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Research Article

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Investigating the Relationships Between COVID-19 Cases, Public Health Interventions, Vaccine Coverage, and Temperature in Ontario and Toronto

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ABSTRACT

Introduction: We examined the relationship between COVID-19 cases and Public Health Interventions (PHIs). We also explored the relationship between cases and vaccine, and temperature. We compared the results with published mathematical models.

Methods: We developed monthly PHI scores using the Oxford COVID-19 Government Response Tracker for May 2020 to May 2021. We calculated PHI scores by summing the highest monthly score of each intervention and expressed the PHI score as a percentage of the maximum. We obtained vaccine coverage and temperature data from January 2021 to September 2023. We calculated Spearman's rank-order correlation coefficients to examine correlations.

Results: Correlation for cases and PHI was positive ($r = 0.947$, $p < .0001$). Correlation for cases and vaccine coverage was approximately zero ($r = 0.0165$, $p = 0.957$) for January 2021 to January 2022, and negative for February 2022 to September 2023 ($r = -0.816$, $p < .0001$). Correlation for cases and temperature was negative for January 2021 to January 2022 ($r = -0.676$, $p = 0.0112$), and almost zero for February 2022 to September 2023 ($r = -0.162$, $p = 0.494$). Models showed negative correlation for PHI and vaccine coverage, and mixed results for temperature.

Conclusion: There was a positive correlation between cases and PHI. Prior to vaccine threshold coverage, there was no correlation for vaccination and negative correlation for temperature. Post vaccine threshold, there was a negative correlation for vaccination and no correlation for temperature. Correlation results for PHI and temperature differed from mathematical models.

Keywords: Covid-19, Epidemiology, Public Health Surveillance, Correlation

Highlights

- Public Health Interventions (PHIs) correlated positively with case numbers. Prior studies that used mathematical models found negative association.
- There was a biphasic correlation between vaccine coverage and cases, with a significant negative association after 77.3% coverage.
- Temperature's correlation with cases decreased once vaccine coverage surpassed 77.3%, suggesting minimal influence once vaccination coverage increased.
- Measures to address the effect of cold temperature may be less important when 77.3% and higher vaccine coverage is achieved.
- Results highlight the need for timely and threshold-informed PHIs, and sustained vaccination strategies in managing COVID-19 cases.

Introduction

The first case of COVID-19 in Canada was identified on January 25th, 2020, in Ontario [1]. Canada's response to COVID-19 included federal and provincial public health interventions, aiming to minimize serious illness and death, while reducing societal disruptions [2]. The federal government was responsible for several measures such as restricting international travel, providing economic support, and vaccine distribution. Provincial governments implemented other measures including case management, closure of non-essential businesses, and social distancing.

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The relationship between COVID-19 cases and PHIs have been explored in previous studies using mathematical models and correlation analysis over wide geographic regions, with time frames of less than 4 months leading up to May 2020 [3-6]. Notably, these studies reported a negative relationship between cases and PHIs [7,8].

Vaccines were pharmaceutical measures implemented by the federal government beginning in December 2020 [9]. By September of 2023, 80.5% of Canadian population had received two doses of COVID-19 vaccine [10]. Moreover, only a few studies explored the relationship between vaccination coverage and cases [11,12]. For instance, Wu et al., used mathematical modeling to show that vaccine effectiveness against infections decreased over time [13]. These studies focus on cross-country data with study periods less than 19 months. It is important to further explore the impact of vaccination in more localized geographic regions over an extended period.

Temperature has been found to significantly influence the development of respiratory infections [14]. It is important to further explore the impact of temperature on respiratory infections. Previous findings show that Low temperature and low radiation/sunlight lead to better survival of coronaviruses in winter [15]. Identifying the seasonal patterns of viral respiratory infections can inform healthcare systems and facilitate timely public health interventions, thereby protecting populations from infections.

Previous studies have investigated the relationship between COVID-19 cases and temperature [16-18]. This relationship has been examined over intervals ranging from 5 weeks to 5 months, utilizing data at country, province, and city levels. Various statistical methodologies, including correlation analysis and mathematical models, have been employed. However, the findings regarding the direction of this relationship are conflicting, as some studies show a negative association, while others indicate a positive association [17-19].

This study aimed to use correlation analysis to investigate the relationship between reported COVID-19 cases, PHIs, vaccine coverage, and temperature. The relationship between cases and PHI was explored from May 2020 to May 2021. The relationship between cases and vaccine coverage in Ontario, and Toronto temperature was analyzed for the period of January 2021 to September 2023.

Methods

Provincial and City Case Data

We gathered data on provincial case numbers for Ontario from open access datasets available through the Government of Canada's COVID-19 epidemiology update tool. We used Ontario cases for PHI and vaccine correlations.

We gathered casa data for Toronto from Public Health Ontario's Respiratory Virus Tool. This open access dataset includes daily new case counts for each public health unit in Ontario. Moreover, we calculated monthly new case counts for Toronto by summing the weekly new cases reported for Toronto public health unit within each month. We used Toronto case data for temperature correlation.

PHI Data and Score

We obtained PHI data from Canadian Institute for Health Information's (CIHI) Canadian Dataset of COVID-19 Interventions. This dataset provided information on various PHIs including case management, distancing, travel restrictions, and vaccination.

We scored PHIs based on a framework adapted from the Oxford COVID-19 Government Response Tracker [20]. The time scale used for calculating the PHI score was one month. Moreover, we recorded interventions based on an ordinal or binary scale, with the highest value denoting the most stringent level. We calculated PHI scores, expressed as a percentage, by dividing the sum of highest scores for each intervention by the maximum possible score. Table 1 demonstrates an example of the framework used for scoring workplace closing intervention implemented from March to September 2020. Data demonstrating scoring framework and calculated PHI scores is available upon request from the authors. The maximum score represented a scenario where each intervention implemented at their most stringent level. When interventions varied in stringency within a month, we used the highest level for score calculation. If there was no change recorded in the stringency of a PHI compared to the previous month, the score for that intervention remained the same.

Table 1: The adapted scoring framework used to obtain monthly Public Health Intervention (PHI) score for workplace closing intervention, implemented in Ontario from March to September 2020. PHI data is from Canadian Institute for Health Information's (CIHI) Canadian Dataset of COVID-19 Interventions. The PHI scores are calculated based on a framework adapted from the Oxford COVID-19 Government Response Tracker [20].

Score	May	June	July	August	September
0 = no measures					
1 = recommend closing or all businesses open with alterations			1	1	1
2 = require closing or working from home for some sectors or categories of workers	2	2			
3 = require closing or working from home for all non-essential workplaces					
Max Score [a] (All PHIs Included)	35	35	35	35	35
Actual Score [b] (All PHIs Included)	21	20	16	16	17
Actual Score [c] (% of MAX)	60.0	57.1	45.7	45.7	48.6

[a]Max score is the sum of highest possible score for all PHIs in each month.
[b]Actual score is the sum of highest score for each PHI implemented in each month
[c]Actual score as percentage of maximum score is obtained by dividing actual score by max score

Vaccine Coverage Data
We gathered vaccine coverage data for Ontario from publicly accessible dataset available through the Government of Canada's COVID-19 Vaccination Coverage Monitoring dashboard [10]. This dataset included the reported weekly proportion of fully vaccinated individuals for each Canadian province. Fully vaccinated meant receiving two doses of an authorized vaccine. We used the reported proportion for the last week of each month as the monthly vaccination proportion. We used vaccination data for the timeframe from January 2021 to September 2023.

Temperature Data
We used reported temperature data for Toronto including monthly average mean temperatures [21]. We based the temperature data, measured in degrees Celsius, on readings from the Toronto International Airport weather station, covering the period from January 2021 to September 2023. Cases were obtained from Public Health Toronto (Table 2).

Table 2: Monthly Toronto new cases and reported Toronto average mean temperatures, measured in degrees Celsius for January 2021 to September 2023. Casa data for Toronto is from Public Health Ontario's Respiratory Virus Tool. We calculated monthly new case counts by summing the weekly new cases reported for Toronto public health unit within each month. Temperature data is from the Toronto International Airport weather station readings [21].

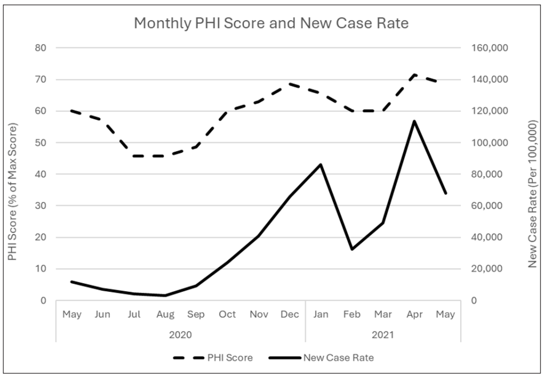
Year	Month	Mean Temp	New Cases
2021	January	-2.7	25801
2021	February	-5.1	9367
2021	March	3.1	16551
2021	April	7.9	32747
2021	May	13.6	17194
2021	June	21.8	1623
2021	July	21.2	807
2021	August	24.0	4227
2021	September	17.6	3584
2021	October	13.5	2392
2021	November	4.2	2569
2021	December	2.1	48036
2022	January	-8.3	55835
2022	February	-4.5	7717
2022	March	1.1	9758
2022	April	6.7	15990
2022	May	15.8	9658
2022	June	19.6	5241
2022	July	22.7	12472
2022	August	22.5	6458
2022	September	17.8	5038
2022	October	10.4	7427
2022	November	5.4	3929
2022	December	-0.6	4964
2023	January	-0.9	5238
2023	February	-1.4	2425
2023	March	0.9	1786
2023	April	9.0	1764
2023	May	13.5	1098
2023	June	19.4	711
2023	July	22.1	646
2023	August	20.1	845
2023	September	18.7	1772

Ethics
Since our study used publicly available, de-identified data therefore, ethics approval was not required.

Statistical Analysis
Case data from Ontario and Toronto did not fulfill the normality assumption of Pearson's correlation (Shapiro-wilk test of normality, W=0.650, p < .0001). Thus, we conducted the non-parametric correlation analysis, Spearman's rank-order correlation, to examine the relationships between new cases, PHIs, vaccine coverage, and temperature. Additionally, to examine the delayed effect of PHIs on case rates, we calculated the correlation between cases and PHIs with a month delay in cases. To better illustrate the relationship between vaccine coverage and temperature prior to and after vaccine coverage threshold, we conducted correlation analyses over two intervals of January 2021 to January 2022 and February 2022 to September 2023. We conducted correlation analysis using SAS OnDemand for Academics.

Results
Correlation Between PHI Scores and New Cases in Ontario
Figure 1 showed a positive correlation between new cases and PHI score. The first peak in new cases occurred in January 2021 while the PHI score peaked in December 2020. The second peak in cases occurred in April 2021 which coincided with the PHI peak. The Spearman's rank-order correlation was positive and significant (r = 0.947, p= <0.0001). The correlation analysis with a one-month delay in new cases also showed a positive and significant correlation (r=0.788, p=0.0023).

Figure 1: Monthly new COVID-19 case rate (per 100,000) and PHI score as percentage of the maximum score for Ontario from May 2020 to May 2021. Solid black line = New case rates. Dashed black line = PHI Score. New case rates are calculated by dividing the monthly new case counts by Ontario population size reported for 2020 rounded to nearest thousand (148000 Million) [22]. We obtained Ontario case data from open access datasets available through the Government of Canada's COVID-19 epidemiology update tool. PHI data is from Canadian Institute for Health Information's (CIHI) Canadian Dataset of COVID-19 Interventions. The PHI scores are calculated based on a framework adapted from the Oxford COVID-19 Government Response Tracker [20].



Year	Month	New Case Rate (Per 100,000)	PHI Score (%)
2020	May	11672	60
2020	June	7209	57.1
2020	July	4141	45.7
2020	August	3100	45.7
2020	September	9401	48.6
2020	October	24020	60
2020	November	40762	62.9
2020	December	65667	68.6
2021	January	86052	65.7
2021	February	32605	60
2021	March	49087	60
2021	April	113461	71.4
2021	May	68095	68.6

Correlation Between New Cases and Percent Vaccine Coverage in Ontario

The percent of fully vaccinated people increased rapidly from January 2021 to January 2022 (Figure 2). During this period, new case counts decreased during summer then rose in fall and winter. When vaccine coverage reached 77.3% in January 2022, new cases began decreasing to September 2023.

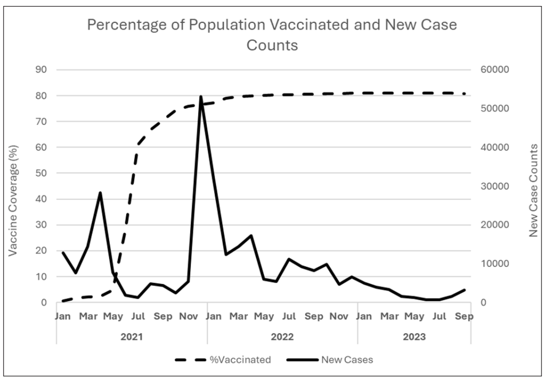


Figure 2: Trend of monthly percentage of population vaccinated in Ontario and new case counts in Ontario from January 2021 to September 2023. Solid black line = New case counts. Dashed black line = Percentage of population vaccinated. We obtained Ontario case data from open access datasets available through the Government of Canada's COVID-19 epidemiology update tool. Vaccine coverage data for Ontario is from publicly accessible dataset available through the Government of Canada's COVID-19 Vaccination Coverage Monitoring dashboard [22]. Vaccine proportions for the last week of each month is used as the monthly proportion of population vaccinated.

Correlation for cases and vaccine coverage was approximately zero (r = 0.0165, p = 0.957) for January 2021 to January 2022, and negative for February 2022 to September 2023 (r = -0.816, p <.0001) (Figure 3).

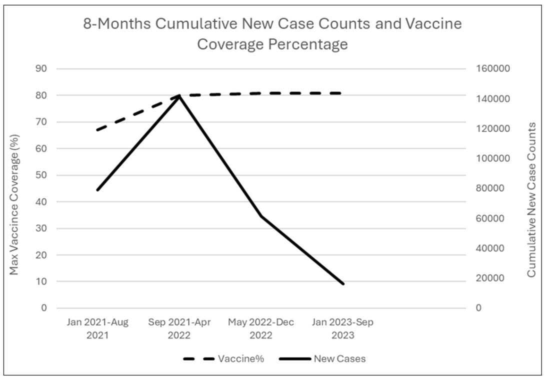


Figure 3: Trend of maximum vaccine coverage percentage and 8-month cumulative new case counts in Ontario from January 2021 to September 2023. Solid black line = 8-month cumulative new case counts. Dashed black line = Maximum percentage of population vaccinated. We obtained Ontario case data from open access datasets available through the Government of Canada's COVID-19 epidemiology update tool. Vaccine coverage data for Ontario is from publicly accessible dataset available through the Government of Canada's COVID-19 Vaccination Coverage Monitoring dashboard [22]. Vaccine proportions for the last week of each month is used as the monthly proportion of population vaccinated.

Year	Month	New Cases	Vaccine Proportion
2021	January	12774	0.5
2021	February	7682	1.8
2021	March	14400	2.1
2021	April	28350	2.4
2021	May	7766	4.7
2021	June	1884	28.1
2021	July	1349	61.0
2021	August	4765	66.9
2021	September	4400	70.6
2021	October	2505	74.3
2021	November	5435	75.9
2021	December	53158	76.6
2022	January	32121	77.3
2022	February	12360	79.1
2022	March	14363	79.7
2022	April	17176	80.0
2022	May	6059	80.2
2022	June	5434	80.3

2022	July	11240	80.4
2022	August	9199	80.5
2022	September	8225	80.6
2022	October	9908	80.7
2022	November	4611	80.8
2022	December	6635	80.9
2023	January	4976	80.9
2023	February	3945	80.9
2023	March	3396	80.9
2023	April	1519	80.9
2023	May	1207	80.9
2023	June	633	80.9
2023	July	705	80.9
2023	August	1559	80.9
2023	September	3226	80.8

Month	New Cases	Vaccine %
Jan 2021-Aug 2021	78970	67
Sep 2021-Apr 2022	141518	80
May 2022-Dec 2022	61311	80.9
Jan 2023-Sep 2023	16190	80.9

Correlation Between New Cases and Average Temperatures in Toronto

Correlation coefficient for Toronto's new cases and mean temperature from January 2021 to January 2022 was negative and significant ($r = -0.645$, $p = 0.0112$). From February 2022 to September 2023 the correlation approached zero and was not significant ($r = -0.162$, $p = 0.494$).

Discussion

This study revealed a significant positive correlation between new COVID-19 cases and PHI. Additionally, during the period when vaccine coverage ranged from 0% to 77.3%, there was almost no correlation between case numbers and vaccine coverage. However, once vaccine coverage exceeded 77.3%, a negative and significant correlation was observed between cases and vaccine coverage. Prior to reaching the vaccine coverage threshold of 77.3%, our analysis also found a negative and significant correlation between cases and temperature. After crossing the threshold, the correlation between cases and temperature was almost zero.

The positive correlation between new cases and PHI contradicted previously published models that showed a negative correlation. For instance, Rees et al., investigated the relationship between PHI and COVID-19 transmission from April 2020 to March 2021 for 6 Canadian provinces [7]. Similar to our methodology, this study adapted a framework from University of Oxford to calculate the PHI score. They used the effective reproduction number (Rt) as a measure of COVID-19 transmission. Their results showed a negative association between Rt and PHI score. Moreover, Stevens et al., investigated the impact of PHIs on cases and social mobility from April to October 2020 [8]. Using regression models, they concluded that mask mandate and higher PHI scores were associated with reduced cases. Cyr et al., investigated the correlation between the days of intervention and the number of reported COVID-19 cases in Canadian provinces, including Ontario, over a 3-month period from January 25 to April 30, 2020 [6]. Contrary to our study, they did not develop a PHI score and used Pearson's correlation. Nevertheless, they analyzed similar PHIs and found a positive and significant relationship between cases and PHI duration.

The positive correlation between reported cases and PHI suggested that when cases increased, PHIs were increased, and when cases decreased, PHIs were decreased. This observation does not imply ineffectiveness of PHIs but rather suboptimal timing. The policy implication highlights the importance of establishing a proactive threshold for implementation of more stringent PHIs at a set point for rising cases. Similarly, establishing a proactive threshold for implementation of less stringent PHIs at a set point for falling cases.

The results showed a biphasic correlation between cases and vaccine coverage, namely almost zero correlation until coverage reached 77.3% followed by a negative and significant correlation at higher coverage. Previous studies have evaluated this association using cross-country data including Canada [11,12]. For some countries, the Spearman correlation coefficient was positive, while for others it was negative. Canada showed a positive but not significant correlation. Moreover, Huang et al., concluded that rising vaccination coverage was correlated with lower new cases after coverage reached 60% [12]. The global scope and different populations may account for the different vaccination coverage threshold that leads to decreasing cases. The policy implications for the results of our study support the approach used by Ontario Public Health, namely, to reach the vaccine coverage threshold as soon as possible.

The results also showed a biphasic correlation between Toronto cases and temperature from May 2020 to September 2023. Initially from May 2020 to January 2022, when vaccine coverage was below the threshold, the correlation was negative and significant, followed by almost zero correlation when vaccine coverage exceeded 77.3%. This suggested when vaccine coverage is greater than threshold, vaccines may be a stronger driver of cases in comparison to temperature.

Previous investigations on the correlation between cases and temperature included mixed findings. Menebo found a positive but weak correlation between daily cases and maximum temperature in Oslo, Norway over a 7.6-week interval from February 27 to May 2, 2020 [19]. Conversely, Mandal and Panwar found a negative but weak correlation using data from approximately 200 countries over a 3.6-week interval from March 25 to April 18, 2020 [17]. Both studies were based on data collected over a short period and without accounting for seasonal changes in temperature that was possible only over a study period of more than one season. A study conducted by To et al., explored the relationship between incident cases and mean temperature from January to May 2020 in Ontario, Alberta, British Columbia, and Quebec [18]. Using multiple regression analysis, they found a positive correlation between cumulative incidence and mean temperature that was not significant. Differences in methodology such as the duration of the study period and larger geographic regions, could explain the difference from our findings.

Strengths and Limitations

The strength of our study is centred on methodology including an extended study period, temperature data over a smaller geographic area, PHI score calculation, and reported cases. Cases were based on provincial and public health unit reported information to ensure reliability and accuracy. The one-year study period for investigating the relationship between cases and PHIs included three case peaks, an interval during which vaccine coverage was less than 5%, therefore not affected by vaccine coverage. This extended interval facilitated the observation of the correlation between cases and a broader range of PHIs. The PHI score was calculated as a percentage of maximum score for each month. This standardized calculation allowed for PHI score comparisons by month. Additionally, our study provided evidence of the relationship between cases and vaccination, and temperature over a 32-month period, substantially longer than previous reports. The study period allowed us to examine how the correlations evolved throughout the pandemic. Moreover, the accuracy of a more localized region such as the city of Toronto to determine the correlation between cases and temperature improved the reliability of the results [23-27].

Our study also had limitations. The PHI score calculation assigned equal weight to each intervention, not considering potential variation in stringency and effectiveness of different PHIs. PHI score was calculated using the same ordinal scale for all interventions, assuming comparable magnitude and impact of increased stringency. Additionally, public health interventions such as closures and openings followed a regional implementation. Therefore, during some months different regions of the province had varying levels of restrictions. PHI scores calculated for these interventions were based on the highest level of restriction regardless of geographic region.

Conclusion

This study explored the relationship between cases, PHI, vaccine coverage, and temperature using provincial public health measures, provincial vaccine coverage, and city temperature from May 2020 to September 2023. The correlation between cases and PHIs was positive and significant. The correlation between cases and vaccine coverage was negative and significant once vaccine coverage exceeded the threshold level of 77.3%. Additionally, the correlation between cases and temperature was negative and significant before vaccine coverage reached 77.3%. Thereafter the correlation approached zero. These results differed from mathematical models.

Author contributions: All authors contributed to the study conceptualization, methodology, data curation, and formal analysis. The first draft of the manuscript was written by both authors, and they reviewed subsequent versions of the manuscript. Both authors read and approved the final manuscript. The content and views expressed in this article are those of the authors and do not necessarily reflect those of the Government of Canada.

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