Counterfactuals of effects of vaccination and public health measures on COVID-19 cases in Canada: What could have happened? — Supplemental material

Nicholas H Ogden, Patricia Turgeon, Aamir Fazil, Julia Clark, Vanessa Gabriele-Rivet, Theresa Tam, Victoria Ng

Agent-based model background

The agent-based model (ABM) has been previously published (1–3) and additional publicly-available technical information can be found at https://nccid.ca/phac-agent-based-model-on-covid-19/.

The model is an age-stratified agent-based simulation for the transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in the Canadian population. Community transmission is assumed to have begun on February 7, 2020 based on the date of onset reported by the first domestic coronavirus disease 2019 (COVID-19) cases emerging in Canada (4). Transmission was initiated with ten cases over a two-week period to propagate local transmission. The model assumed there was an importation rate of one permanent and one transient imported case per 100,000 per week during the initial phase of the epidemic (see "Imported cases" section), representing infected travellers returning to Canada prior to, or during, their infectious period. The model uses a daily time step over 784 days (day 0 representing February 7, 2020 and day 783 representing March 31, 2022).

Agents were modelled in ten distinct age groups to account for differences in age-specific health outcomes and contact rates.

Population structure and demographics

The model is a simplified version of movement and connectivity in the Canadian population. Models were run on a population size of 100,000; with demographics and household structure scaled to the Canadian population (**Table S1** and **Table S2**, respectively) (5,6).

Table S1: Proportion of agents by age group

Category name	Age group (years)	Proportion of agents distributed according to the 2019 Canadian population estimates (5)
Child 1	0–4	0.051695
Child 2	5–9	0.054254
Child 3	10–14	0.054052
Youth	15–19	0.056256
Adult 1	20–44	0.338052
Adult 2	45–54	0.130332
Adult 3	55–64	0.13997
Senior 1	65–74	0.101182
Senior 2	75–84	0.051903
Elderly	85 or older	0.022301

Table S2: Household structure in the model

Household size	Number of households according to the 2016 Canadian census (6)	Total agents
1-member	11,725	11,725
2-member	13,900	27,800
3-member	6,200	18,600
4-member	5,800	23,200
5-member	2,500	12,500
6-member	750	4,500
7-member	125	875
8-member	100	800
Total	41,100 households	100,000 agents

Model environment and agent movement

Agents were assigned to a designated household and common environment (school, workplace or a mixed age meeting venue) according to their age, using contact rate projections for Canada as a guide to assigning agents of age groups that are likely to come into contact with each other at home, at work, at school and in other locations (called mixed age venues in the model) (7). Mixed age venues were defined as any place where individuals have contact with agents from a range of different age groups; this could include restaurants, cafes, shopping centres, museums, libraries, movie theatres, grocery supermarkets, public parks and beaches. There was no distinction between indoor and outdoor environments in the model. In comparison, workplaces were defined by a more restrictive group of age groups mixing, primarily those between the ages of 17 and 74 years with most agents assigned from the middle year age groups. Agents under 17 years and over 74 years were not assigned to workplaces. Schools included daycares, elementary and high schools, with most agents between the ages of 0–16 years assigned to schools, some agents remained at home with guardians. Agents were distributed into the three common environments on weekdays as summarized in **Table S3**. A total of 40 schools, 750 workplaces and 415 mixed age venues per 100,000 persons were modelled to give an approximate density of 500 agents/school, 50 agents/workplace and 100 agents/mixed age venue. These were our estimates for the average Canadian population.

Table S3: Distribution of agents by age into common mixing environments on weekdays

Category	Age group (years)	Schools	Workplaces[a]	Mixed age venues
Child 1	0–4	60%	0%	40%
Child 2	5–9	100%	0%	0%
Child 3	10–14	100%	0%	0%
Youth	15–19	80%	10%[a]	10%
Adult 1	20–44	2%	50%	48%
Adult 2	45–54	5%	60%	35%
Adult 3	55–64	5%	70%	25%
Senior 1	65–74	0%	30%	70%
Senior 2	75–84	0%	0%	100%
Elderly	85 or older	0%	0%	100%

[a] Only agents 17 years of age or older could be assigned to workplaces

At model initialization, agents moved between their household and common environment during the weekday spending on average of eight hours per day outside of home. Each weekend, a different group of agents were selected at random to visit a different mixed age environment than their regularly assigned one; it was assumed schools and workplaces are closed on weekends.

Mobility varied by age and between weekdays and weekends; older agents were not as mobile during the weekdays as younger individuals but for simplicity it was assumed weekend movement was uniform across age groups (**Table S4**). Mobility was determined daily for each agent; agents could leave the household if selected by chance based on the probability estimated for their age group. Mobility therefore varied by agent and by day of the week throughout the model run (in addition to restrictions that limited mobility; for example, closures and vaccine mandates, etc. See "Public health interventions in the model" section.

Table S4: Mobility probabilities by age group on weekdays and the weekend

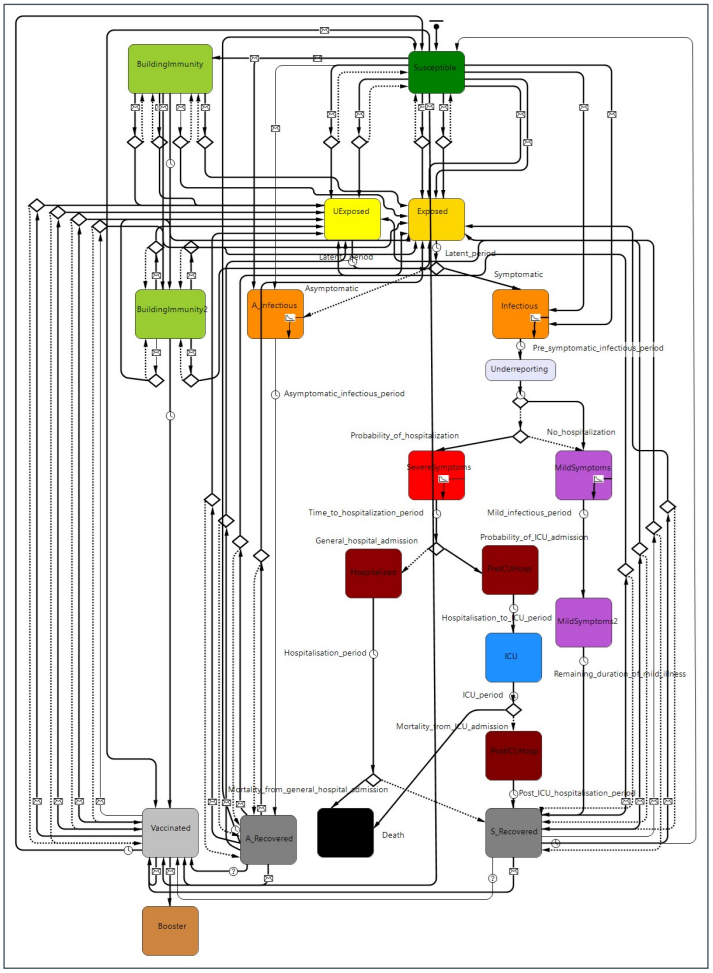
Category	Age group	Mobility on weekdays	Mobility on the weekend
Child 1	0–4	0.7	0.7
Child 2	5–9	0.95	0.7
Child 3	10–14	0.95	0.7
Youth	15–19	0.95	0.7
Adult 1	20–44	0.9	0.7
Adult 2	45–54	0.9	0.7
Adult 3	55–64	0.9	0.7
Senior 1	65–74	0.8	0.7
Senior 2	75–84	0.7	0.7
Elderly	85 or older	0.6	0.7

Health and hospitalization states of agents

A framework of compartments was developed to represent epidemiological health states of agents (**Figure S1**). All agents begin as susceptible (it was assumed the Canadian population was completely naive to SARS-CoV-2) except for initially infected agents used to seed transmission. Infection occurs on successful contact between susceptible and infectious agents. Infectious agents occur as four states: asymptomatic; pre-symptomatic; mild symptomatic; and severe symptomatic. Severe cases, after a pre-symptomatic period, remained at home until hospitalization and could only transmit infection to household members at a reduced rate of 50%. In contrast, asymptomatic, pre-symptomatic and mild cases can infect both at home to household members and in common environments. On infection, agents progress through different health states beginning with the exposed states (distinguished by those exposed by a symptomatic case and those exposed by an asymptomatic case) until either recovery or death is reached. Recovered individuals, after a period of waning of immunity, can become reinfected again (see "Vaccination and infection-acquired protection" section). The duration in which agents remained in each epidemiological health state varied and was determined by sampling from probability distributions defined by the literature or Canadian data (**Table S5**). Vaccination states included building immunity after dose 1, building immunity after dose 2, vaccinated (full protection from two doses) and booster (full protection from three doses). Agents were selected for vaccination in a number of different health states and on receipt

of a dose of the vaccine, moved into the respective vaccination states. A small proportion of agents who received the vaccine did not move into the vaccination states, reflecting imperfect vaccine effectiveness (Table S5). Agents remained in the vaccinated or booster states for the duration of the model run or until they were infected (see "Vaccination and Infection-acquired protection" section).

Figure S1: Schematic of the agent-based model structure[a] for coronavirus disease 2019 transmission



Abbreviations: A_, asymptomtic; Asymp, asymptomatic; Hosp; hospitalization; ICU, intensive care unit; infec, infection; S_, symptomatic; VOC, variant of concern

[a] The Public Health Agency of Canada agent-based model explored vaccines against the wild-type and variants with unique characteristics in addition to other public health interventions (see "Public health interventions in the model" section)

Transmission of COVID-19 from infected agents to susceptible agents occurred within the household and within common environments. For simplicity, the current model did not incorporate transmission during agent's commute or in other unique environments such as in hospitals or long-term care facilities. The model therefore represented the baseline number of infections, hospitalizations and deaths excluding isolated outbreaks such as those seen in long-term care facility, hospitals and other localized outbreaks. To adjust for hospitalization and mortality rates that were inflated due to deaths in long-term case facilities and hospitals, cases linked to outbreaks in institutions and transmission in hospitals were removed to provide a better estimate of hospitalization and mortality rate due to general community transmission (Table S5). At the end of 2021, as a result of under-reporting during the Omicron wave, an under-reporting compartment was created in order to fit projected hospitalization prevalence in the model to Canadian hospitalization data.

Transmission probability calibration

The transmission probability parameter (β) was calibrated by fitting cumulative clinical cases from the model to domestically-acquired Canadian cases per 100,000 from February 20 to March 26, 2020 using a simulation optimization engine in AnyLogic. The three-week delay in data fitting was due to restrictions on optimization on integers. The end date was selected as we assumed the impact of community closures in mid-March would be observed after March 26 and the goal was to determine the natural transmission of COVID-19 in Canada prior to restrictive public health intervention. The model was calibrated to the Canadian data assuming 20% of cases were detected and isolated during their mild symptomatic period and 50% of contacts of the 20% of cases detected were identified and quarantined to account for estimated intervention efforts in Canada over this period (41). The calibrated transmission probability per contact value when applied to the contact matrices in the model and the average duration of infectiousness returned an estimated R_0 of 2.7 at the beginning of the outbreak in Canada. This was consistent with other studies (42). We assumed susceptibility was uniform across age groups due to the current lack of evidence on this phenomenon; for this reason, we fitted the transmission parameter uniformly across all age groups.

Contact matrices

Four contact matrices were incorporated in the model; one for each location in the model for which contact between agents can occur. The number of daily contacts per agent was defined by age using projections for Canada from the POLYMOD study and adapted by Prem *et al.* (**Table S6)** (7). Contacts were distributed amongst agents based on location and defined by four contact matrices also derived from Canadian projections from the same study (**Table S7** sections a to d) (7).

Table S6: Age-dependent daily contact rates[a]

Category	Age group (years)	Daily contact rates
Child 1	0–4	9.0957
Child 2	5–9	10.5341
Child 3	10–14	13.0621
Youth	15–19	20.3667
Adult 1	20–44	15.3519
Adult 2	45–54	14.9039
Adult 3	55–64	11.0106
Senior 1	65–74	6.5229
Senior 2	75–84	4.5929
Elderly	85 or older	4.5929

[a] Adapted from (7)

Table S5: Model parameters

Parameter (unit)	Description	Value(s) (age range, years)	Reference/s or sources of information
Transmission probability (β) without vaccination (per contact)	β was calibrated to the model using Canadian case data linked to community transmission from February 20 to March 30, 2020. See "Transmission probability calibration" section for additional information β was 50%, 100% and 250% more transmissible than wild type (WT) for Alpha, Delta and Omicron BA.1, respectively	0.03931058 Due to a lack of data in the literature to date, β was assumed to be uniform across age groups	Fitted value (8)
Age-specific contact rate (contacts per day)	Contact rate between individuals by age group. Younger individuals generally had higher daily contact rates than older agents	9.0957 (0–4 years) 10.5341 (5–9 years) 13.0621 (10–14 years) 20.3667 (15–19 years) 15.3519 (20–44 years) 14.9039(45–54 years) 11.0106 (55–64 years) 6.5229 (65–74 years) 4.5929(75–84 years) 4.5929 (85 or older)	(7)
Latent period (days)	Time from successful contact; i.e. infection, to the time when a person can transmit infection to another person	PERT[a] distribution (2, 5, 3.77) μ (mean) – 3.68 σ (standard deviation) – 0.5	(9)
Probability of symptomatic infection without vaccination (proportion)	Probability of developing symptoms given infection. Adjusted for the Canadian population, approximately 38% of WT, Alpha and Delta infections were asymptomatic Probabilities were halved for Omicron BA.1 reflecting milder infections (approximately 19%, or 1 in 5 infections were asymptomatic)	0.5 (0–4 years) 0.5 (5–9 years) 0.5 (10–14 years) 0.5 (15–19 years) 0.6 (20–44 years) 0.7 (45–54 years) 0.7 (55–64 years) 0.8 (65–74 years) 0.95 (75–84 years) 1.0 (85 or older)	(10–15)
Pre-symptomatic infectious period (days)	Duration of time from when a case (who eventually developed symptoms) can transmit infection to another person prior to becoming symptomatic	PERT distribution (1, 3, 2.5) μ – 2.33; σ – 0.33	(16–22)
Asymptomatic infectious period (days)	Duration of time from when a case (who remained asymptomatic for the duration of their illness) can transmit infection to another person	PERT distribution (3.5, 10, 6) μ – 6.25; σ – 1.08	(23)
Probability of hospitalization without vaccination (proportion)[b]	Proportion of symptomatic cases with severe and critical illness requiring acute hospitalization for a WT infection Hospitalization increased by 40% for Alpha infections, 80% for Delta infections and was reduced by 30% for Omicron BA.1 strains compared to WT	0.03671 (0–4 years) 0.00818 (5–9 years) 0.01668 (10–14 years) 0.02658 (15–19 years) 0.05348 (20–44 years) 0.11904 (45–54 years) 0.21184 (55–64 years) 0.40341 (65–74 years) 0.52133 (75–84 years) 0.44169 (85 or older)	(4)
Mild infectious period (days)	Duration of time in the first phase of mild illness when cases are symptomatic and can transmit infection to others	PERT distribution (3, 7, 3.5) μ – 4.0; σ – 0.67	(21,24)
Remaining duration of mild illness (days)	Duration of time in the second phase of mild illness when cases were still symptomatic but were no longer able to transmit infection to others	PERT distribution (2, 5, 3) μ – 3.17; σ – 0.5	Estimate

Table S5: Model parameters (*continued*)

Parameter (unit)	Description	Value(s) (age range, years)	Reference/s or sources of information
Time to hospitalization period (days)	Duration of time between when a case developed symptoms to when they sought medical care at the hospital	Normal distribution (0.5, 5) μ – 5; σ – 0.5	(25–28)
Probability of ICU admission without vaccination (proportion)	Proportion of cases that were critical that were hospitalized first, and then moved on to being admitted into the ICU	0.17241 (0–4 years) 0.0 (5–9 years) 0.29412 (10–14 years) 0.20513 (15–19 years) 0.22644 (20–44 years) 0.28866 (45–54 years) 0.30579 (55–64 years) 0.28292 (65–74 years) 0.15492 (75–84 years) 0.04819 (85 or older)	(4)
Hospitalization period; i.e. hospital length of stay (days)	Duration of time a severe case spent in general hospitalization for medical care to the time that they recovered or died Adjusted similarly for probability of hospitalization, hospital length of stay increased by 40% for Alpha infections, 80% for Delta infections and was reduced by 30% for Omicron BA.1	PERT distribution (3, 14, 10) μ – 9.5; σ – 1.83 Alpha: PERT distribution (4, 20, 14) Delta: PERT distribution (2, 25, 18) Omicron BA.1: PERT distribution (2, 10, 7)	(28–34)
Hospitalization to ICU period (days)	Duration of time a critical case spent in hospital prior to being admitted into the ICU	Normal distribution (0.3, 3) μ – 3; σ – 0.3	(29–31,35)
ICU period (days)	Duration of time a critical case spent in the ICU for medical care to post-ICU hospitalization or death	PERT distribution (4, 13, 8) μ – 8.17; σ – 1.5	(29–31,33,35–38)
Post-ICU hospitalization period (days)	Duration of time a critical case spends in hospital after being discharged from the ICU to recovery or to death	PERT distribution (3, 10 ,7) μ – 6.83; σ – 1.17	(29–31,35)
General admission hospital beds and ICU beds	Number of beds available per 100,000 for COVID-19 patients	31 hospital beds per 100,000[c] 6 ICU beds per 100,000[c]	(*personal communication, Alan Diener, Health Canada, January 25, 2021*)
Mortality rate from general hospital admissions without vaccination (proportion)	Age specific mortality rate occurring from general hospitalization. Approximately 40% of all deaths occurred from hospitalized cases Mortality rate was doubled when hospital beds were overcapacity (39,40)	(0–4 years) (5–9 years) (10–14 years) 0.0 (15–19 years) 0.0088 (20–44 years) 0.0188 (45–54 years) 0.0758 (55–64 years) 0.2252 (65–74 years) 0.352 (75–84 years) 0.4719 (85 or older)	(4)

Table S5: Model parameters (*continued*)

Parameter (unit)	Description	Value(s) (age range, years)	Reference/s or sources of information
Mortality rate from ICU admissions without vaccination (proportion)	Age specific mortality rate occurring from cases admitted into the ICU. Approximately 60% of all deaths occurred from ICU-admitted cases Mortality rate was doubled when hospital beds were at overcapacity (39,40)	(0–4 years) (5–9 years) (10–14 years) 0.0 (15–19 years) 0.0927 (20–44 years) 0.1559 (45–54 years) 0.2432 (55–64 years) 0.3555 (65–74 years) 0.5294 (75–84 years) 0.7294 (85 or older)	(4)

Abbreviations: COVID-19, coronavirus disease 2019; ICU, intensive care unit
[a] The PERT distribution was used due limited information about the distribution of some parameters for COVID-19
[b] COVID-19 cases linked to long-term care facilities and healthcare workers were removed to provide a better estimate of hospitalization rates and mortality rate of COVID-19 in the general population and because our model did not explore outbreaks from long-term care facilities and hospital transmission
[c] Updated on January 25, 2021

Table S7: Contact matrices showing the contact probabilities per agent, for each age group, within home, school, workplace and mixed age venues[a]

a) Home

Age group	0–4	5–9	10–14	15–19	20–44	45–54	55–64	65–74	75–84	85+
0–4	0.185268924	0.136841211	0.062772461	0.026486915	0.531074593	0.03755945	0.015109835	0.003183077	0.000851768	0.000851768
5–9	0.079574435	0.248676333	0.108828251	0.034129466	0.467304082	0.048113943	0.009440427	0.002962686	0.000485188	0.000485188
10–14	0.033961819	0.102913604	0.37182724	0.096565139	0.302666114	0.079605258	0.007342565	0.004159194	0.000479533	0.000479533
15–19	0.017385409	0.034227758	0.12479159	0.367875165	0.244262838	0.187289277	0.018563829	0.004803152	0.000400491	0.000400491
20–44	0.113845916	0.122409498	0.097124589	0.070114248	0.481927257	0.078010985	0.030122423	0.005147394	0.000648845	0.000648845
45–54	0.044172607	0.061014183	0.114531315	0.167415659	0.244274449	0.323341426	0.03645493	0.004878245	0.001958592	0.001958592
55–64	0.083402037	0.078014699	0.057054872	0.07080258	0.276447468	0.08018985	0.325864426	0.027005	0.000609534	0.000609534
65–74	0.052446418	0.100139912	0.09313197	0.064808552	0.258083077	0.060366748	0.073748958	0.281306523	0.007983922	0.007983922
75–84	0.063506226	0.077012341	0.121626883	0.095200131	0.21448991	0.177675224	0.053772675	0.065268719	0.065723945	0.065723945
85+	0.063506226	0.077012341	0.121626883	0.095200131	0.21448991	0.177675224	0.053772675	0.065268719	0.065723945	0.065723945

b) School

Age group	0–4	5–9	10–14	15–19	20–44	45–54	55–64	65–74	75–84	85+
0–4	0.667455938	0.102112522	0.019015295	0.025222437	0.140713216	0.035820713	0.009659879	0	0	0
5–9	0.093550235	0.74692461	0.043109234	0.005861935	0.077623144	0.027317591	0.005613251	0	0	0
10–14	0.000609077	0.126442172	0.761358414	0.029027584	0.052282537	0.023829317	0.006450899	0	0	0
15–19	0.002700024	0.004018615	0.175545221	0.745851841	0.045619098	0.020741558	0.005523643	0	0	0
20–44	0.047182146	0.139244496	0.092980462	0.307656708	0.345093209	0.052082954	0.015760025	0	0	0
45–54	0.086538354	0.176213291	0.188880134	0.364729195	0.107361531	0.06051167	0.015765826	0	0	0
55–64	0.123645408	0.199257947	0.166457593	0.288427887	0.130244678	0.052309999	0.039656489	0	0	0
65–74	0	0	0	0	0	0	0	0	0	0
75–84	0	0	0	0	0	0	0	0	0	0
85+	0	0	0	0	0	0	0	0	0	0

Table S7: Contact matrices showing the contact probabilities per agent, for each age group, within home, school, workplace and mixed age venues[a] (*continued*)

c) Workplace

Age group	0–4	5–9	10–14	15–19	20–44	45–54	55–64	65–74	75–84	85+
0–4	0	0	0	0	0	0	0	0	0	0
5–9	0	0	0	0	0	0	0	0	0	0
10–14	0	0	0	0	0	0	0	0	0	0
15–19	0	0	0	0.230344513	0.609452032	0.135180423	0.025020481	2.5502E-06	0	0
20–44	0	0	0	0.050490031	0.708783724	0.20152575	0.039198385	2.11074E-06	0	0
45–54	0	0	0	0.045763147	0.612394359	0.282820703	0.059019454	2.33625E-06	0	0
55–64	0	0	0	0.037551598	0.610427672	0.267233687	0.084779535	7.50828E-06	0	0
65–74	0	0	0	0.041277242	0.504506081	0.24778632	0.180746366	0.025683991	0	0
75–84	0	0	0	0	0	0	0	0	0	0
85+	0	0	0	0	0	0	0	0	0	0

d) Mixed age venues

Age group	0–4	5–9	10–14	15–19	20–44	45–54	55–64	65–74	75–84	85+
0–4	0.168139804	0.073182455	0.037321849	0.031165597	0.401946649	0.118595541	0.101926314	0.057947786	0.004887003	0.004887003
5–9	0.073632396	0.278855522	0.101848468	0.031936905	0.314583842	0.07404201	0.075324436	0.040830057	0.004473181	0.004473181
10–14	0.019946287	0.106621397	0.375858913	0.066411771	0.262526143	0.086224369	0.041503389	0.030674833	0.005116449	0.005116449
15–19	0.008794229	0.027834342	0.129072814	0.437577757	0.291204474	0.068153243	0.021106225	0.013213285	0.001521815	0.001521815
20–44	0.024976547	0.023353486	0.02849828	0.074076533	0.610138038	0.133566987	0.067573564	0.031134162	0.003341201	0.003341201
45–54	0.011246284	0.020290879	0.024054085	0.044471599	0.473232159	0.239180085	0.12707165	0.051900294	0.004276483	0.004276483
55–64	0.015610564	0.01520968	0.014876674	0.022550805	0.436932485	0.183184314	0.205882008	0.095600726	0.005076372	0.005076372
65–74	0.010953225	0.016417351	0.014351632	0.023580045	0.358445882	0.164433878	0.213938798	0.180408283	0.008735454	0.008735454
75–84	0.015412188	0.015768683	0.023208638	0.014490252	0.315027559	0.183117471	0.166447925	0.205473912	0.030526687	0.030526687
85+	0.015412188	0.015768683	0.023208638	0.014490252	0.315027559	0.183117471	0.166447925	0.205473912	0.030526687	0.030526687

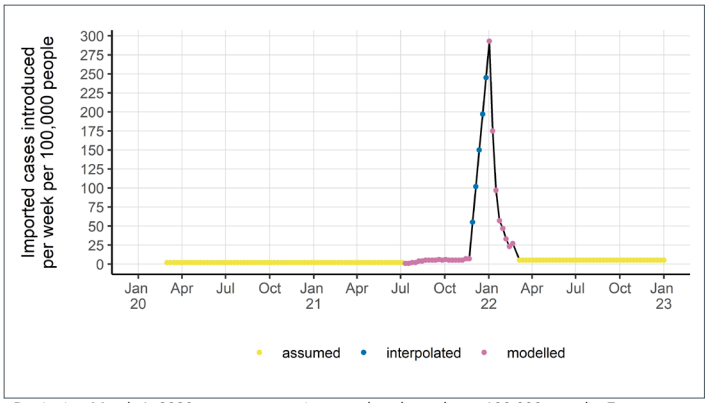
[a] Adapted from (7)

Imported cases

Where possible, the number of infected travellers entering the ABM population was estimated from the Public Health Agency of Canada (PHAC) importation risk model. These numbers represent the number of infected travellers who either entered Canada after being tested at least 72 hours prior to travelling to Canada (pre-departure testing) and were assumed to have evaded detection or were exempt from testing (43,44). For the entire model run, the weekly number of imported cases per 100,000 in the ABM was allocated to one permanent case (staying in the population indefinitely) with remaining cases set as transient cases (staying in the population for one to five full days). Permanent cases leading to hospitalizations were captured in the model outputs whereas transient cases leading to hospitalizations are not captured in the model outputs.

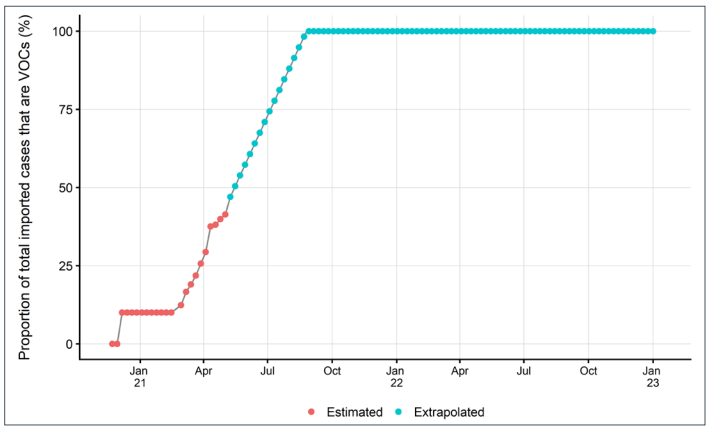
During the first year of the pandemic (March 2020 to February 2021), the number of infected travellers entering Canada was assumed to remain constant at two cases per 100,000 per week representing a closed border (**Figure S2**). From July 11, 2021 to February 26, 2022, the number of imported cases were estimated and extracted from the PHAC importation risk model (manuscript in progress). Due to an underestimation of the importation risk model during the Omicron wave, the model estimates were corrected based on border testing data for the months of January and February 2022. Linear interpolation was used to estimate the number of imported cases throughout the month of December due to a lack of reliable data from the model. The counts from the importation risk model were adjusted to match the population size for the ABM resulting in 293 imported cases per week entering a Canadian population of 100,000 during the peak of the omicron wave (winter 2022). Subsequently, it was assumed that the number of imported cases remained constant at five cases per week per 100,000 from February 27, 2022 to the end of the model run.

Figure S2: Imported cases introduced into the agent-based model per week over time[a]



[a] Beginning March 1, 2020, two cases are imported each week per 100,000 people. From July 11, 2021 to February 26, 2022, the agent-based model imported cases were based on weekly estimates of the Public Health Agency of Canada importation risk model, with linearly interpolated estimates during the month of December 2021. The number of imported cases remains at five per 100,000 people for the remainder of the model time

Figure S3: Proportion of imported cases that are variants of concern as estimated by the Public Health Agency of Canada importation risk model[a]



Abbreviation: VOC, variant of concern

[a] The red markers indicate proportions estimated from model outputs, the blue markers indicate extrapolated data points estimated for future time periods. The proportion of imported cases that represent a variant of concern reached 100% by August 29, 2021

Variants of concern

The introduction of variants of concern (VOC) occurred via imported returning travellers. When a susceptible agent was exposed, the strain of SARS-CoV-2 from the infector was tracked to allow for the calculation of the probability of successful infection on exposure and the probability of onward infection to other agents in the model. The model explored five strains of SARS-CoV-2: the original wild-type (WT) and three VOC (Alpha, Delta, Omicron BA.1), each has different characteristics including transmissibility, virulence, immune escape from protection against infections, clinical symptoms, hospitalizations and deaths acquired from vaccines, a previous infection, or both. **Figure S3** shows the probability of VOC entering the model population via an imported case. The data points from December 1, 2020 to February 7, 2021 were assumed to be equal to 10% (red markers). The values from December 2020 to May 9, 2021 were estimated from the PHAC importation risk model (red markers) and the subsequent data points (blue markers) were linearly extrapolated with the proportion of imported cases projected to be VOCs reaching 100% by August 29, 2021.

The model assumed the emergence of Alpha on December 1, 2020, introduced by imported cases entering the population with a 10% probability that an imported case entered infected with the Alpha variant. The Alpha variant is 50% more transmissible and 40% more virulent than the WT but does not demonstrate immune escape characteristics (Table S5 and **Table S8**) (7,45,46).

On March 9, 2021, imported cases entering the model population with a VOC could be either an Alpha or Delta variant, representing the co-circulation of these two variants in Canada around this period. The number of Delta introductions was calculated as inversely proportional to Alpha introductions and reflected the global situation as Delta dominated over time. Delta was introduced into the population with a 1.6% probability of all VOCs introduced on March 9, 2021 and increased linearly over time to complete dominance (100%) by August 29, 2021. Delta is 100% more transmissible and 80% more virulent than WT (7,45,46), and can partially evade protection afforded by messenger ribonucleic acid (mRNA) vaccines and protection acquired from previous infections with other variants (Table S5 and Table S8). Delta immune escape was modelled as a 33% reduction in the protection against infection following the first dose (before receiving the second dose) and 6% reduction following the second dose and the booster (7,45,46) (Table S8).

On November 20, 2021, imported cases entering the model population could be either a Delta variant or Omicron BA.1 (B.1.1.529) variant. The proportion of imported VOCs that were Omicron BA.1 increased linearly over time from 10% to complete dominance (100%) by December 31, 2021. It was assumed that Omicron BA.1 is 250% more transmissible than the WT (i.e. 175% more transmissible than Delta) and 30% less virulent than the WT (47) (Table S5 and Table S8). The Omicron BA.1 variant was assumed to partially evade protection afforded by mRNA vaccines and protection from previous infections with other variants, with a reduction in protection against infection, symptoms and hospitalizations (Table S8) (48,49).

All variant-specific characteristics, including transmissibility, virulence and immune escape properties, are assumed to be uniform across all age groups. Vaccination and infection-acquired protection

Vaccination rollout

Vaccination began on December 14, 2020. Individuals were selected for vaccination if they 1) met the minimum age requirement, 2) did not present symptoms of infection (but when individuals recovered from an infection, they were available for

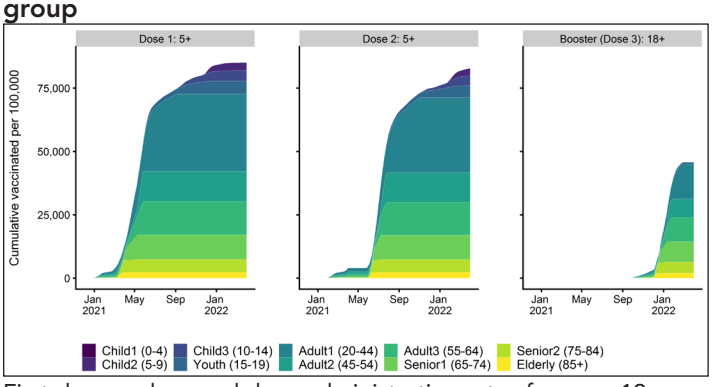
Table S8: Characteristics for variants of concern as modelled in the agent-based model

Characteristics		Variant of concern		
		Alpha (B.1.1.7)	Delta (B.1.617.2)	Omicron (B.1.1.529)
Transmissibility compared to WT strain		50% increase	100% increase	BA.1: 250% increase
Virulence compared to WT strain		40% increase	80% increase	30% reduction
Immune escape compared to WT strain (see Table S10)	Protection against infection	**No reduction** Dose 1: 60%, same as WT protection Dose 2/natural infection: 92%, same as WT protection Booster: 92%, same as WT protection	Dose 1: 33% reduction on the 60% WT protection Dose 2/natural infection: 6% reduction on the 92% WT protection Booster: 6% reduction on the 92% WT protection	Dose 1: 67% reduction on the 60% WT protection Dose 2/natural infection: 51% reduction on the 92% WT protection Booster: 24% reduction on the 92% WT protection
	Protection against symptoms	**No reduction** Dose 1: 66%, same as WT protection Dose 2/natural infection: 94%, same as WT protection Booster: 94%, same as WT protection	**No reduction** Dose 1: 66%, same as WT protection Dose 2/natural infection: 94%, same as WT protection Booster: 94%, same as WT protection	Dose 1: 63% reduction on the 66% WT protection Dose 2/natural infection: 36% reduction on the 94% WT protection Booster: 23% reduction on the 94% WT protection
	Protection against hospitalizations	**No reduction** Dose 1: 80%, same as WT protection Dose 2/natural infection: 96%, same as WT protection Booster: 96%, same as WT protection	**No reduction** Dose 1: 80%, same as WT protection Dose 2/natural infection: 96%, same as WT protection Booster: 96%, same as WT protection	Dose 1: 27% reduction on the 80% WT protection Dose 2/natural infection: 10% reduction on the 96% WT protection Booster: 10% reduction on the 96% WT protection
	Protection against death	**No reduction**	**No reduction**	**No reduction**

Abbreviation: WT, wild-type

vaccination) and 3) were willing to be vaccinated according to an age-specific vaccine acceptance level (see "Vaccine acceptance" section). In the model, the rollout of vaccines followed the order of priority groups as recommended by the National Advisory Committee on Immunization (NACI) (**Figure S4**) (50). The model accounted for the limited supply of vaccines in Canada between January and May 2021 and implemented an extended interval between the first and second dose as of March 4, 2021, as recommended by NACI (51,52). Individuals in the model vaccinated prior to March 4, 2021 received a second dose of the vaccine 28 days after the first dose, while individuals vaccinated on or after March 4, 2021 received a second dose with a delayed dose interval of four months. After this point, first and second doses were administered simultaneously, with the proportion of first dose administration decreasing over time. First dose administration of individuals in the 5–11 years age group began on November 19, 2021, with a 56-day (8-week) dose interval between first and second doses as recommended by NACI (53). A one-time booster dose was administered in the model starting on September 17, 2021 to individuals aged 18 years and over, after a minimum of three months following the receipt of the second dose, based on NACI recommendation (54). Boosters were administered following the same order of prioritization as the administration of the first and second doses, which in the general population, was ordered from the eldest to the youngest, with a portion of priority given to a proportion of the population representing high priority groups such as frontline workers, immunocompromised and high-density household members.

Figure S4: Cumulative number of individuals vaccinated with the first dose (left column), the second dose (middle column) and the booster (right column), by age group



First dose and second dose administration rates for ages 12 and older were based on real life data from the COVID-19 Vaccination Tracker, including data up to November 24, 2021 (52). From November 25, 2021 onward, it was assumed that the vaccination rate of individuals 12 years of age and older

was maintained at 50 doses per 100,000 per day. First and second dose administration rates for children age 5–11 years of age were based on data from the Canadian Immunization Committee (CIC) report dated March 17, 2022, including data up to March 13, 2022, reflecting real-life vaccination rate for this age group (55). Children vaccination peaked at 158 doses per day per 100,000 people in the first week of December 2021 and has since declined gradually to one per day per 100,000 by the beginning of March 2022; it was assumed that this rate was maintained constant for the following months. Third dose (booster) administration rates for ages 18 years and older are based on the COVID-19 Vaccination Tracker, including data up to March 17, 2022 (52), after which estimates were projected to be maintained at 225 booster doses per 100,000 per day. According to the estimated target rates, second dose administration (including individuals of the 5–11 years age group) ended approximately at the end of November 2021 (second dose) and the booster administration (18 years and older) ends approximately in the beginning of March 2022.

Vaccine acceptance

Willingness to vaccinate was based on real-life age-specific vaccine acceptance data (52). Willingness to vaccinate for children (5–11 years) and adolescents (12–17 years) was dependent on vaccine acceptance in households, i.e. the probability of being vaccinated was applied only if at least one adult in the household was willing to vaccinate. Parents of children have a slightly reduced willingness to accept vaccination for their children compared to parents of adolescents; based on survey and empirical data (55,56) (**Table S9**). Vaccine acceptance for the second dose was modelled as a proportion of those who have received their first dose. Similar to the second dose, the booster dose was modelled as a proportion of those who have received their second dose (Table S9). Vaccine acceptance in the model was based on the CIC March 17, 2022 report with data up to and including March 13, 2022 (55). An additional 1% to 2% of vaccine acceptance of the first dose was projected for the 12–59 years while an additional 8% was projected for the 5–11 years; representing the respective anticipated uptake in the model based on actual vaccine uptake in recent weeks (55). The actual second dose coverage given first dose was modelled for all age groups except in the 5–11 years age group due to ongoing second dose administration in this group. Second dose acceptance in 5–11 years was modelled on 12–17 years acceptance data (Table S9) (55). The overall modelled willingness to receive two doses was 81% of the total population and 86% of the eligible population five years and over. The overall modelled booster acceptance was 55% for the adult population.

Table S9: Age-specific modelled and actual vaccine acceptance of the first, second and third (booster) doses

Age group (years)	First dose acceptance		Second dose acceptance given first dose		Third dose acceptance given second dose	
	Actual (56)	Modelled	Actual (56)	Modelled	Actual (4)	Modelled
5–11 (children)	57%[a]	65%	65%[a]	95%	0.02%	N/A
12–17 (adolescents)	88%	90%	96%	96%	15%	N/A
18–29	90%	90%	96%	96%	39%	39%
30–39	89%	90%	97%	97%	48%	48%
40–49	91%	92%	98%	98%	57%	57%
50–59	91%	92%	98%	98%	68%	68%
60–69	95%	95%	98%	99%	80%	80%
70–79	98%	98%	99%	99%	86%	86%
80 and older	99%	99%	98%	99%	87%	87%

Abbreviation: N/A, not applicable

[a] First and second dose vaccination in the 5–11 years age group is ongoing as of March 13, 2022; the acceptance values are therefore modelled higher than actual values compared to the other age groups

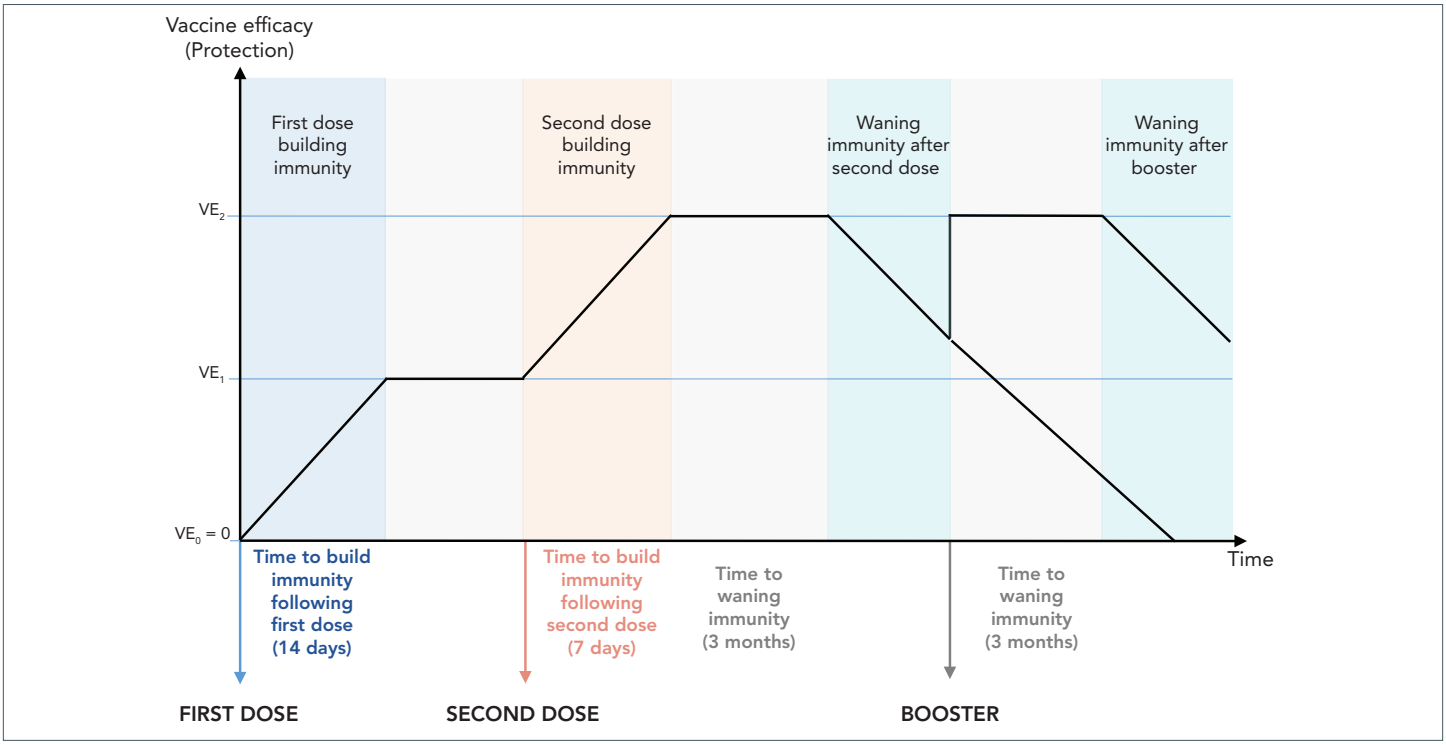
Vaccine-acquired protection

To simulate the impact of vaccination, the model included three vaccination states representing the first, second and third dose (booster) administrations of vaccines (BuildingImmunity, BuildingImmunity2 and Booster) (**Figure S5**). The model tracked the vaccination time since the first, second and third dose; which was used to calculate protective and waning effects of vaccination. The level of protection acquired from vaccination varied for each SARS-CoV-2 strain that an agent was exposed to (Table S8 and **Table S10**). Agents could be infected via contact with an infectious agent during vaccination (i.e. while acquiring immunity after receiving the first and second doses) or infected post-vaccination (after the second dose, between the second and third dose and after third dose). The protection acquired from vaccination increased each day from the first to second dose, plateauing at 14-days and 7-days after the receipt of the first and second doses, respectively. Waning begins after a period of 90 days (Table S10 and Figure S5).

Vaccination in the model was time-dependent and vaccine effectiveness (VE) against infection, clinical symptoms and severe health outcomes were modelled as follows:

- Vaccine effectiveness increased linearly with time from receipt of the first dose, with full immunity acquired 14 days after the first dose (Figure S5).
- Similarly, VE increased linearly with time from receipt of the second dose, with full immunity acquired seven days after the second dose (Figure S5).
- After a 90-day period following the second dose, VE linearly declined with time during a waning immunity period (Figure S5 green bar, see "Waning immunity" section).
- On receipt of a third (booster) dose during the waning immunity period, VE was automatically reset to the maximum protection afforded by the second dose (i.e. full immunity acquired seven days after the second dose) for WT, Alpha and Delta variants (Figure S5). For the Omicron BA.1 variant, the booster brought the protection against infection and symptoms at a higher level relative to the protection acquired from two doses; however, protection acquired from boosters against Omicron infections, ymptoms and hospitalizations remained lower compared to protection against WT and the other variants due to greater immune escape characteristics.
- After a 90-day period following the booster, VE declined linearly with time during a waning immunity period (Figure S5 green bar, see "Waning immunity" section).

Figure S5: Timing and acquisition of vaccine effectiveness[a] against infection, clinical symptoms and severe outcomes after the first dose, second dose and booster (third dose)



[a] VE_1 and VE_2 corresponded to the maximal protection (vaccine effectiveness) against infection, symptoms, hospitalizations or death after doses one and two, respectively. VE_0 was the protection prior to receiving any doses, which was equal to 0. The protection against infection and health outcomes increased over time after dose one and two administrations (building immunity periods). After a three-month period in which immunity was retained following dose two and the booster, the protection decreased over time (waning immunity period). This figure is not drawn to scale

Table S10: Assumptions on levels and duration of protection against infection, clinical symptoms, hospitalizations and death following vaccinations and infection, for each virus strain

Variant	Dose	Protection against	Population-level protection		
			Maximal protection	Minimal protection	Time-to-waning period + duration of waning period
Wild-type and Alpha	Dose 1	Infection	60%	N/A—no waning after dose 1	
		Symptoms	66%		
		Hospitalization	80%		
		Death	85%		
	Dose 2, booster and natural infection	Infection	92%	0%	90 + 1,434 days
		Symptoms	94%	0%	90 + 1,434 days
		Hospitalization	96%	0%	90 + 6,321 days
		Death	96%	N/A—no waning of protection against death	
Delta	Dose 1	Infection	40%[a]	N/A—no waning after dose 1	
		Symptoms	66%		
		Hospitalization	80%		
		Death	85%		
	Dose 2, booster and natural infection	Infection	86%[a]	0%	90 + 1,434 days
		Symptoms	94%	0%	90 + 1,434 days
		Hospitalization	96%	0%	90 + 6,321 days
		Death	96%	N/A—no waning of protection against death	
Omicron (BA.1)	Dose 1	Infection	20%[a]	N/A—no waning after dose 1	
		Symptoms	25%[a]		
		Hospitalization	58%[a]		
		Death	85%		
	Dose 2 and natural infection	Infection	45%[a]	5%	90 + 220 days
		Symptoms	60%[a]	5%	90 + 220 days
		Hospitalization	86%[a]	5%	90 + 5,443 days
		Death	96%	N/A—no waning of protection against death	
	Booster	Infection	70%[a]	5%	90 + 220 days
		Symptoms	72%[a]	5%	90 + 220 days
		Hospitalization	86%[a]	5%	90 + 5,443 days
		Death	96%	N/A—no waning of protection against death	
Same variant reinfection protection; i.e. Alpha against Alpha reinfection, Delta against Delta, etc.		Infection	99%	0% (Alpha/Delta), 5% (Omicron BA.1)	90 + 1,434 days (Alpha/Delta), 90 + 220 days (Omicron BA.1)
		Symptoms	99.5%	0% (Alpha/Delta), 5% (Omicron BA.1)	90 + 1,434 days (Alpha/Delta), 90 + 220 days (Omicron BA.1)
		Hospitalization	99.9%	0% (Alpha/Delta), 5% (Omicron BA.1)	90 + 6,321 days (Alpha/Delta), 90 + 5,443 days (Omicron BA.1)
		Death	99.9%	N/A—no waning of protection against death	

Abbreviation: N/A, not applicable
[a] The variants Delta and Omicron are associated with lower maximal protection due to their immune escape characteristics

Infection-acquired protection

Initial infection: The ABM assumed that natural infection provided the same level of protection afforded by two doses of the vaccine (Table S10). After full recovery from infection, the maximal protection is retained during a 90-day period before waning begins, with protection declining at the same rate as the second dose vaccine protection (see "Vaccine-acquired protection" and "Waning immunity" sections).

Reinfection of the same SARS-CoV-2 strain: A previous infection with a specific SARS-CoV-2 strain was assumed to provide a higher level of protection against reinfection of the same strain compared to protection provided by two doses of the vaccine (Table S10). Maximal protection against reinfection, developing symptoms, hospitalizations and deaths was set to 99%, 99.5%, 99.9% and 99.9%, respectively, prior to waning. Time to waning and duration of waning after reinfection was assumed to be the same as waning after two doses of the vaccine (Table S10).

Waning immunity

In the ABM, it was assumed that waning immunity commenced after a 90-day period following full recovery from infection or following a second or a booster dose, with immunity waning linearly over time (Table S10). Waning was assumed to decrease both infection and vaccine-acquired protection against SARS-CoV-2 infection, symptoms and hospitalization but protection against death persisted. Waning of protection against infection and symptoms declined much faster than waning of protection against hospitalization. Immunity declined linearly from a maximal protection level down to a minimal protection level over a given time period (Table S10), after which protection was retained at the minimal protection level indefinitely. The linear decrease of protection over time was applied at the population-level probability estimates (with conditional probability estimates recalculated each day based on the linear decrease, see "Population level vs conditional protection" section). Immunity waned at a rate specific to each variant and to each outcome (i.e. infection, symptoms and hospitalizations) (57,58). The rate of decline was assumed to be constant across age groups.

Population-level vs conditional protection

The model included nested conditional probabilities for applying protection against infection, clinical symptoms, hospitalizations and deaths following infection or vaccination. The population-level protection against clinical symptoms, hospitalizations and death were adjusted as conditional protections; that is, protection against symptoms given infection, protection against hospitalizations given symptoms and protection against death given hospitalization. These conditional protections are calculated as follows:

$$Protection_{symp|inf} = 1 - \frac{(1 - Protection_{symp})}{(1 - Protection_{inf})} \quad (1)$$

$$Protection_{hosp|symp} = 1 - \frac{(1 - Protection_{hosp})}{(1 - Protection_{symp})} \quad (2)$$

$$Protection_{décès|hosp} = 1 - \frac{(1 - Protection_{décès})}{(1 - Protection_{hosp})} \quad (3)$$

Public health interventions in the model

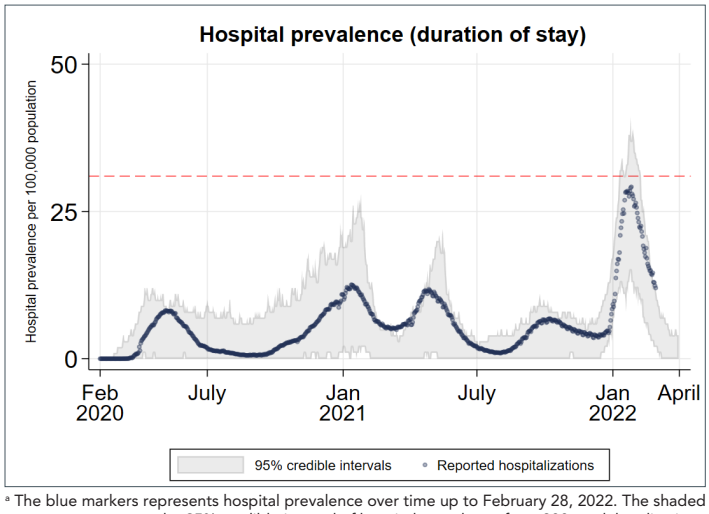
Table S11 summarizes the public health interventions that can be explored in the model, the impact these have on an agent's ability to transmit infection to other agents, and the health states in which these interventions are implemented.

Baseline calibration to Canadian data and public health interventions applied in Canada

Model baseline (last calibrated in March 2022)

The Canadian baseline scenario (**Figure S6**) took into account historical public health measures that were implemented and has been calibrated and fitted against hospital prevalence data at the national level (59). Model assumptions were based on data where available and are summarized below.

Figure S6: Baseline scenario[a]



[a] The blue markers represents hospital prevalence over time up to February 28, 2022. The shaded grey area represents the 95% credible interval of hospital prevalence from 200 model realizations from February 7, 2021 to November 3, 2022. This baseline includes the vaccination rollout and all public health measures implemented to date as well as projected measures according to the model scenarios presented in this report

Table S11: Summary of interventions explored in the Public Health Agency of Canada agent-based model

Intervention type	Impact of intervention	Health state[a]
Contact tracing and quarantine	Contact tracing to identify cases that had already been exposed but are not yet infectious. This intervention is one of the most effective because an agent that is quarantined for 14 days (default, but modifiable) in the exposed state will not be a source for community infection at any point during their infection.	Exposed
Case detection and isolation	Case testing to identify symptomatic cases resulted in isolation of these cases in their household, thereby reducing community transmission. Agents that were identified via case testing were isolated at home for 14 days (default, but modifiable). In addition, a proportion of household members can also isolate if they had not been previously infected and were immune.	Mild symptoms[b]
Asymptomatic testing and isolation	Similar to case detection of symptomatic cases, asymptomatic testing allowed for the detection of asymptomatic and infectious agents resulting in the isolation of these cases and reducing community transmission.	A_Infectious
Physical distancing	Reduced the number of contacts per day, can be applied to the entire population or targeted by age group. Physical distancing was only applied outside of the household.	N/A
Community closure	Closure of schools, workplaces and mixed age venues either as a proportion (i.e. 100% of schools) or as a threshold (i.e. schools with 50 or more agents). Agents assigned to an environment that was closed were forced to stay at home until closure had ended. If a child was under the age of 15 years and their school was closed, a guardian from the household was forced to stay home with the child.	N/A
Vaccination	Vaccines provided a high level of protection against infection, clinical symptoms, hospitalizations and deaths. Each subsequent vaccine dose provided additional protection or a top up to protection acquired from previous doses (see Table S10). Vaccination drastically reduced the number of effective contacts and successful infections between agents. This intervention had a long-lasting impact compared to other interventions despite waning immunity occurring within 90 days.	Building Immunity, Building Immunity 2, Vaccinated and Boostered
Vaccine mandate	A vaccine mandate could have been implemented for a specific location (i.e. school, workplace, mixed age venues or a mixture of locations) and targeted to specific age groups (i.e. over 18 years of age only). A vaccine mandate prevented an unvaccinated agent from entering an assigned environment, even if the environment was opened, effectively forcing an unvaccinated agent to stay at home until the mandate had been lifted or to enter only essential-businesses. This intervention reduced contacts between vaccinated and unvaccinated agents.	N/A

Abbreviation: N/A, not applicable
[a] Health States refer to the health state that each corresponding intervention type can be implemented in, see Figure S1
[b] For mild cases, by the time agents arrive in the mild symptoms state, they have already been infectious for one to three days but isolating them in this state will prevent a further three to seven days of potential transmission. Isolated agents can continue to infect household members, but at a reduced rate of 50% as we assume sick individuals will distance themselves from household members. Severe cases are assumed to be too ill to be out in the community, therefore case testing and isolation only applies to mild cases

Assumptions on case detection and isolation:

- 20% of cases were detected and isolated for the entire model period except when cases reached 150 active cases per 100,000; when this occurred, case detection and isolation were halved (10%), representing the collapse of the surveillance system (42,60,61).

Assumptions on contact tracing and quarantine:

- 50% of detected cases were contact traced and identified for quarantine. When cases reached 50 active cases per 100,000, contact tracing ceased for the entire model period due to over-stretching of tracing capacity (62,63).

Assumptions on physical distancing:

- Physical distancing (i.e. daily rates each person contacted other people) varied over the course of the pandemic (details have been published previously (1,2)) with varying levels of compliance across age groups according to survey data (45,46,64). Physical distancing accounted for many public health measures that reduced effective contact between individuals, for example, masking, restrictions on gathering, reducing contact rates, etc., but these were not modelled explicitly.
- Physical distancing was maintained at a level corresponding to the stringency index at the time of each wave and was adjusted according to other public health measures in place (for example, vaccine mandate and shutdowns). It was assumed that physical distancing was maintained at the same level for the duration of each shutdown but gradually increased after each shutdown and until the next shutdown began.
- In general, physical distancing resulted in a substantial reduction in contact rates compared to pre-COVID-19 contact rates. Contact rates were reduced to approximately 45% pre-COVID contact rates for the earlier waves (first, second and third), approximately 65% during the Delta wave (with a vaccine mandate in place) and approximately 50% during the Omicron BA.1 wave.
- During shutdowns, it was assumed that approximately 90% of the population was compliant with physical distancing uniformly across age groups. Between shutdowns, compliance was reduced to approximately 65% of the population being compliant and ranged from 50% in the under 20 years age group to 90% in the 65 years and over age group.

Assumptions on restrictive closures:

- Closures occurred regularly over the course of the epidemic in Canada and were modelled on the decline in mobility observed during corresponding time periods using Google mobility data and Statistics Canada's survey on Canadians working from home (65,66). Closures included 100% of schools, 50% of workplaces and 50% of mixed age venues corresponding to the decline in mobility observed by location (65,66).
- In the ABM, closures were modelled on the stringency index and relative to other public health measures in place at the time (for example, vaccine mandates and physical distancing) and the duration of closures ranged from 28 to 56 days.
- When closures were implemented, they were effective immediately, whereas reopening occurred gradually after each wave. The gradual reopening varied between waves in terms of the speed of reopening but was consistent in the types of reopening, with 100% of schools reopening first, 80% of workplaces reopening gradually (representing a portion of the workforce that continued to telework indefinitely) and 100% of essential businesses reopened gradually.
- In the summers of 2020 and 2021, 65% of schools remained open, allowing for summer camps and activities that brought children together. On September 8, 2020 and September 7 2021, the start of the respective school years, schools reopened to 100% full capacity.
- From March 2022, no further closures occur.

Assumptions on imported cases:

- The importation rate representing a closed border was two imported cases per 100,000 per week (67). From July 11, 2021 to February 26, 2022, the ABM imported cases were based on weekly estimates of the PHAC importation risk model, with linearly interpolated estimates during the month of December 2021. The number of imported cases per week remained at five per 100,000 people for the remainder of the model time.
- The weekly number of imported cases per 100,000 in the ABM were broken down to one permanent case, with remaining cases set as transient cases (staying in the population for one to five days).
- Imported cases adhered to public health measures at the same level as the population but with border testing and monitoring, while in reality imported cases may adhere to public health measures at a higher level than the general population, i.e. quarantine, isolation, physical distancing (though the model estimates were derived from a model that accounted for cases that evaded detection prior to entry into Canada).

Assumptions on SARS-CoV-2 wild-type and variants of concern:

- From December 1, 2020 onward, there was a 10% probability that each imported case was a VOC (estimate). The proportion of VOC imported cases changed dynamically over time using data points estimated from the PHAC importation risk model (see Figure S3) (67).
- The VOC was modelled on the Alpha (B.1.1.7) variant, which is 50% more transmissible (68) and 40% more virulent, causing higher levels of hospitalizations than the WT (71), but is not characterized by immune escape. It was assumed that infection with Alpha would provide very high immunity to future exposures to Alpha infections but not complete immunity from reinfection.
- The baseline included the introduction of the Delta (B.1.617.2) variant, which was introduced on March 9, 2021 and which dominated by August 29, 2021. Delta is characterized by immune escape on protection against infection and is 100% more transmissible and 80% more virulent than the WT. It was assumed that infection with Delta would provide very high immunity to future exposures to Delta infections but not complete immunity from reinfection.
- The Omicron BA.1 (B.1.1.529) subvariant was introduced on November 20, 2021 and dominated by December 31, 2021. This variant is characterized by immune escape on protection against infection, symptoms and hospitalizations. Omicron is assumed to be 250% more transmissible and 30% less virulent than the WT. Omicron infection is assumed to produce 50% fewer symptomatic infections compared to WT and the other variants, this reduction varies by age group (assumption). It was assumed that infection with Omicron BA.1 would provide very high immunity to future exposures to Omicron BA.1 infections but not complete immunity from reinfection.

Assumptions on vaccination and waning immunity:

- There is a three-month period in which immunity is retained before waning begins (70,71).
- Following vaccination or natural infection, after a three month period, protection against SARS-CoV-2 infection, symptoms and hospitalization declined linearly over time but protection against death persists and did not wane (71).
- The maximal protection against infection, symptoms, hospitalization and death, the rate at which the protection declines during the waning period and the residual protection levels retained following waning immunity varied depending on the SARS-CoV-02.
- Infection-acquired immunity and second dose vaccine-acquired immunity waned within the same time period.

- Immunity following a third dose booster against WT, Alpha and Delta infections waned over time at the same rate as waning following second dose administration. Immunity following a third dose booster against Omicron infections waned at a faster rate than waning following second dose administration because protection against infection and hospitalization for Omicron infections was slightly higher after a booster compared to a second dose.
- The linear decrease of protection in time was applied on the population-level protection (with conditional protections recalculated each day based on this decrease).

Assumptions on booster doses:

- Boosters were administered in the same order of priority as the first and second doses, in general, from the eldest to the youngest, the minimum age of boosting in the model is 18 years.
- Boosters were administered at a minimum of three months after the receipt of the second dose.
- Booster weekly administration rates were estimated from COVID-19 Vaccination Tracker from September 17, 2021 to March 18, 2022 (52).
- Boosters were imperfect and provided protection against infection, symptoms, hospitalizations and deaths up to the level acquired by two doses of the vaccine (Table S10). For Omicron, the level of protection against infection and symptoms from the booster was higher than the two-dose acquired immunity.
- On receipt of a booster dose, the time to waning immunity was reset providing another three-month period in which immunity was retained before waning begins.
- Booster protection varied, depending on the variant and immune escape properties (see Table S10).

Assumptions on vaccine mandate:

- From September 15, 2021 to March 1, 2022, a vaccine mandate was introduced to the population restricting unvaccinated individuals from entering non-essential businesses (approximately 50% of mixed age venues). The March 1, 2022 end date reflects the lifting of a vaccine mandate across multiple provinces and territories between the end of February and mid-March 2022.

References

1. Ng V, Fazil A, Waddell LA, Bancej C, Turgeon P, Otten A, Atchessi N, Ogden NH. Projected effects of nonpharmaceutical public health interventions to prevent resurgence of SARS-CoV-2 transmission in Canada. CMAJ 2020;192(37):E1053. DOI

2. Ng V, Fazil A, Waddell LA, Turgeon P, Otten A, Ogden NH. Modelling the impact of shutdowns on resurging SARS-CoV-2 transmission in Canada. R Soc Open Sci 2021;8(5):210233. DOI

3. Gabriele-Rivet V, Spence KL, Ogden NH, Fazil A, Turgeon P, Otten A, Waddell LA, Ng V. Modelling the impact of age-stratified public health measures on SARS-CoV-2 transmission in Canada. R Soc Open Sci 2021;8:210834. DOI

4. Public Health Agency of Canada. National line list of COVID-19 cases. Ottawa (ON): PHAC; 2020; (accessed 2020-06-06). https://health-infobase.canada.ca/covid-19/

5. Statistics Canada. Population estimates on July 1st, by age and sex. Ottawa (ON): StatCan; 2020; (accessed 2020-04-16). https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710000501

6. Statistics Canada. Census Profile, 2016 Census. Ottawa (ON): StatCan; (modified 2021; accessed 2020-04-16). https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=PR&Code1=35&Geo2=PR&Code2=01&Data=Count&SearchText=35&SearchType=Begins&SearchPR=01&B1=All&Custom=&TABID=3

7. Prem K, Cook AR, Jit M. Projecting social contact matrices in 152 countries using contact surveys and demographic data. PLoS Comput Biol 2017;13(9):e1005697. DOI

8. Government of Canada. COVID-19 Situation Awareness Dashboard. Ottawa (ON): Government of Canada; 2020; (accessed 2020-12-08). https://resources-covid19canada.hub.arcgis.com/

9. Li R, Pei S, Chen B, Song Y, Zhang T, Yang W, Shaman J. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV-2). Science 2020;368(6490):489–93. DOI

10. Arons MM, Hatfield KM, Reddy SC, Kimball A, James A, Jacobs JR, Taylor J, Spicer K, Bardossy AC, Oakley LP, Tanwar S, Dyal JW, Harney J, Chisty Z, Bell JM, Methner M, Paul P, Carlson CM, McLaughlin HP, Thornburg N, Tong S, Tamin A, Tao Y, Uehara A, Harcourt J, Clark S, Brostrom-Smith C, Page LC, Kay M, Lewis J, Montgomery P, Stone ND, Clark TA, Honein MA, Duchin JS, Jernigan JA; Public Health–Seattle and King County and CDC COVID-19 Investigation Team. Presymptomatic SARS-CoV-2 Infections and Transmission in a Skilled Nursing Facility. New Engl J Med 2020;382(22):2081–90. DOI

11. Grzelak L, Temmam S, Planchais C, Demeret C, Huon C, Guivel-Benhassine F, Staropoli I, Chazal M, Dufloo J, Planas D, Buchrieser J,Rajah MM, Robinot R, Porrot F, Albert M,Chen K-Y, Crescenzo B, Donati F, Anna F, Souque P, Gransagne M, Bellalou J, Nowakowski M, Backovic M, Bouadma L, Le Fevre L, Le Hingrat Q, Descamps D, Pourbaix A, Yazdanpanah Y, Tondeur L, Besombes C, UngeheuerM-N, Mellon G, Morel P, Rolland S, Rey F, Behillil S, Enouf V, Lemaitre A, Créach M-A, Petres S, Escriou N, Charneau P,Fontanet A, Hoen B, Bruel T, Eloit M, Mouquet H, Schwartz O, van der Werf S. SARS-CoV-2 serological analysis of COVID-19 hospitalized patients, pauci-symptomatic individuals and blood donors. medRxiv 2020;2020.04.21.20068858. DOI

12. Gudbjartsson DF, Helgason A, Jonsson H, Magnusson OT, Melsted P, Norddahl GL, Saemundsdottir J, Sigurdsson A, Sulem P, Agustsdottir AB, Eiriksdottir B, Fridriksdottir R, Gardarsdottir EE, Georgsson G, Gretarsdottir OS, Gudmundsson KR, Gunnarsdottir TR, Gylfason A, Holm H, Jensson BO, Jonasdottir A, Jonsson F, Josefsdottir KS, Kristjansson T, Magnusdottir DN, le Roux L, Sigmundsdottir G, Sveinbjornsson G, Sveinsdottir KE, Sveinsdottir M, Thorarensen EA, Thorbjornsson B, Löve A, Masson G, Jonsdottir I, Möller AD, Gudnason T, Kristinsson KG, Thorsteinsdottir U, Stefansson K. Spread of SARS-CoV-2 in the Icelandic Population. N Engl J Med 2020;382(24): 2302–15. DOI

13. Peebles A, Brown KV, Clukey K. New York finds virus marker in 13.9%, suggesting wide spread. Bloomberg News. 2020 April 23. https://www.bloomberg.com/news/articles/2020-04-23/new-york-finds-virus-marker-in-13-9-suggesting-wide-spread

14. He W, Yi GY, Zhu Y. Estimation of the basic reproduction number, average incubation time, asymptomatic infection rate, and case fatality rate for COVID-19: Meta-analysis and sensitivity analysis. J Med Virol 2020;92(11):2543–50. DOI

15. Davies NG, Klepac P, Liu Y, Prem K, Jit M; CMMID COVID-19 working group, Eggo RM. Age-dependent effects in the transmission and control of COVID-19 epidemics. Nat Med 2020;26(8):1205–11. DOI

16. Tong ZD, Tang A, Li KF, Li P, Wang HL, Yi JP, Zhang YL, Yan JB. Potential Presymptomatic Transmission of SARS-CoV-2, Zhejiang Province, China, 2020. Emerg Infect Dis 2020;26(5):1052–4. DOI

17. Xia W, Liao J, Li C, Li Y, Qian X, Sun X, Xu H, Majai G, Zhao X, Shi L, Liu J, Yu L, Wang M, Wang Q, Namat A, Li Y, Qu J, Liu Q, Lin X, Cao S, Huan S, Xiao J, Ruan F, Wang H, Xu Q, Ding X, Fang X, Qiu F, Ma J, Zhang Y, Wang A, Xing Y, Xu S. Transmission of corona virus disease 2019 during the incubation period may lead to a quarantine loophole. medRxiv 2020;2020.03.06.20031955. DOI

18. Li C, Ji F, Wang L, Wang L, Hao J, Dai M, Liu Y, Pan X, Fu J, Li L, Yang G, Yang J, Yan X, Gu B. Asymptomatic and Human-to-Human Transmission of SARS-CoV-2 in a 2-Family Cluster, Xuzhou, China. Emerg Infect Dis 2020;26(7):1626–8. DOI

19. Li G, Li W, He X, Cao Y. Asymptomatic and Presymptomatic Infectors: Hidden Sources of COVID-19 Disease. Clin Infect Dis 2020;71(8):2018. DOI

20. Qian G, Yang N, Ma AHY, Wang L, Li G, Chen X, Chen X. A COVID-19 Transmission within a family cluster by presymptomatic infectors in China. Clin Infect Dis 2020;71(15):861–2. DOI

21. He X, Lau EHY, Wu P, Deng X, Wang J, Hao X, Lau YC, Wong JY, Guan Y, Tan X, Mo X, Chen Y, Liao B, Chen W, Hu F, Zhang Q, Zhong M, Wu Y, Zhao L, Zhang F, Cowling BJ, Li F, Leung GM. Temporal dynamics in viral shedding and transmissibility of COVID-19. Nat Med 2020;26(5):672–5. DOI

22. Tindale LC, Coombe M, Stockdale JE, Garlock ES, Transmission interval estimates suggest pre-symptomatic spread of COVID-19. eLife 2020;9:e57149. DOI

23. Hu Z, Song C, Xu C, Jin G, Chen Y, Xu X, Ma H, Chen W, Lin Y, Zheng Y, Wang J, Hu Z, Yi Y, Shen H. Clinical characteristics of 24 asymptomatic infections with COVID-19 screened among close contacts in Nanjing, China. Sci China Life Sci 2020;63(5):706–11. DOI

24. Bi Q, Wu Y, Mei S, Ye C, Zou X, Zhang Z, Liu X, Wei L, Truelove SA, Zhang T, Gao W, Cheng C, Tang X, Wu X, Wu Y, Sun B, Huang S, Sun Y, Zhang J, Ma T, Lessler J, Feng T. Epidemiology and transmission of COVID-19 in 391 cases and 1286 of their close contacts in Shenzhen, China: a retrospective cohort study. Lancet Infect Dis 2020;20(8): 911–9. DOI

25. Linton NM, Kobayashi T, Yang Y, Hayashi K, Akhmetzhanov AR, Jung SM, Yuan B, Kinoshita R, Nishiura H. Incubation Period and Other Epidemiological Characteristics of 2019 Novel Coronavirus Infections with Right Truncation: A Statistical Analysis of Publicly Available Case Data. J Clin Med 2020;9(2):538. DOI

26. Lauer SA, Grantz KH, Bi Q, Jones FK, Zheng Q, Meredith HR, Azman AS, Reich NG, Lessler J. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. Ann Intern Med 2020;172(9):577–82. DOI

27. Wang P, Lu J-a, Jin Y, Zhu M, Wang L, Chen S. Epidemiological characteristics of 1212 COVID-19 patients in Henan, China. medRxiv 2020;2020.02.21.20026112. DOI

28. Wang D, Hu B, Hu C, Zhu F, Liu X, Zhang J, Wang B, Xiang H, Cheng Z, Xiong Y, Zhao Y, Li Y, Wang X, Peng Z. Clinical Characteristics of 138 Hospitalized Patients With 2019 Novel Coronavirus–Infected Pneumonia in Wuhan, China. JAMA 2020;323(11):1061–9. DOI

29. Argenziano MG, Bruce SL, Slater CL, Tiao JR, Baldwin MR, Barr RG, Chang BP, Chau KH, Choi JJ, Gavin N, Goyal P, Mills AM, Patel AA, Romney MS, Safford MM, Schluger NW, Sengupta S, Sobieszczyk ME, Zucker JE, Asadourian PA, Bell FM, Boyd R, Cohen MF, Colquhoun MI, Colville LA, de Jonge JH, Dershowitz LB, Dey SA, Eiseman KA, Girvin ZP, Goni DT, Harb AA, Herzik N, Householder S, Karaaslan LE, Lee H, Lieberman E, Ling A, Lu R, Shou AY, Sisti AC, Snow ZE, Sperring CP, Xiong Y, Zhou HW, Natarajan K, Hripcsak G, Chen R. Characterization and Clinical Course of 1000 Patients with COVID-19 in New York: retrospective case series. BMJ 2020;369:m1996. DOI

30. Zhao W, Zha X, Wang N, Li D, Li A, Yu S. Clinical characteristics and durations of hospitalized patients with COVID-19 in Beijing: a retrospective cohort study. CVIA 2021;6(1):33–44. DOI

31. Guan WJ, Ni ZY, Hu Y, Liang WH, Ou CQ, He JX, Liu L, Shan H, Lei CL, Hui DSC, Du B, Li LJ, Zeng G, Yuen KY, Chen RC, Tang CL, Wang T, Chen PY, Xiang J, Li SY, Wang JL, Liang ZJ, Peng YX, Wei L, Liu Y, Hu YH, Peng P, Wang JM, Liu JY, Chen Z, Li G, Zheng ZJ, Qiu SQ, Luo J, Ye CJ, Zhu SY, Zhong NS; China Medical Treatment Expert Group for Covid-19. Clinical Characteristics of Coronavirus Disease 2019 in China. N Engl J Med 2020;382(18):1708–20. DOI

32. Spiteri G, Fielding J, Diercke M, Campese C, Enouf V, Gaymard A, Bella A, Sognamiglio P, Sierra Moros MJ, Riutort AN, Demina YV, Mahieu R, Broas M, Bengnér M, Buda S, Schilling J, Filleul L, Lepoutre A, Saura C, Mailles A, Levy-Bruhl D, Coignard B, Bernard-Stoecklin S, Behillil S, van der Werf S, Valette M, Lina B, Riccardo F, Nicastri E, Casas I, Larrauri A, Salom Castell M, Pozo F, Maksyutov RA, Martin C, Van Ranst M, Bossuyt N, Siira L, Sane J, Tegmark-Wisell K, Palmérus M, Broberg EK, Beauté J, Jorgensen P, Bundle N, Pereyaslov D, Adlhoch C, Pukkila J, Pebody R, Olsen S, Ciancio BC. First cases of coronavirus disease 2019 (COVID-19) in the WHO European Region, 24 January to 21 February 2020. Euro Surveill 2020;25(9):2000178. DOI

33. Bhatraju PK, Ghassemieh BJ, Nichols M, Kim R, Jerome KR, Nalla AK, Greninger AL, Pipavath S, Wurfel MM, Evans L, Kritek PA, West TE, Luks A, Gerbino A, Dale CR, Goldman JD, O'Mahony S, Mikacenic C. Covid-19 in Critically Ill Patients in the Seattle Region - Case Series. N Engl J Med 2020;382(21):2012–12. DOI

34. Gold JAW, Wong KK, Szablewski CM, Patel PR, Rossow J, da Silva J, Natarajan P, Morris SB, Fanfair RN, Rogers-Brown J, Bruce BB, Browning SD, Hernandez-Romieu AC, Furukawa NW, Kang M, Evans ME, Oosmanally N, Tobin-D'Angelo M, Drenzek C, Murphy DJ, Hollberg J, Blum JM, Jansen R, Wright DW, Sewell WM 3rd, Owens JD, Lefkove B, Brown FW, Burton DC, Uyeki TM, Bialek SR, Jackson BR. Characteristics and Clinical Outcomes of Adult Patients Hospitalized with COVID-19 — Georgia, March 2020. MMWR Morb Mortal Wkly Rep 2020;545–50. DOI

35. Yang X, Yu Y, Xu J, Shu H, Xia J, Liu H, Wu Y, Zhang L, Yu Z, Fang M, Yu T, Wang Y, Pan S, Zou X, Yuan S, Shang Y. Clinical course and outcomes of critically ill patients with SARS-CoV-2 pneumonia in Wuhan, China: a single-centered, retrospective, observational study. Lancet Respir Med 2020;8(5):475–81. DOI

36. Zhang G, Hu C, Luo L, Fang F, Chen Y, Li J, Peng Z, Pan H. Clinical features and outcomes of 221 patients with COVID-19 in Wuhan, China. J Clin Virol 2020;127:104364. DOI

37. Zhou F, Yu T, Du R, Fan G, Liu Y, Liu Z, Xiang J, Wang Y, Song B, Gu X, Guan L, Wei Y, Li H, Wu X, Xu J, Tu S, Zhang Y, Chen H, Cao B. Clinical course and risk factors for mortality of adult inpatients with COVID-19 in Wuhan, China: a retrospective cohort study. Lancet 2020;395(10229): 1054–62. DOI

38. Grasselli G, Zangrillo A, Zanella A, Antonelli M, Cabrini L, Castelli A, Cereda D, Coluccello A, Foti G, Fumagalli R, Iotti G, Latronico N, Lorini L, Merler S, Natalini G, Piatti A, Ranieri MV, Scandroglio AM, Storti E, Cecconi M, Pesenti A; COVID-19 Lombardy ICU Network. Baseline Characteristics and Outcomes of 1591 Patients Infected With SARS-CoV-2 Admitted to ICUs of the Lombardy Region, Italy. JAMA 2020;323(16):1574–81. DOI

39. Rajgor DD, Lee MH, Archuleta S, Bagdasarian N, Quek SC. The many estimates of the COVID-19 case fatality rate. Lancet Infect Dis. 2020;20(7):776–7. DOI

40. Odone A, Delmonte D, Scognamiglio T, Signorelli C. COVID-19 deaths in Lombardy, Italy: data in context. Lancet Public Health. 2020;5(6):e310. DOI

41. Centre for Mathematical Modelling of Infectious Diseases. Russell TE, Hellewell J, Abbott S, Golding N, Gibbs H, Jarvis CI, van Zandvoort K, CMMID COVID-19 working group, Flasche S, Eggo RM, Edmunds WJ, Kucharski AJ. Using a delay-adjusted case fatality ratio to estimate under-reporting. CMMID; 2020; (accessed 2020-04-19). https://bmcmedicine.biomedcentral.com/articles/10.1186/s12916-020-01790-9

42. Davies NG, Kucharski AJ, Eggo RM, Gimma A, Edmunds WJ; Centre for the Mathematical Modelling of Infectious Diseases COVID-19 working group. Effects of non-pharmaceutical interventions on COVID-19 cases, deaths, and demand for hospital services in the UK: a modelling study. Lancet Public Health 2020;5(7):p. e375–85. DOI

43. Government of Canada. Travel to Canada: Testing and quarantine if not qualified as fully vaccinated. Ottawa (ON): Government of Canada; 2021; (accessed 2021-06-01). https://travel.gc.ca/travel-covid/travel-restrictions/driving-canada-checklist/covid-19-testing-travellers-driving

44. Government of Canada. Flying to Canada: COVID-19 testing for travellers. Ottawa (ON): Government of Canada; 2021; (accessed 2021-06-01). https://travel.gc.ca/travel-covid/travel-restrictions/flying-canada-checklist/covid-19-testing-travellers-coming-into-canada

45. Institut national de santé publique du Québec. CONNECT : étude des contacts sociaux des Québécois. INSPQ; 2020. https://www.inspq.qc.ca/covid-19/donnees/connect

46. Brankston G, Merkley E, Fisman DN, Tuite AR, Poljak Z, Loewen PJ, Greer AL. Quantifying Contact Patterns in Response to COVID-19 Public Health Measures in Canada. BMC Public Health 2021;21(1):2040. DOI

47. MRC Centre for Global Infectious Disease analysis. Ferguson N, Ghani A, Hinsley W, Volz E on behalf of the Imperial College COVID-19 response team. Report 50: Hospitalisation risk for Omicron cases in England. London (UK): MRC CGIDA; 2021. https://www.imperial.ac.uk/mrc-global-infectious-disease-analysis/covid-19/report-50-severity-omicron/

48. UK Health Security Agency. SARS-CoV-2 variants of concern and variants under investigation in England, Technical Briefing. Update on hospitalisation and vaccine effectiveness for Omicron VOC-21NOV-01 (B.1.1.529). UKHSA; 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1045619/Technical-Briefing-31-Dec-2021-Omicron_severity_update.pdf

49. Sheikh A, Kerr S, Woolhouse M, McMenamin J, Robertson C; EAVE II Collaborators. Severity of Omicron variant of concern and vaccine effectiveness against symptomatic disease: national cohort with nested test negative design study in Scotland. Lancet Infect dis 2022;22(7):959–66. DOI

50. National Advisory Committee on Immunization (NACI). Guidance on the prioritization of initial doses of COVID-19 vaccine(s) (2020-12-18). Ottawa (ON): NACI; 2021. https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/guidance-prioritization-initial-doses-covid-19-vaccines.html

51. National Advisory Committee on Immunization (NACI). NACI rapid response: Extended dose intervals for COVID-19 vaccines to optimize early vaccine rollout and population protection in Canada. (2021-03-03). Ottawa (ON): NACI; 2021; (accessed 2021-03-04). https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/rapid-response-extended-dose-intervals-covid-19-vaccines-early-rollout-population-protection.html

52. COVID-19 Tracker Canada. COVID-19 Vaccination Tracker. 2022; (accessed 2022-01-08). https://covid19tracker.ca/vaccinationtracker.html

53. National Advisory Committee on Immunization (NACI). National Advisory Committee on Immunization (NACI) statement: Recommendation on the use of the Pfizer-BioNTech COVID-19 vaccine (10 mcg) in children 5 to 11 years of age. (2021-11-19) Ottawa (ON): NACI; 2021. https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/recommendations-use-covid-19-vaccines/pfizer-biontech-10-mcg-children-5-11-years-age.html

54. National Advisory Committee on Immunization (NACI). NACI updated guidance on booster COVID-19 vaccine doses in Canada. Ottawa (ON): NACI; 2022; (accessed 2021-12-03). https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/guidance-booster-covid-19-vaccine-doses.html

55. Public Health Agency of Canada. Canadian Immunization Committee. COVID-19 vaccination coverage in Canada. Weekly report to the Canadian Immunization Committee (CIC), March 17, 2022. https://health-infobase.canada.ca/covid-19/vaccination-coverage/

56. Humble RM, Sell H, Dubé E, MacDonald NE, Robinson J, Driedger SM, Sadarangani M, Meyer SB, Wilson S, Benzies KM, Lemaire-Paquette S, MacDonald SE. Parents' COVID-19 vaccination intentions for children: COVImm national survey preliminary results, collected Dec 10-24 2020. Vaccine 2021 20;39(52):7669–7676. DOI

57. Buchan SA, Chung H, Brown KA, Austin PC, Fell DB, Gubbay JB, Nasreen S, Schwartz KL, Sundaram ME, Tadrous M, Wilson K, Wilson SE, Kwong JC, The Canadian Immunization Research Network (CIRN) Provincial Collaborative Network (PCN) Investigators. Effectiveness of COVID-19 vaccines against Omicron or Delta symptomatic infection and severe outcomes. medRxiv 2022;2021.12.30.21268565. DOI

58. UK Health Security Agency. COVID-19 vaccine surveillance report, Week 4, 27 January 2022. UKHSA; 2022. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1050721/Vaccine-surveillance-report-week-4.pdf

59. Li MWZ. COVID19-Canada. Hospital prevalence data. Hamilton, ON: McMaster University; 2022. (accessed 2022-03-10) https://wzmli.github.io/COVID19-Canada/

60. Dougherty BP, Smith BA, Carson CA, Ogden NH. Exploring the percentage of COVID-19 cases reported in the community in Canada and associated case fatality ratios. Infect Dis Model 2020;6:123–32. DOI

61. Public Health Ontario. Enhanced Epidemiological Summary: COVID-19 Case Fatality, Case Identification, and Attack Rates in Ontario. Toronto (ON): PHO;2020. https://www.publichealthontario.ca/-/media/documents/ncov/epi/2020/06/covid19-epi-case-identification-age-only-template.pdf?sc_lang=en

62. Toronto Public Health. Temporary Change in Contact Tracing. Toronto, ON: TPH; October 8, 2020. https://www.toronto.ca/wp-content/uploads/2020/10/8e62-TPH-Change-to-Contact-Tracing-October-8-2020.pdf

63. City of Toronto. COVID-19. Toronto, ON: City of Toronto Case and Outbreak counts; (updated 2022; accessed 2020-11-19). https://www.toronto.ca/home/covid-19/covid-19-pandemic-data/covid-19-case-outbreak-counts/

64. Montreal Behavioural Medicine Centre. iCARE Study (Internaional COVID-19 Awareness and Response Evlauation Study). Montréal (QC); MBMC; 2020; (accessed 2020-11-16). https://mbmc-cmcm.ca/covid19/research/stats/adherence/

65. Google Canada. COVID-19 Community Mobility Report. Google Canada; 2020; (accessed 2020-12-23). https://www.gstatic.com/covid19/mobility/2020-05-09_CA_Mobility_Report_en.pdf

66. Statistics Canada. Canadian Perspectives Survey Series 1: COVID-19 and working from home, 2020. Ottawa (ON): StatCan; 2020; (accessed 2020-04-16). https://www150.statcan.gc.ca/n1/daily-quotidien/200417/dq200417a-eng.pdf

67. Public Health Agency of Canada. Public Health Agency of Canada biweekly modelling report: Importation Risk by Air and Land. PHAC modelling group report. Ottawa (ON): PHAC; 2021. https://nccid.ca/covid-19-phac-modelling-group/#subMenuSection1

68. Volz E, Mishra S, Chand M, Barrett JC, Johnson R, Geidelberg L, Hinsley WR, Laydon DJ, Dabrera G, O'Toole Á, Amato R, Ragonnet-Cronin M, Harrison I, Jackson B, Ariani CV, Boyd O, Loman NJ, McCrone JT, Gonçalves S, Jorgensen D, Myers R, Hill V, Jackson DK, Gaythorpe K, Groves N, Sillitoe J, Kwiatkowski DP; COVID-19 Genomics UK (COG-UK) consortium, Flaxman S, Ratmann O, Bhatt S, Hopkins S, Gandy A, Rambaut A, Ferguson NM. Assessing transmissibility of SARS-CoV-2 Lineage B.1.1.7 in England. Nature 2021;593(7858):266–9. DOI

69. Public Health Agency of Canada. Updates on COVID-19 Variants of Concern (VOC), Update April 6, 2021. https://nccid.ca/covid-19-variants/

70. Levin EG, Lustig Y, Cohen C, Fluss R, Indenbaum V, Amit S, Doolman R, Asraf K, Mendelson E, Ziv A, Rubin C, Freedman L, Kreiss Y, Regev-Yochay G. Waning Immune Humoral Response to BNT162b2 Covid-19 Vaccine over 6 Months. N Engl J Med 2021385(24):e84. DOI

71. Chemaitelly H, Tang P, Hasan MR, AlMukdad S, Yassine HM, Benslimane FM, Al Khatib HA, Coyle P, Ayoub HH, Al Kanaani Z, Al Kuwari E, Jeremijenko A, Kaleeckal AH, Latif AN, Shaik RM, Abdul Rahim HF, Nasrallah GK, Al Kuwari MG, Al Romaihi HE, Butt AA, Al-Thani MH, Al Khal A, Bertollini R, Abu-Raddad LJ. Waning of BNT162b2 Vaccine Protection against SARS-CoV-2 Infection in Qatar. N Engl J Med 2021;385(24):383. DOI