize the normalized mean square error (NMSE) between data and model predictions to obtain the estimated parameters. We choose the 1000 best-fitting parameters vectors based on the modified NMSE indicator during the chosen 7-day window. The modified indicator facilitates a combination of prediction error with respect to the cumulative case, hospitalized case, ICU cases, and cumulative death data together, despite their different magnitudes. For the next 7-day window, another 200,000 parameter vectors are sampled from the posterior distribution of the most recent 7-day window (75%) and the initial parameter prior distribution (25%). Then we obtain the blended parameter sets of the best-fitting models over time. The median and range of estimated parameters over the last 7 days of data are presented in Table S7.

2.5. Scenarios

The list of all the scenarios studied is presented in Table 1 (details in Table S8). The total number of cases and severe outcomes until August 31, 2022, are presented and compared amongst a combination of different testing strategies and different levels of lifting of restrictions (labeled as scenario A), and different turnaround times of PCR test (labeled as scenario

Table 1
List of scenarios related to testing, vaccination strategy, and social behavior as well as the parameters of investigation used to project cases and severe outcomes.

Variation: Parameters of investigation \ Strategy	Testing (A)			Testing and lifting (B)		
PCR tests turnaround time for mild symptomatic cases in non-high-risk setting	Base line (2 days) 4 days			Base line (2 days)		
Transmission risk	Base line			Base line Level 1 Level 1+Level 2		
Proportion of non-high-risk setting individuals getting PCR test	Canada	Ontario	Toronto	Canada	Ontario	Toronto
	Base line (5.6%) 20%	Base line (5.5%) 20%	Base line (5.4%) 20%	Base line (5.6%) 20%	Base line (5.5%) 20%	Base line (5.4%) 20%
Proportion of non-high-risk setting individuals self testing	Canada	Ontario	Toronto	Canada	Ontario	Toronto
	Base line (10.2 %) 30%	Base line (10.6 %) 30%	Base line (10.5 %) 30%	Base line (10.2 %) 30%	Base line (10.6 %) 30%	Base line (10.5 %) 30%

Variation: Parameters of investigation \ Strategy	Transmission and vaccine (C)	Transmission and adherence (D)	Transmission and awareness (E)
Transmission risk	Base line Level 1 Level 1+Level 2	Base line Level 1 Level 1+Level 2	Base line Level 1 Level 1+Level 2
Vaccine coverage	60% 80%	80%	80%
Adherence	Base line	50% 70% 90%	Base line
Awareness of the reported cases	With awareness	With awareness	With awareness Without awareness

Transmission risk definitions	
Base line	Partial closure after January 31, 2022: Limit capacity of social gatherings and indoor public settings & events venues Transmission: estimated parameters using data until February 9, 2022
Level 1	Partial opening starting February 17, 2022: Increased limit capacity of social gatherings and indoor public settings & events venues Transmission: increased by 50% (Ontario and Toronto) or 40% (Canada)
Level 2	Total reopening starting March 1, 2022: Lifting capacity limits and proof of vaccination requirement. Transmission: increased by 100% (Ontario and Toronto) or 80% (Canada)

B). We also investigate the combination of different levels of lifting of restrictions and third booster dose coverage, adherence to isolation measures, and the awareness of the epidemic (labeled as C, D, E respectively). Scenario A contains 9 simulations for each jurisdiction, with combinations of lifting baseline (level 1 or level 1 + level 2) and testing baseline (PCR testing, 20%, or self-testing, 30%). The detailed simulations included in other scenarios are presented in Table 1 and Table S8. The projections are obtained using the median of 1000 simulations for each scenario.

2.6. Sensitivity analysis

Given the uncertainty of the parameters related to the transmission, testing and adherence, we employ the Latin Hypercube Sampling/Partial Rank Correlation Coefficient (LHS/PRCC) sensitivity analysis method to identify which parameters are more significant on the model outputs, such as cumulative cases and deaths. We generate 2000 samples using uniform distribution and used parameters related to Canada. The parameters studied and the sampling ranges are provided in Table S9. Parameters are defined as significant if their PRCC is, in absolute value, larger than 0.5.

3. Results

3.1. The model fitting and uncover the underreported COVID case counts

Our model is calibrated forward by a 7-day window and the model fitting results are shown in Fig. S1. It is critical to iteratively calibrate the model as the social behavior change can significantly affect the transmission. Also, the test strategy focused on the populations in “high risk” settings may underestimate the transmission in the community, while the sequential calibration may better capture the change of the transmission risk and uncover the underreported cases.

By fitting the model to reported cases in HRS (Fig. S1), the numbers of unreported cases in non-HRS are estimated at 2.34 (95%CI: 1.22–3.38), 2.20 (95%CI: 1.15–3.72), and 1.97 (95%CI: 1.13–3.41), times the reported cases for Toronto, the province of Ontario and Canada respectively (Fig. 2).

3.2. The comparison of the effect of different test strategies on the transmission, short and middle term

It is vital to explore the effect of PCR test on the transmission, under the circumstance of the fast transmission of Omicron and limited PCR test capacity. We observe that with an increased accessibility to PCR tests, the cases reported show an increase, however the total case counts will decrease, indicating the benefits of implementing rigorous PCR testing (Figs. 3–5, Tables S10–12), and the mitigation effects are observed in both the short (in 2 incubation period) and middle term (till August 31, 2022). But for the deaths, the different test strategies do not show much difference in the short run, while the more PCR tests and self-tests help reduce deaths in the middle run (Figs. 3–5).

Moreover, shortening the turnaround time for PCR test results, resulting in earlier isolation of infective people, further reduces transmission (Fig. 4). However, if four days are necessary to confirm cases, we observe lower deaths when there is more self-testing compared to more PCR tests, and in this case, a better strategy is to have more people conducting self-testing and isolation. Hence, if PCR testing capability is limited to ensure the current rules (test symptomatic infections in HRS and severe symptomatic infections in nHRS), encouraging self-testing will help mitigate transmission and severe outcomes.

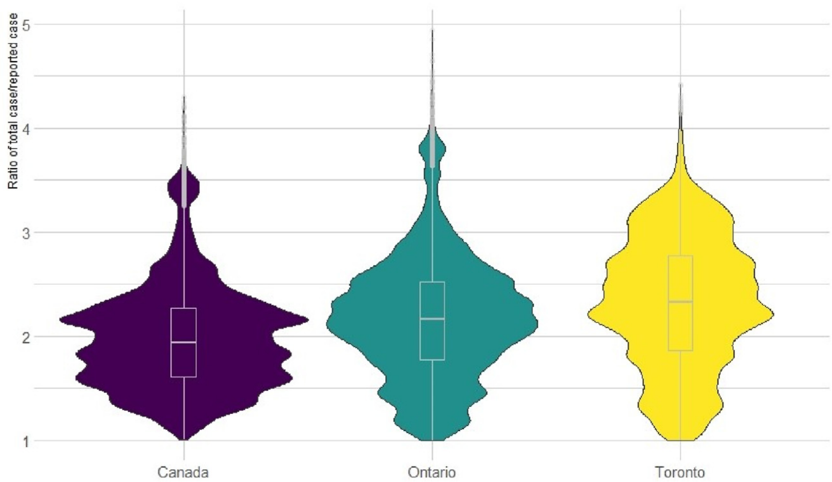

Fig. 2. The estimated ratio of total cases and reported cases during Jan 1, 2022–Feb 9, 2022, for Canada (purple), Ontario (green), and Toronto (yellow) are 2.34, 2.20, and 1.97 times larger than reported cases, respectively.

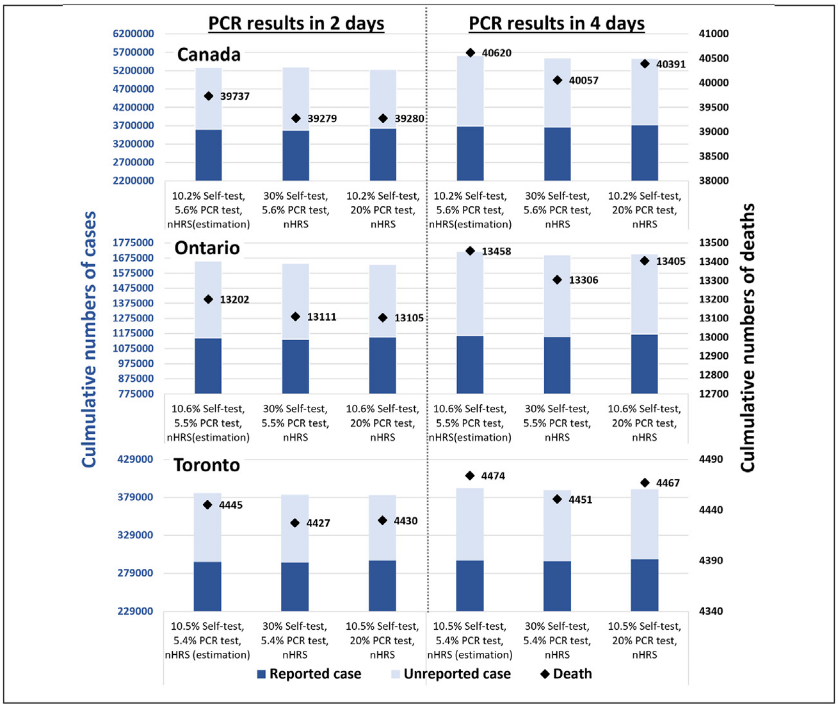

Fig. 3. The impact of increasing PCR result turnaround time to 2 days (left hand column) from 4 days (right hand column). The cumulative number of cases and death are the projections till Aug 31, 2022 (scenario B in Table 1).

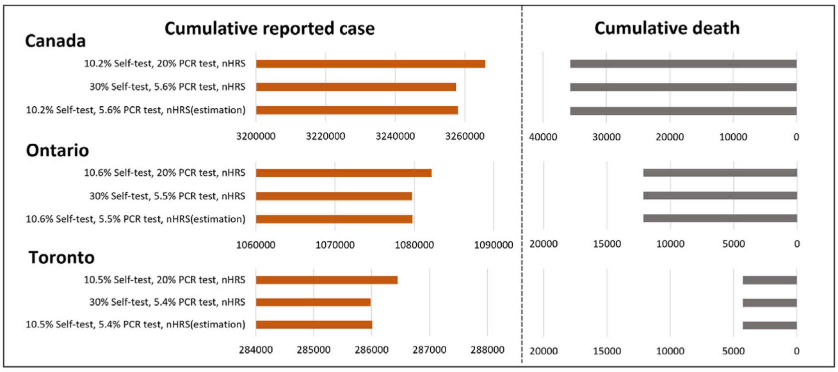

Fig. 4. The impact of different test strategies on the COVID cases and death in Toronto, Ontario, and Canada, in the short run. The cumulative number of cases and death are the projections till February 15, 2022 (the 2 incubation periods after data).

3.3. *A resurgent wave may occur with lifting of restrictions, peaking in late March or April 2022*

For the city of Toronto, the province of Ontario and Canada as a whole, a resurgence of hospitalizations (illustrated as numbers of daily ICU occupancy) is predicted to occur in late March/early April through May 2022 (Fig. 5, S2 and S3, Tables S10–12) if all restrictive public health measures are lifted. The resurgence is predicted to be proportionally higher for Canada as a whole, than for Toronto and Ontario. The size of the resurgence was reduced if a greater proportion of cases were detected by either self-testing or, to a greater extent, by PCR testing, and then isolated (Fig. 5, S2 and S3, Tables S10–12). If the transmission is kept low, with partial closure or limited reopening, then no resurgence is observed, and the current strategy appears to be beneficial as the one employing more testing (Fig. 5, S2 and S3, Tables S10–12). Our results show that, regardless the level of reopening, if more PCR tests are conducted the reported cases are higher than the ones shown under other scenarios, however the total cases are lower.

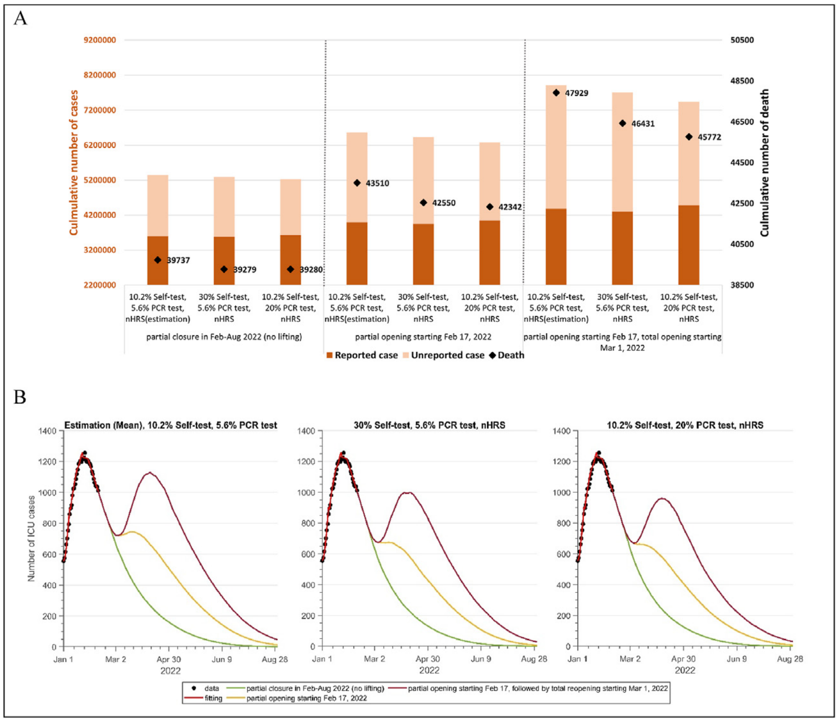

Fig. 5. Simulation results for Canada as a whole under scenarios for testing strategies & lifting of restrictions. Panel A: the cumulative case count & death in Canada up to August 31, 2022; Panel B the epidemic curves for the scenarios.

3.4. 60% coverage of booster third dose in eligible population cannot prevent a resurgence

After an important immunization campaign with the two doses, the administration of the third dose has started towards the end of 2021. Given the vaccination uptake at the time of writing, we investigate the total and reported cases, and severe outcomes under different vaccine coverages (80% vs 60%) and reopening strategies (Fig. 6, Tables S10–12). As expected, cases and severe outcomes decrease as the coverage of immunization increases and if the level of reopening is low. However, the resurgences can be seen in Toronto, Ontario, and Canada even with partial opening, if with 60% coverage of booster third dose in eligible population. We also observe that if only 60% of the population is vaccinated, reopening with some restrictions in place is more beneficial than achieving a higher coverage (80%) and implementing a full reopening.

3.5. Social behavior and resurgence waves with the lifting of restrictions

Awareness of new infections reduces the risk of spreading the disease (Figs. 7A, S4A, S5A, Tables S10–12). When people realize that daily new infections are high and consciously protect themselves, the peak of daily ICU occupancy is smaller than the wave in January 2022, although we observe an outbreak in late March after full opening. But if people are unaware of the outbreak, even if with partially open, a resurgence in late March or early April may overwhelm the healthcare system, let alone fully opening. On the other hand, this also shows that the number of infections will be greatly overestimated when people's social behavior is not considered. This also suggests that our model projections may be closer to the actual transmission.

The new testing requires self-isolation of individuals who are symptomatic in non-high-risk settings. However, it is possible to assume that not 100% of symptomatic respect the isolation. Fig. 7B shows possible resurgence after lifting restrictions. Overall, the higher the proportion of people adhering the restrictions, the lower the number of cases and severe outcomes (Figs. 7B, S4B, S5B, Tables S10–12). As expected, the magnitude of the new wave is higher for low compliance levels.

3.6. Parameter uncertainty and sensitivity analysis

Our findings from the sensitivity analysis show that the parameters that the most affect cumulative infections and total infection as well as deaths are the ones related to adherence to isolation of mild cases, reduction of contacts, susceptibility, scaling factor of contacts and infectiousness of asymptomatic cases (Fig. S6). In detail, of the mentioned parameters, the one showing a negative significant correlation is the reduction of contacts, and all the remainings show a positive correlation. The

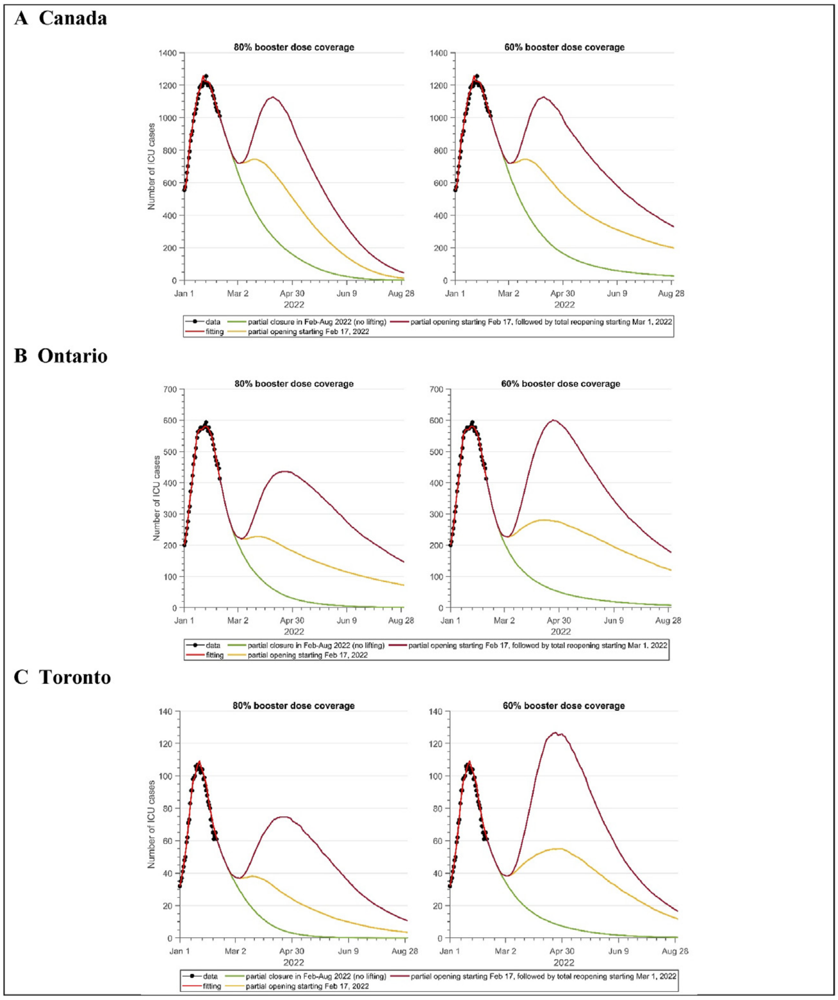

Fig. 6. The impact of booster dose coverage on the daily ICU occupancy after lifting the restriction measures. (A) Canada (B) Ontario (C) Toronto.

result suggests that to reduce the infections and severe outcomes is important to limit contacts, promote adherence to isolation, more adequate personal protective equipment for the most susceptible individuals and detect asymptomatic cases.

4. Discussion

We develope a COVID-19 transmission model introducing the new testing guideline, and its limitations, implemented in Canada after the rapid emergence of cases due to the Omicron variant. The population is divided into two subgroups depending on the settings they belong to: “high risk” settings (eligible for PCR testing under the new guidelines) and “non-high risk” settings (eligible for PCR testing under the new guidelines only under few circumstances). The model is calibrated to surveillance data in Toronto, Ontario, and Canada by implementing an iterative data-model assimilation approach and Bayesian estimation weekly forward. The structure of our model allows projections and analyses for any jurisdiction with available data.

Our model fitting suggests that current testing may capture a third of the total cases, leaving a large proportion of infected unreported. The unreported cases in the community are a worrying source of infection, which may result in further spreading or new waves. Although more rigorous PCR tests are effective in detecting the possible infections, mitigating the transmission, and reducing severe outcomes, the promotion of self covid test kits is also an alternative option with the consideration of costs and capacity of PCR testing. Although PCR testing is time consuming, to improve the control of the virus, returning the tests in a limited time is crucial.

Our results show that lifting restrictions will lead to a resurgent wave of infections and, consequently, hospitalisations, peaking in late March or April 2022. Our findings suggest that, to prevent any possible future resurgence, other measures such as vaccination, isolation and awareness of the epidemic are highly effective.

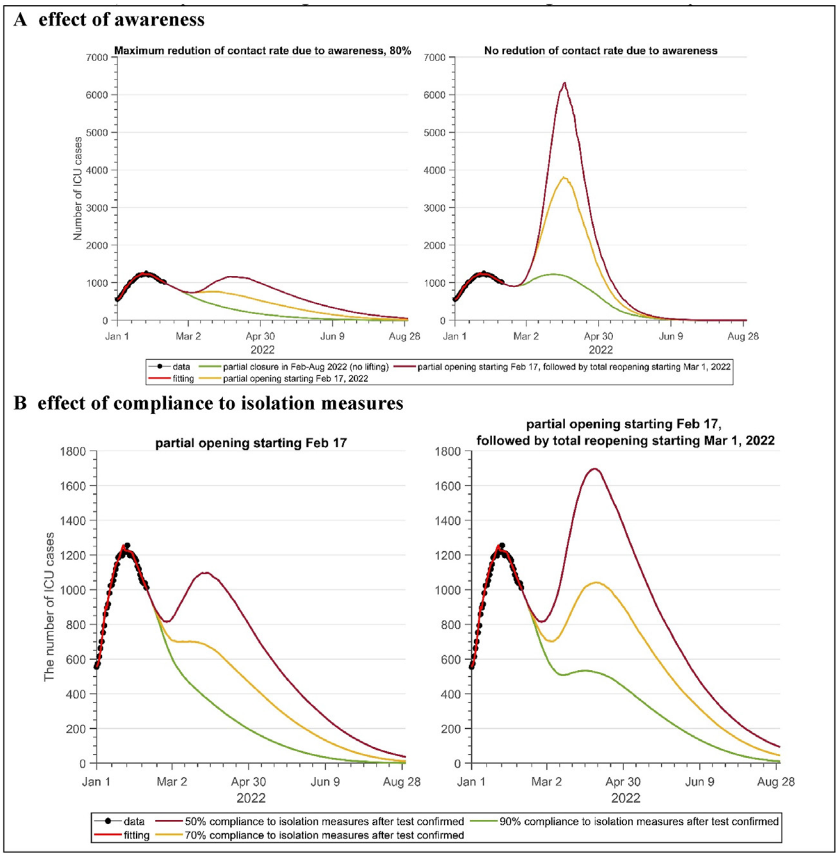

Fig. 7. The impact of social behaviors on the daily ICU occupancy in Canada after lifting the restriction measures.

The current testing guidelines, focused on the testing of symptomatic infections in high-risk settings, such as hospitals and congregate living settings, are efficient if strict NPIs are enforced, supported with booster third doses and the adherence to the social measures (Fig. 5, Tables S10–12). This also illustrates the feasibility of transition to endemic following the current testing strategy.

If more PCR tests are conducted, then more cases will be detected, and hence reported, but the reported deaths will not immediately affect the cases counts in about two incubation periods. The containment effect of PCR testing on transmission requires the high compliance of tested and confirmed population to the isolation measures and the adjustment of social behavior with people's awareness of the epidemic (Fig. 7).

Although our model describes the reality as much as possible, our work presents some limitations. The age is an important structure to include in a transmission model, given the significant differences within and between age groups in terms of population mixing and susceptibility. Hence, we are aware that this factor should be included to better reflect reality; however, extending our model with age-stratification will require more compartments and the applicable contact matrix as well as appropriate age-related parameters parameterization. On the other hand, our model captures the different transmission risks in groups by stratifying the population into high risk and non-high-risk settings. And our results can serve as a reasonable approximation of the impacts of this factor to a certain degree. Our projections are based on the latest week of data (early February 2022), further works to address the rapidly changing transmission risk and the intervention measures, will be required to extend the applicability of the present results. The evaluated transmission risk may change over time, and our weekly forward Bayesian estimation can help to capture these changes, which are efficient to generate the projections based on the real time circumstance for our policy makers.

5. Conclusions

A COVID-19 transmission model is modified to allow fitting of the model to recent, more limited, surveillance data. Model fitting estimates under-reporting of cases in the general population. Simulations suggest that, after easing restrictive public health measures, a resurgence of transmission that affects healthcare capacity will occur in late March or April 2022. This resurgence can be mitigated by limiting lifting of restrictions, increased detection of cases by self-testing at home, or by PCR testing by public health (both combined with isolation of those testing positive). The model results suggest that promoting testing and keeping restrictions in place are key factors for an efficient COVID-19 exit strategy.

It is indispensable to the containment of transmission that the public may consciously reduce their social contact when they notice a significant increase in the number of reported cases. The testing conducted by public health sectors is the means to help the identification of the infections, and then beneficial to the government to adjust the public health policy according to the actual infection. Finally, it is the behavior of each person in the community that determines the transmission. Blindly asking for more testing will not fundamentally mitigate the epidemic, but whether people follow public health policies based on the test results is the foundation of controlling transmission. This is even more important in the transition to endemic after the lifting of restrictions.

Funding

This research was supported by the Natural Sciences and Engineering Research Council of Canada and Public Health Agency of Canada OMNI one health modelling network for the Emerging Infectious Diseases Modelling Initiative; the Canadian Institutes of Health Research (CIHR) Canadian COVID-19 Math Modelling Task Force; and by York Research Chair Program.

Author contributions

Research design: H.Z., P.Y., N.O., E.A., Y.T., L.Y.; Literature search: E.A., Y.T., L.Y.; Data collection: Y.T., L.Y., P.Y.; Modelling: H.Z. and all; Simulations: P.Y., E.A.; Draft preparation: P.Y., E.A., Y.T., L.Y.; Writing-reviewing-editing: H.Z., N.O., A.F., E.A., P.Y., Y.T., L.Y.; Supervision: H.Z.

Data sharing

All the data used to generate simulations are reported in Tables S3–S7 in Supplementary materials.

Declaration of competing interest

All authors declare no conflicts of interest in this paper.

Acknowledgments

We thank Sarah Collier and Samantha Akingbola of Toronto Public Health for preparing and the providing the data of Toronto and discussion.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2022.03.004.

References

Arora, A. (2021). *COVID-19 in Canada: A One-year Update on Social and Economic Impacts*. Retrieved from: https://www150.statcan.gc.ca/n1/pub/11-631-x/11-631-x2021001-eng.htm (Accessed February 10, 2022).

Aruffo, E., Yuan, P., Tan, Y., Gatov, E., Gournis, E., Collier, S., et al. (2021). Community structured model for vaccine strategies to control COVID19 spread: A mathematical study. *medRxiv*. https://doi.org/10.1101/2021.01.25.21250505 (in press).

Brankston, G., Merkley, E., Fisman, D. N., Tuite, A. R., Poljak, Z., Loewen, P. J., & Greer, A. L. (2021). Quantifying contact patterns in response to COVID-19 public health measures in Canada. *BMC Public Health, 21*(1), 1–10. https://doi.org/10.1186/s12889-021-12080-1

British Columbia Centre for Disease Control. (2022). *When to get a COVID-19 test*. Retrieved from http://www.bccdc.ca/health-info/diseases-conditions/covid-19/testing/when-to-get-a-covid-19-test. (Accessed 10 January 2022).

Brüssow, H., & Zuber, S. (2022). Can a combination of vaccination and face mask wearing contain the COVID-19 pandemic? *Microbial Biotechnology, 15*(3). https://doi.org/10.1111/1751-7915.13997, 1721–737.

Caldwell, J. M., de Lara-Tuprio, E., Teng, T. R., Estuar, M. R. J. E., Sarmiento, R. F. R., Abayawardana, M., et al. (2021). Understanding COVID-19 dynamics and the effects of interventions in the Philippines: A mathematical modelling study. *The Lancet Regional Health-Western Pacific, 14*, Article 100211. https://doi.org/10.1016/j.lanwpc.2021.100211

Centers for Disease Control and Prevention. (2022). *Vaccines and immunizations, Interim Clinical Considerations for Use of COVID-19 Vaccines Currently Approved or Authorized in the United States*. Retrieved from: https://www.cdc.gov/vaccines/covid-19/clinical-considerations/covid-19-vaccines-us.html (Accessed January 20, 2022).

City of Toronto. (2022a). *COVID-19: Monitoring dashboard*. Retrieved from: https://www.toronto.ca/home/covid-19/covid-19-pandemic-data/covid-19-monitoring-dashboard-data/. (Accessed 10 February 2022).

City of Toronto. (2022b). *COVID-19: Pandemic data*. Retrieved from https://www.toronto.ca/home/covid-19/covid-19-pandemic-data/. (Accessed 15 February 2022).

Cleveland Clinic medical professional. (2021). *COVID-19 and PCR testing*. Retrieved from https://my.clevelandclinic.org/health/diagnostics/21462-covid-19-and-pcr-testing. (Accessed 10 January 2022).

Del Rio, C., Omer, S. B., & Malani, P. N. (2022). Winter of omicron—the evolving COVID-19 pandemic. *JAMA, 327*(4), 319–320. https://doi.org/10.1001/jama.2021.24315

Ejigu, B. A., Asfaw, M. D., Cavalerie, L., Abebaw, T., Nanyingi, M., & Baylis, M. (2021). Assessing the impact of non-pharmaceutical interventions (NPI) on the dynamics of COVID-19: A mathematical modelling study of the case of Ethiopia. *PLoS One, 16*(11), Article e0259874. https://doi.org/10.1371/journal.pone.0259874

Forde, J. E., & Ciupe, S. M. (2021). Quantification of the tradeoff between test sensitivity and test frequency in a COVID-19 epidemic—a multi-scale modeling approach. *Viruses, 13*(3), 457. https://doi.org/10.3390/v13030457

Goldberg, Y., Mandel, M., Bar-On, Y. M., Bodenheimer, O., Freedman, L., Haas, E. J., et al. (2021). Waning immunity after the BNT162b2 vaccine in Israel. *New England Journal of Medicine, 385*(24), e85. https://doi.org/10.1056/NEJMoa2114228

Government of Canada. (2022). *COVID-19 daily epidemiology update*. Retrieved from https://health-infobase.canada.ca/covid-19/epidemiological-summary-covid-19-cases.html. (Accessed 10 February 2022).

Government of Manitoba. (2022). *COVID-19 testing*. Retrieved from https://www.gov.mb.ca/covid19/testing/index.html. (Accessed 10 January 2022).

Government of Ontario. (2021). *Updated Eligibility for PCR Testing and Case and Contact Management Guidance in Ontario*. Retrieved from: https://news.ontario.ca/en/backgrounder/1001387/updated-eligibility-for-pcr-testing-and-case-and-contact-management-guidance-in-ontario (Accessed January 10, 2022).

Government of Quebec. (2022). *Get a COVID-19 test*. Retrieved from https://www.quebec.ca/en/health/health-issues/a-z/2019-coronavirus/testing-for-covid-19/get-covid-19-test#c129059. (Accessed 10 January 2022).

Grannis, S. J., Rowley, E. A., Ong, T. C., Stenehjem, E., Klein, N. P., DeSilva, M. B., et al. (2021). Interim estimates of COVID-19 vaccine effectiveness against COVID-19–associated emergency department or urgent care clinic encounters and hospitalizations among adults during SARS-CoV-2 B. 1.617. 2 (Delta) variant predominance—nine States, June–August 2021. *Morbidity and Mortality Weekly Report, 70*(37), 1291. https://stacks.cdc.gov/view/cdc/113718.

Grundel, S., Heyder, S., Hotz, T., Ritschel, T. K., Sauerteig, P., & Worthmann, K. (2022). How much testing and social distancing is required to control COVID-19? Some insight based on an age-differentiated compartmental model. *SIAM Journal on Control and Optimization*, S145–S169. https://doi.org/10.1137/20M1377783, 0.

Hellewell, J., Abbott, S., Gimma, A., Bosse, N. I., Jarvis, C. I., Russell, T. W., et al. (2020). Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts. *Lancet Global Health, 8*(4), e488–e496. https://doi.org/10.1016/S2214-109X(20)30074-7

Holmdahl, I., Kahn, R., Hay, J. A., Buckee, C. O., & Mina, M. J. (2021). Estimation of transmission of COVID-19 in simulated nursing homes with frequent testing and immunity-based staffing. *JAMA Network Open, 4*(5). https://doi.org/10.1001/jamanetworkopen.2021.10071. e2110071-e2110071.

Korenkov, M., Poopalasingam, N., Madler, M., Vanshylla, K., Eggeling, R., Wirtz, M., et al. (2021). Evaluation of a rapid antigen test to detect SARS-CoV-2 infection and identify potentially infectious individuals. *Journal of Clinical Microbiology, 59*(9). https://doi.org/10.1128/JCM.00896-21. e00896-21.

Lafzi, A., Boodaghi, M., Zamani, S., Mohammadshafie, N., & Hasti, V. R. (2021). Analysis of the effectiveness of face-coverings on the death ratio of COVID-19 using machine learning. *Scientific Reports, 11*(1), 1–12. https://doi.org/10.1038/s41598-021-01005-y

Larremore, D. B., Wilder, B., Lester, E., Shehata, S., Burke, J. M., Hay, J. A., et al. (2021). Test sensitivity is secondary to frequency and turnaround time for COVID-19 screening. *Science Advances, 7*(1), eabd5393. https://www.science.org/doi/10.1126/sciadv.abd5393.

Layton, A. T., & Sadria, M. (2022). Understanding the dynamics of SARS-CoV-2 variants of concern in Ontario, Canada: A modeling study. *Scientific Reports, 12*(1), 1–16. https://doi.org/10.1038/s41598-022-06159-x

Levin, E. G., Lustig, Y., Cohen, C., Fluss, R., Indenbaum, V., Amit, S., et al. (2021). Waning immune humoral response to BNT162b2 Covid-19 vaccine over 6 months. *New England Journal of Medicine, 385*(24), e84. https://doi.org/10.1056/NEJMoa2114583

Lin, Q., Zhao, S., Gao, D., Lou, Y., Yang, S., Musa, S. S., et al. (2020). A conceptual model for the coronavirus disease 2019 (COVID-19) outbreak in Wuhan, China with individual reaction and governmental action. *International Journal of Infectious Diseases, 93*, 211–216. https://doi.org/10.1016/j.ijid.2020.02.058

Mahase, E. (2021). Covid-19: Omicron and the need for boosters. *BMJ, 375*, n3079. https://doi.org/10.1136/bmj.n3079

McCoy, L. G., Smith, J., Anchuri, K., Berry, I., Pineda, J., Harish, V., et al. (2020). Characterizing early Canadian federal, provincial, territorial and municipal nonpharmaceutical interventions in response to COVID-19: A descriptive analysis. *Canadian Medical Association Open Access Journal, 8*(3), E545–E553. https://doi.org/10.9778/cmajo.20200100

Newcomb, K., Smith, M. E., Donohue, R. E., Wyngaard, S., Reinking, C., Sweet, C. R., et al. (2022). Iterative data-driven forecasting of the transmission and management of SARS-CoV-2/COVID-19 using social interventions at the county-level. *Scientific Reports, 12*(1), 1–19. https://doi.org/10.1038/s41598-022-04899-4

Ngonghala, C. N., Iboi, E., Eikenberry, S., Scotch, M., MacIntyre, C. R., Bonds, M. H., & Gumel, A. B. (2020). Mathematical assessment of the impact of non-pharmaceutical interventions on curtailing the 2019 novel Coronavirus. *Mathematical Biosciences, 325*, Article 108364. https://doi.org/10.1016/j.mbs.2020.108364

Pedro, S. A., Ndjomatchoua, F. T., Jentsch, P., Tchuenche, J. M., Anand, M., & Bauch, C. T. (2020). Conditions for a second wave of COVID-19 due to interactions between disease dynamics and social processes. *Frontiers in Physics, 8*, 428. https://doi.org/10.3389/fphy.2020.574514

Peeling, R. W., Olliaro, P. L., Boeras, D. I., & Fongwen, N. (2021). Scaling up COVID-19 rapid antigen tests: Promises and challenges. *The Lancet Infectious Diseases, 21*(9), e290–e295. https://doi.org/10.1016/S1473-3099(21)00048-7

Prince-Guerra, J. L., Almendares, O., Nolen, L. D., Gunn, J. K., Dale, A. P., Buono, S. A., et al. (2021). Evaluation of Abbott BinaxNOW rapid antigen test for SARS-CoV-2 infection at two community-based testing sites—Pima County, Arizona, November 3–17, 2020. *Morbidity and Mortality Weekly Report, 70*(3), 100. https://doi.org/10.15585/mmwr.mm7003e3

Public Health Ontario. (2022). *Ontario COVID-19 Data Tool*. Retrieved from: https://www.publichealthontario.ca/en/data-and-analysis/infectious-disease/covid-19-data-surveillance/covid-19-data-tool?tab=summary (Accessed February 10, 2022).

Smith, D. R., Duval, A., Zahar, J. R., Opatowski, L., & Temime, L. (2022). Rapid antigen testing as a reactive response to surges in nosocomial SARS-CoV-2 outbreak risk. *Nature Communications, 13*(1), 1–10. https://doi.org/10.1038/s41467-021-27845-w

Swaminathan, S. (2022). *Omicron shows the urgent need for a catch-all vaccine*. Retrieved from: https://www.nature.com/articles/d44151-022-00010-y (Accessed February 15, 2022).

Tartof, S. Y., Slezak, J. M., Puzniak, L., Hong, V., Frankland, T. B., Ackerson, B. K., et al. (2022). Effectiveness of a third dose of BNT162b2 mRNA COVID-19 vaccine in a large US health system: A retrospective cohort study. *The Lancet Regional Health-Americas*. , Article 100198. https://doi.org/10.1016/j.lana.2022.100198

Tong, C., Shi, W., Zhang, A., & Shi, Z. (2022). Tracking and controlling the spatiotemporal spread of SARS-CoV-2 Omicron variant in South Africa. *Travel Medicine and Infectious Disease, 46*, Article 102252. https://doi.org/10.1016/j.tmaid.2021.102252

Weitz, J. S., Park, S. W., Eksin, C., & Dushoff, J. (2020). Awareness-driven behavior changes can shift the shape of epidemics away from peaks and toward plateaus, shoulders, and oscillations. *Proceedings of the National Academy of Sciences, 117*(51), 32764–32771. https://doi.org/10.1073/pnas.2009911117

Yuan, P., Aruffo, E., Gatov, E., Tan, Y., Li, Q., Ogden, N., et al. (2022). School and community reopening during the COVID-19 pandemic: A mathematical modelling study. *Royal Society Open Science, 9*, Article 211883. https://doi.org/10.1098/rsos.211883

Yuan, P., Li, J., Aruffo, E., Li, Q., Zheng, T., Ogden, N., et al. (2020). *Efficacy of'Stay-at-Home'Policy and transmission of COVID-19 in Toronto, Canada: A mathematical modeling study*. https://www.medrxiv.org/content/10.1101/2020.10.19.20181057v1 (accepted CMAJ).

Yu, J., Huang, Y., & Shen, Z. J. (2021). Optimizing and evaluating PCR-based pooled screening during COVID-19 pandemics. *Scientific Reports, 11*(1), 1–14. https://doi.org/10.1038/s41598-021-01065-0