ORIGINAL ARTICLE

Potential intensive care unit ventilator demand/ capacity mismatch due to novel swine-origin H1N1 in Canada

Paul Smetanin MQF[1], David Stiff PhD[1], Anand Kumar MD[2], Paul Kobak MSc[1], Ryan Zarychanski MD[3], Neil Simonsen MD[4], Frank Plummer MD[4]

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PURPOSE: To investigate the ability of Canadian intensive care units (ICUs) and ventilators to handle widespread re-emergence of the swine-origin H1N1 virus in the context of an aggressive strategy of vaccination.
METHOD: Data collected during the first wave in Winnipeg, Manitoba, were applied to a variety of second wave pandemic models to determine potential ICU and ventilator demand.
RESULTS: For attack rates greater than 20% to 25%, significant shortages in ventilators may be expected across Canada regardless of the duration of the pandemic if vaccination is not considered. The shortfall arises largely due to the extended durations that patients must remain on ventilation. From the Winnipeg study, 50% of patients required ventilation for more than two weeks. For larger attack rates of 35%, ventilator demand may exceed capacity for over five weeks, with a peak shortfall of 700 ventilators. Vaccination can significantly reduce the attack rates, and is expected to reduce ventilator demand to manageable levels
CONCLUSION: Canada's health care system must be prepared for the possibility of a significant influx of ICU patients during the second wave of swine-origin H1N1. Efficient vaccination and other disease prevention measures can reduce the attack rate to manageable levels.

Key Words: *H1N1; Influenza; Intensive care; Mathematical modelling Pandemic*

Écart potentiel entre l'offre et la demande de ventilateurs dans les unités de soins intensifs en raison de la pandémie de grippe AH1N1 au Canada

OBJECTIF : Vérifier si les unités de soins intensifs (USI) canadiennes et les respirateurs dont elles disposent permettront d'assurer la prise en charge d'une importante ré-émergence de la grippe AH1N1 dans le contexte d'une stratégie énergique de vaccination.
MÉTHODE : Les données recueillies durant la première vague de la pandémie de grippe AH1N1 à Winnipeg, au Manitoba, ont été appliquées à une variété de modèles pandémiques applicables à une seconde vague afin d'évaluer les pressions potentielles exercées sur les USI et la demande de respirateurs.
RÉSULTATS : Si les taux d'attaque dépassent 20 % à 25 %, d'importantes pénuries de ventilateurs sont à prévoir partout au Canada, peu importe la durée de la pandémie et si on ne tient pas compte de la vaccination. La pénurie serait principalement due à la durée de l'intubation des patients. Selon l'étude de Winnipeg, 50 % des patients sont restés sous respirateur pendant plus de deux semaines. Si les taux d'attaque dépassent 35 %, les demandes de ventilateurs pourraient excéder la capacité pendant plus de cinq semaines, avec une pénurie de 700 ventilateurs au pire de la crise. La vaccination peut significativement réduire les taux d'attaque et on s'attend à ce qu'elle maintienne la demande de ventilateurs à des niveaux gérables.
CONCLUSION : Le système de soins de santé canadien doit se préparer à un afflux massif de patients dans les USI au cours de la seconde vague de grippe AH1N1. Une vaccination efficace et d'autres mesures de prévention de la maladie peuvent contribuer à maintenir le taux d'attaque à des niveaux gérables

The initial Canadian outbreak of the novel swine-origin influenza A/H1N1 (soH1N1) virus in Manitoba in the spring of 2009 severely tested intensive care unit (ICU) and ventilator surge capacity in the Winnipeg region. Similar or worse ICU demand has been reported in the southern hemisphere where the pandemic coincided with the seasonal flu period. As the flu season for the northern hemisphere approaches, it is critical to investigate the ability of the Canadian health care system to handle widespread re-emergence of the soH1N1 virus.

ICUs and ventilators are vital resources for the treatment of severely ill 2009 pandemic soH1N1-infected patients. Although the current overall Canadian experience of the soH1N1 pandemic has been relatively mild to date, local outbreaks have highlighted the excessive demand that could be placed upon critical care resources. During the outbreak in Manitoba in the spring of 2009, almost 45 ICU beds and 40 ventilators were in use at the peak of the epidemic for confirmed or probable soH1N1 cases (A Kumar, unpublished data). This represents approximately one-half of the ventilator-capable beds normally funded in the province and more than 100% of the normal ventilator use at any given time. In the case of a more severe outbreak, these fractions could significantly increase. Experience in Australia and New Zealand, where the current soH1N1 outbreak has coincided with their seasonal flu period, has illustrated the paradox of the soH1N1 strain where the primary impact is being felt in ICU demand, rather than total mortalities (1).

Pandemics are notoriously unpredictable, and accurate forecasts for the fall wave are likely to change as more data become available. Therefore, rather than focusing on a single fall wave projection, a variety of data sources (including comprehensive

[1]RiskAnalytica Research, Toronto, Ontario; [2]Section of Critical Care Medicine, Health Sciences Centre/St Boniface Hospital, University of Manitoba; [3]Department of Medical Oncology and Hematology, Cancercare Manitoba; [4]Canadian Science Centre for Human and Animal Health, National Microbiology Laboratory, Winnipeg, Manitoba
Correspondence: Paul Smetanin, RiskAnalytica Research, 4576 Yonge Street, Suite 400, Toronto, Ontario M2N 6N4. Telephone 416-782-7475 ext 401, e-mail paul@riskanalytica.com

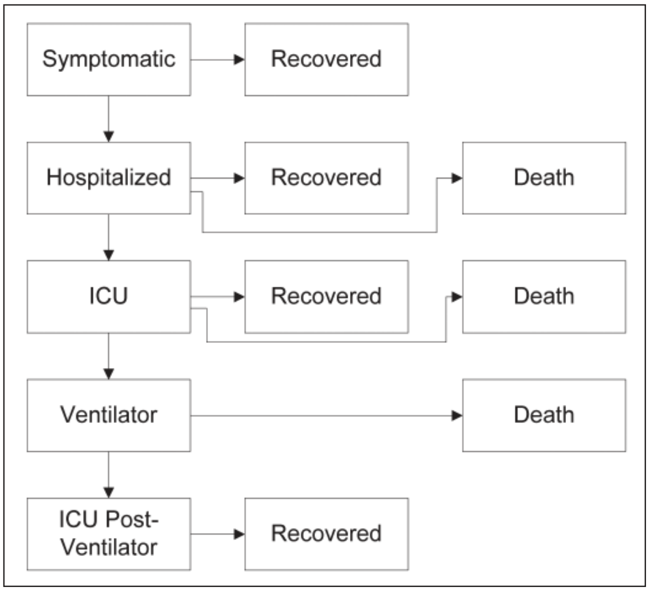

Figure 1) *Patient flow diagram from symptomatic through to recovery or death. ICU Intensive care unit*

data from the Manitoba outbreak) have been used to model characteristics of the second wave using a range of plausible attack rates and epidemic wave durations. The potential impact of a broadly implemented vaccination strategy on ICU resource demand is also assessed.

METHODS

The data used to drive this model were primarily derived from a Manitoba study of soH1N1-associated ICU admissions (published as a subset of a Canada-wide study) (2) and Canada's national surveillance system, FluWatch. The Winnipeg Regional Health Authority ICUs operate as an integrated system with ongoing communication among sites. This allows for real-time awareness of bed utilization and capacity. Data on all polymerase chain reaction-positive (n=56) and epidemiologically or clinically highly suspect (n=6; based on epidemiological and clinical factors as determined by the attending physician of record) potential soH1N1 influenza virus infections requiring ICU care were prospectively collected using a pre-positioned data collection tool (3) during the epidemic. Additional data collection during the resolution phase of the epidemic were also performed to supplement the real-time data. Cross-referencing of all ICU cases with pharmacy records for oseltamivir prescriptions and the Manitoba laboratory for soH1N1 polymerase chain reaction-positive test results allowed for data collection on 100% of all suspected cases admitted to ICU within the region. The data used in the present study considered ICU admissions up to July 26, 2009. All data were collected with the approval of the University of Manitoba Research Ethics Board under a waived consent protocol.

Estimating the expected ICU and ventilator demand requires both models of the pandemic behaviour, and patient flow through the hospital. The infectious disease model used is an age-dependent Susceptible, Exposed, Infectious, Recovered (SEIR) system (4,5). Appendix A covers the technical details of the model. Because pandemics are inherently uncertain, it is difficult for models to accurately predict the course of impacts. As a result, to identify the characteristics of a second soH1N1 wave that could stress the Canadian health care system, a variety of attack rates, pandemic durations and populations are investigated. Attack rates of 15%, 20%, 25%, 30%, 35% and 40% were considered. For each attack rate, pandemic durations of five, six, eight, 10 and 15 weeks were also considered. The duration is defined as the time between 5% and 95% of total infections. Note that no attempt has been made in this study to match the numerical models of pandemic with the current observations. However, SEIR models have been used to model past pandemics and influenza epidemics with considerable accuracy (6,7). Therefore, it is expected that one of the combinations of attack rate and duration would be a reasonable approximation of the second wave of the current pandemic.

TABLE 1
Probabilities derived from the pandemic models, FluWatch, and the Manitoba data set

Transition	Probability	Counts	Source
Hospitalized given symptomatic	0.4%	–	Southern hemisphere studies and Canadian pandemic fit models
ICU given hospitalized	17.6%	240/1366	FluWatch data
Direct recovery given ICU	6.8%	4/59	Manitoba data set
Ventilation given ICU	93.2%	55/59	Manitoba data set
Recovery given ventilation	83.6%	46/55	Manitoba data set
Death given ventilation	16.4%	9/55	Manitoba data set

Extensive vaccination of the at-risk population could also affect the demand for ICU and ventilator support. Therefore, scenarios are also considered where vaccines are administered. To prevent an over-complication of the model, it was assumed that 50% of the population would seek vaccination, vaccines are 100% effective, and they are broadly available for the entire population. No targeting of high-risk groups was considered. Vaccinations start in the model when the number of mortalities reached three per million, which roughly corresponds to the number of mortalities observed in Canada when vaccines became available. Vaccines were assumed to be administered at two million doses per week across Canada and the rate was scaled accordingly for smaller populations. The potential impact of antiviral therapy was not considered because there are no data on the impact of such therapy on disease progression.

The model of hospital resource utilization consists of tracking patients from initial hospitalization through to recovery or death. Figure 1 illustrates the possible paths through the hospital system. For each patient who becomes ill, a random path through the patient flow diagram is chosen, with durations of stay in each state selected according to the observed distributions of confirmed (n=56) and highly suspect (n=6) cases. This allows one to determine the start and stop time for the utilization of ICU beds and ventilators, and ultimately determine the peak demand. Table 1 shows the probabilities of each branch in Figure 1, and Figure 2 illustrates the distributions for each stage derived from the Winnipeg study. For example, once a patient is in the ICU, there is a 6.8% chance that that patient would recover without requiring ventilation. The duration of the stay in the ICU is then chosen from the distribution of observed ICU stays for patients not requiring ventilation. The critical piece of information not available from the Winnipeg study is

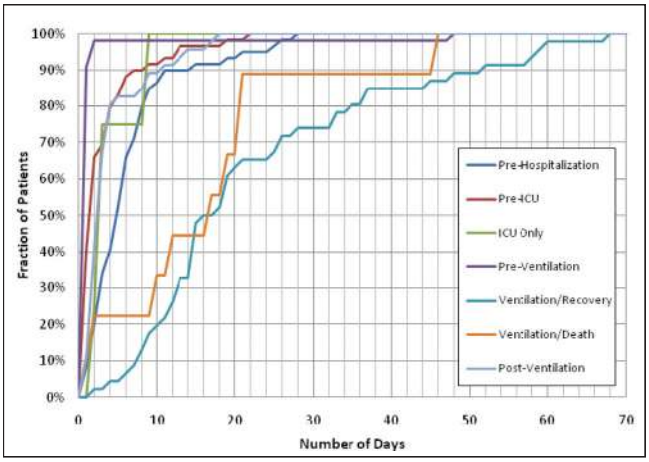

Figure 2) *The cumulative distribution of times spent in each hospitalization state used in the model. Prehospitalization is the time between symptom onset and hospitalization. Pre-intensive care unit (Pre-ICU) is the time between hospitalization and admission to the ICU. ICU Only refers to patients who are in ICU but do not require ventilation and recover. Pre-Ventilation is the time patients spend in ICU before requiring ventilation. Ventilation/Recovery is the duration on ventilation for patients who recover, while Ventilation/Death is the time on ventilation for those who die. Finally, Post-Ventilation is the time that patients spend in ICU after ventilation before being released from ICU*

the case hospitalization rate. A hospitalization rate of 0.4% was adopted for the present study. This is similar to the rate reported in the Australian (1) and New Zealand (8) studies and in line with models based upon fitting the current pandemic (P Smetanin, personal communication).

To determine if there could be an ICU or ventilator shortage, the number of ICU beds and ventilators in Canada is required. Unfortunately, there are no Canada-wide data and the best estimate that can be obtained is an extrapolation from a recent survey from Ontario that found 8.7 mechanically ventilated beds per 100,000 population (9). However, because of the existence of operating room ventilators and various other poorly enumerated ventilator resources, the final number of useful ventilators nationally and within regions is uncertain at best. This is particularly true in view of the variability in need for advanced ventilatory support among those critically ill with soH1N1 (ie, a significant fraction of ventilators not designed for ICU use may be inadequate to the task). The number of ICU beds is an even more ambiguous quantity because there is no clear definition as to what exactly constitutes an ICU bed. For example, some hospitals may be able to convert beds that are traditionally classified as non-ICU into an ICU bed if required. Therefore, while the demand for ICU beds is addressed in the present study, the focus is on the demand for ventilators to identify characteristics of the pandemic that may result in ventilator shortages.

For each attack rate, pandemic duration and population combination, 200 stochastic trials were run to determine the ICU and ventilator demand. Figure 3 shows the typical curves of cumulative ICU admissions, ICU releases (due to recovery or death), and number of patients residing in the ICU for a single trial.

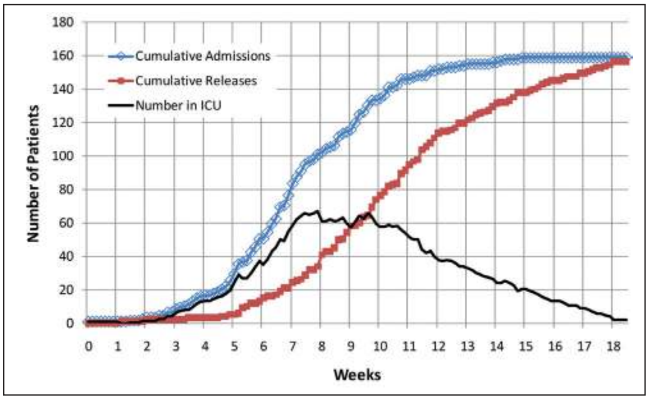

Figure 3) *Typical cumulative admissions and releases from the intensive care unit (ICU) for a population of one million, attack rate 25% and duration of eight weeks. The number of patients in ICU is the difference between the cumulative admissions and releases*

RESULTS

The considerable offset between the admissions curve and the release curve is reflective of the large number of patients remaining in ICU during the peak of the pandemic. Tables 2A and 2B show the expected ventilator demand, along with the fifth and 95th percentile from the stochastic models. Under the assumption that one-third of the total ventilators would be in use for non-soH1N1 causes, the table is highlighted to indicate the parameters where demand for mechanical ventilation would exceed the projected ventilator-capable bed resources.

Expected ventilator demand in comparison to anticipated ventilator resources was calculated for regions of differing populations. Canadian ICUs run at a normal occupancy rate of approximately 90% or higher at most times (9,10). It was assumed that fully two-thirds of ventilator-capable bed capacity in ICUs could be cleared for use during a mass casualty event stretching over several weeks by cancelling elective high-risk procedures and other administrative measures, a fraction comparable to that achieved during the Winnipeg outbreak. Nonetheless, in the absence of vaccination, attack rates of greater than 25% yield an expected ventilator demand that is predicted to exceed normal capacity in all cases except for pandemics with a duration greater than approximately nine weeks. If more than one-third of ventilator-capable beds are required for noninfluenza patients or if these beds cannot be made available as quickly as the increase in demand, the mismatch worsens substantially. The situation is significantly different when vaccination is considered. Under the vaccination assumptions used here that mimic current vaccination efforts, the attack rates are sufficiently reduced so that only very fast pandemics with high attack rates will significantly stress the health care system.

As the area of a geographic region increases, the pandemic duration tends to increase. As can be seen in Tables 2A and 2B, the longer the duration of the pandemic, the higher the critical attack rate is where ventilation demand becomes an issue. Therefore, it is of interest to look at Canada as a whole to determine under what circumstances demand could exceed the total supply of Canadian ventilators. Tables 3A and 3B show the results for modelling Canada as a single region with a population of 33.5 million. These data suggest that the current

TABLE 2A

Peak ventilator demand assuming one-third of ventilators would be unavailable for H1N1 patients in regions of different populations without vaccination. The colours indicate where supply exceeds maximum demand (green), where supply exceeds median demand (amber), where the median demand exceeds supply (red); and where minimum demand exceeds supply (dark red)

Population 100,000: Available ICUs With Ventilator = 6						
Duration	15%	20%	25%	30%	35%	40%
5	5 (2 - 8)	6 (3 - 10)	8 (4 - 12)	9 (5 - 13)	10 (6 - 15)	13 (6 - 19)
6	4 (2 - 8)	6 (3 - 9)	7 (3 - 12)	8 (4 - 14)	10 (5 - 14)	12 (6 - 17)
8	4 (1 - 7)	5 (2 - 8)	6 (3 - 10)	7 (3 - 10)	8 (4 - 14)	10 (6 - 16)
10	3 (1 - 6)	4 (1 - 8)	6 (2 - 9)	7 (3 - 11)	8 (4 - 12)	9 (5 - 13)
15	2 (0 - 6)	3 (1 - 6)	4 (2 - 7)	5 (2 - 8)	6 (2 - 10)	7 (3 - 10)
Population 500,000: Available ICUs With Ventilator = 29						
Duration	15%	20%	25%	30%	35%	40%
5	24 (17 - 32)	31 (22 - 41)	40 (30 - 50)	48 (38 - 57)	54 (44 - 66)	62 (51 - 77)
6	21 (14 - 29)	29 (22 - 37)	37 (27 - 45)	43 (33 - 54)	51 (42 - 61)	58 (47 - 71)
8	19 (12 - 24)	25 (18 - 34)	31 (22 - 38)	38 (28 - 47)	44 (34 - 55)	51 (40 - 62)
10	17 (11 - 23)	23 (17 - 30)	27 (19 - 35)	34 (25 - 42)	37 (30 - 47)	43 (33 - 55)
15	13 (7 - 19)	16 (11 - 23)	21 (14 - 27)	26 (17 - 33)	29 (22 - 38)	34 (24 - 43)
Population 1,000,000: Available ICUs With Ventilator = 58						
Duration	15%	20%	25%	30%	35%	40%
5	48 (37 - 58)	63 (49 - 75)	77 (65 - 92)	94 (78 - 109)	108 (90 - 127)	127 (110 - 145)
6	44 (34 - 55)	58 (46 - 70)	71 (59 - 86)	87 (72 - 100)	101 (85 - 118)	118 (99 - 132)
8	37 (29 - 47)	51 (39 - 63)	63 (50 - 75)	75 (62 - 90)	89 (73 - 103)	100 (83 - 117)
10	33 (24 - 42)	44 (34 - 56)	56 (44 - 68)	66 (53 - 78)	76 (62 - 89)	89 (73 - 103)
15	25 (17 - 32)	34 (24 - 41)	43 (32 - 52)	51 (38 - 62)	60 (48 - 70)	67 (54 - 79)

Duration in weeks. ICU Intensive care unit

vaccination strategy should substantially decrease the number of cases requiring ICU and ventilator support so that there is little risk of breaching ICU capacity.

For the models without vaccination, Table 4 shows a similar analysis with both projected peak ventilator-requiring and all ICU cases for each province and territory (values for Canada are included again for reference). Table 5 demonstrates the total projected number of ventilator-requiring and total ICU cases in the fall epidemic wave for each province, territory and for the country as a whole.

A notable difference between the data shown in Tables 5A and 5B is that the total ICU and ventilator demands in 5A are independent of the duration of the pandemic, whereas for Table 5B, an eight-week pandemic is shown. With vaccinations, the attack rate is reduced more in longer pandemics because a greater fraction of the population is vaccinated before the pandemic peaks. Pandemics with durations longer than eight weeks would therefore have a lower demand than shown in Table 5B.

These results show that a national soH1N1 epidemic stretching over a 10- to 15-week duration may have resulted in a demand for ventilator-capable beds exceeding the overall national capacity for attack rates of 25% to 30%. However, this assumes that the epidemic is evenly distributed in space and time across the country. In reality, the pandemic would have been expected to strike different areas at various times. As a consequence, even during a national epidemic in which overall resources are sufficient, ICU ventilator capacity in some regions could have been breached at times when other areas have significant available resources. Without the current extensive vaccination efforts, attack rates of greater than 25% to 30% could have breached national capacity overall at the peak of the epidemic depending on the duration. Figure 4 shows the time dependence of ventilator demand for the case of a 35% attack rate and a 10-week pandemic duration. Ventilator demand exceeds capacity for over five weeks with a peak shortfall of over 700 beds. The large asymmetry in the curve arises from patients remaining on ventilation after the pandemic has passed.

DISCUSSION

There are three primary factors that affect the demand for hospital resources. The first is the overall attack rate of the pandemic, which directly increases the demand. The second is the duration of the pandemic. For a given attack rate, a shorter pandemic duration will increase the number of people falling ill at any given time, which in turn increases peak ICU demand. Finally, resource utilization will also be directly proportional to the fraction of people sick requiring ICU care.

TABLE 2B

Peak ventilator with vaccination demand assuming one-third of ventilators would be unavailable for H1N1 patients in regions of different populations. The colours indicate where supply exceeds maximum demand (green), where supply exceeds median demand (amber), where the median demand exceeds supply (red); and where minimum demand exceeds supply (dark red). Note that the attack rate refers to the no-vaccine case

Population 100,000: Available ICUs With Ventilator = 6						
Duration	15%	20%	25%	30%	35%	40%
5	2 (0 - 4)	3 (1 - 6)	4 (1 - 8)	5 (2 - 9)	6 (3 - 11)	7 (4 - 12)
6	2 (0 - 4)	3 (0 - 5)	3 (1 - 6)	4 (2 - 8)	5 (2 - 9)	6 (3 - 10)
8	1 (0 - 3)	2 (0 - 4)	3 (0 - 5)	3 (1 - 6)	4 (1 - 7)	5 (2 - 7)
10	1 (0 - 3)	2 (0 - 3)	2 (0 - 3)	2 (0 - 5)	3 (1 - 6)	3 (1 - 6)
15	1 (0 - 1)	1 (0 - 2)	1 (0 - 2)	2 (0 - 3)	2 (0 - 3)	2 (0 - 4)
Population 500,000: Available ICUs With Ventilator = 29						
Duration	15%	20%	25%	30%	35%	40%
5	12 (7 - 17)	16 (10 - 23)	20 (13 - 28)	26 (17 - 33)	31 (22 - 42)	38 (29 - 45)
6	10 (6 - 15)	13 (8 - 19)	17 (11 - 23)	21 (15 - 28)	26 (18 - 34)	32 (23 - 39)
8	8 (4 - 11)	10 (6 - 15)	13 (7 - 19)	16 (10 - 23)	18 (12 - 25)	23 (15 - 31)
10	6 (3 - 10)	8 (4 - 12)	10 (5 - 15)	12 (7 - 17)	14 (9 - 21)	18 (12 - 25)
15	4 (1 - 7)	5 (2 - 8)	6 (2 - 10)	7 (3 - 11)	9 (4 - 13)	10 (5 - 15)
Population 1,000,000: Available ICUs With Ventilator = 58						
Duration	15%	20%	25%	30%	35%	40%
5	23 (16 - 31)	32 (23 - 40)	42 (31 - 50)	51 (41 - 64)	62 (48 - 73)	73 (60 - 86)
6	20 (13 - 26)	26 (19 - 34)	34 (26 - 44)	44 (33 - 53)	52 (42 - 63)	63 (52 - 73)
8	14 (9 - 21)	20 (13 - 27)	25 (17 - 34)	32 (23 - 40)	38 (28 - 49)	45 (35 - 56)
10	12 (7 - 17)	15 (9 - 21)	19 (13 - 27)	24 (18 - 32)	29 (21 - 39)	35 (26 - 43)
15	8 (4 - 13)	9 (5 - 14)	12 (7 - 17)	15 (8 - 21)	17 (11 - 23)	21 (13 - 28)

Duration in weeks. ICU Intensive care unit

TABLE 3A

Ventilator demand for the entire Canadian population. Peak ventilator demand assuming one-third of ventilators would be unavailable for H1N1 patients in Canada as a whole. The colours indicate where supply exceeds maximum demand (green), where supply exceeds median demand (amber), where the median demand exceeds supply (red); and where minimum demand exceeds supply (dark red)

Population 33.5 Million: Available ICUs With Ventilator = 1943						
Duration	15%	20%	25%	30%	35%	40%
5	1628 (1528 - 1722)	2095 (1971 - 2237)	2624 (2463 - 2764)	3151 (2975 - 3323)	3659 (3455 - 3859)	4167 (3946 - 4440)
6	1460 (1367 - 1546)	1948 (1842 - 2051)	2421 (2289 - 2549)	2910 (2725 - 3046)	3384 (3235 - 3573)	3875 (3656 - 4064)
8	1267 (1179 - 1351)	1690 (1586 - 1772)	2096 (1991 - 2197)	2474 (2358 - 2606)	2933 (2794 - 3081)	3353 (3208 - 3502)
10	1111 (1047 - 1177)	1481 (1396 - 1554)	1851 (1762 - 1941)	2216 (2110 - 2340)	2576 (2461 - 2710)	2965 (2832 - 3085)
15	844 (790 - 903)	1123 (1054 - 1186)	1409 (1312 - 1483)	1679 (1597 - 1779)	1966 (1867 - 2051)	2254 (2140 - 2381)

Duration in weeks. ICU Intensive care unit

We have shown that a very broad distribution of ventilation duration among critically ill soH1N1 infected patients could have caused a significant national demand for ICU ventilator support. If, as in the Manitoba outbreak, one-half of the patients on ventilation require ventilation for at least two weeks, while approximately 10% of those recovering require ventilation for over 50 days, ventilator bed capacity would be highly stressed. For a rapid pandemic with a relatively high attack rate, available ICU ventilator bed capacity would likely have been overwhelmed in specific regions. With attack rates greater than 25% to 30%, which is within the range seen historically, and pandemic durations of less than 15 weeks, ventilator-capable bed capacity may well have been exceeded nationally. The resulting lack of ICU resources would potentially have resulted

TABLE 3B

Ventilator demand for the entire Canadian population with vaccination. Peak ventilator demand assuming one-third of ventilators would be unavailable for H1N1 patients in Canada as a whole. The colours indicate where supply exceeds maximum demand (green), where supply exceeds median demand (amber), where the median demand exceeds supply (red); and where minimum demand exceeds supply (dark red)

Population 33.5 Million: Available ICUs With Ventilator = 1943						
Duration	15%	20%	25%	30%	35%	40%
5	769 (705 - 826)	1051 (973 - 1127)	1374 (1287 - 1458)	1714 (1605 - 1819)	2088 (1960 - 2197)	2482 (2319 - 2643)
6	645 (603 - 700)	884 (830 - 938)	1146 (1068 - 1211)	1439 (1344 - 1532)	1760 (1644 - 1846)	2086 (1973 - 2205)
8	490 (447 - 534)	650 (596 - 701)	834 (778 - 894)	1032 (960 - 1091)	1279 (1199 - 1354)	1533 (1449 - 1621)
10	390 (356 - 429)	509 (466 - 550)	644 (596 - 696)	799 (748 - 849)	973 (911 - 1032)	1167 (1099 - 1237)
15	259 (232 - 286)	323 (294 - 353)	396 (353 - 431)	474 (428 - 517)	573 (530 - 617)	678 (633 - 725)

Duration in weeks. ICU Intensive care unit

TABLE 4

The regional peak median intensive care unit (ICU) and ventilation demand for attack rates of 25%, 30% and 35%. Note that no assumptions have been made about varying risk of severe disease between regions

		Regional median peak ICU femand											
Attack rate	Duration	BC	AB	SK	MB	ON	QC	NB	NS	PE	NL	Territories	Canada
	5	406	322	92	110	1186	713	69	86	13	47	10	3053
	6	379	300	86	103	1107	666	65	81	12	44	9	2852
25%	8	334	265	76	91	977	588	57	71	11	39	8	2516
	10	299	237	68	81	873	525	51	64	9	35	7	2248
	15	227	180	52	62	664	400	39	48	7	26	5	1711
	5	495	392	113	134	1446	870	85	106	16	57	12	3724
	6	459	364	104	124	1342	807	79	98	15	53	11	3456
30%	8	401	318	91	109	1172	705	69	86	13	46	10	3020
	10	357	283	81	97	1042	627	61	76	11	41	9	2684
	15	276	219	63	75	808	486	47	59	9	32	7	2080
	5	570	452	130	155	1668	1003	98	122	18	66	14	4295
	6	535	424	122	145	1563	940	92	114	17	62	13	4026
35%	8	468	371	106	127	1368	823	80	100	15	54	11	3523
	10	410	325	93	111	1199	721	70	87	13	47	10	3087
	15	321	254	73	87	938	564	55	68	10	37	8	2416

		Regional median peak ventilator demand											
Attack rate	Duration	BC	AB	SK	MB	ON	QC	NB	NS	PE	NL	Territories	Canada
	5	343	272	78	93	1003	603	59	73	11	40	8	2624
25%	6	316	251	72	86	925	556	54	67	10	37	8	2421
	8	281	223	64	76	821	494	48	60	9	32	7	2096
	10	250	198	57	68	730	439	43	53	8	29	6	1851
	15	192	152	44	52	560	337	33	41	6	22	5	1409
	5	419	332	95	113	1225	737	72	89	13	48	10	3151
30%	6	388	308	88	105	1133	682	66	83	12	45	9	2910
	8	334	265	76	91	977	588	57	71	11	39	8	2474
	10	294	233	67	80	860	517	50	63	9	34	7	2216
	15	232	184	53	63	677	407	40	49	7	27	6	1679
	5	481	382	110	130	1407	846	82	103	15	56	12	3659
35%	6	450	357	102	122	1316	791	77	96	14	52	11	3384
	8	397	315	90	107	1159	697	68	85	13	46	9	2933
	10	339	269	77	92	990	595	58	72	11	39	8	2576
	15	267	212	61	72	782	470	46	57	8	31	6	1966

Duration in weeks. AB Alberta; BC British Columbia; MB Manitoba; NL Newfoundland and Labrador; NS Nova Scotia; ON Ontario; PE Prince Edward Island; QC Quebec; SK Saskatchewan

TABLE 5A

Regional estimates for median total intensive care unit (ICU) demand and ventilator demand for each attack rate considered. The total number of patients does not depend upon the duration of the pandemic. Note that no assumptions have been made about varying risk of severe disease between regions

	Regional median total ICU demand											
Attack rate	BC	AB	SK	MB	ON	QC	NB	NS	PE	NL	Territories	Canada
15%	478	379	109	129	1396	840	82	102	15	55	11	3596
20%	629	499	143	170	1838	1105	108	134	20	73	15	4733
25%	785	622	179	213	2294	1380	134	167	25	91	19	5909
30%	938	744	213	254	2741	1648	161	200	30	108	22	7059
35%	1097	870	250	297	3207	1929	188	234	35	127	26	8259
40%	1256	996	286	340	3671	2208	215	268	40	145	30	9455
	Regional median total ventilation demand											
Attack rate	BC	AB	SK	MB	ON	QC	NB	NS	PE	NL	Territories	Canada
15%	445	353	101	121	1301	782	76	95	14	51	11	3350
20%	586	465	133	159	1714	1031	100	125	19	68	14	4413
25%	732	580	167	198	2139	1286	125	156	23	85	17	5508
30%	875	694	199	237	2556	1538	150	187	28	101	21	6584
35%	1022	811	233	277	2988	1797	175	218	32	118	24	7695
40%	1170	928	266	317	3421	2057	200	250	37	135	28	8810

AB Alberta; BC British Columbia; MB Manitoba; NL Newfoundland and Labrador; NS Nova Scotia; ON Ontario; PE Prince Edward Island; QC Quebec; SK Saskatchewan

TABLE 5B

Regional estimates for median total intensive care unit (ICU) demand and ventilator demand for an eight-week pandemic for each attack rate considered with vaccination. Note that no assumptions have been made about varying risk of severe disease between regions

	Regional median total ICU demand											
Attack rate	BC	AB	SK	MB	ON	QC	NB	NS	PE	NL	Territories	Canada
15%	155	123	35	42	453	273	27	33	5	18	4	1167
20%	213	169	48	58	621	374	36	45	7	25	5	1600
25%	278	220	63	75	813	489	48	59	9	32	7	2093
30%	347	275	79	94	1014	610	59	74	11	40	8	2612
35%	437	346	99	118	1276	768	75	93	14	50	10	3287
40%	524	415	119	142	1531	921	90	112	17	61	13	3942
	Regional median total ventilation demand											
Attack rate	BC	AB	SK	MB	ON	QC	NB	NS	PE	NL	Territories	Canada
15%	145	115	33	39	423	254	25	31	5	17	3	1089
20%	198	157	45	54	579	348	34	42	6	23	5	1490
25%	259	206	59	70	758	456	44	55	8	30	6	1952
30%	323	257	74	88	945	569	55	69	10	37	8	2435
35%	407	323	93	110	1190	716	70	87	13	47	10	3065
40%	488	387	111	132	1427	858	84	104	15	56	12	3674

AB Alberta; BC British Columbia; MB Manitoba; NL Newfoundland and Labrador; NS Nova Scotia; ON Ontario; PE Prince Edward Island; QC Quebec; SK Saskatchewan

in a significant increase in the overall mortality rate. Because the primary factor contributing to the ICU demand is not simply the number of people falling ill, but also the very long duration that patients remain on ventilation in ICUs, identifying those patients at risk of extended ventilation periods and working to either prevent their infection or minimize their time in ICU could significantly reduce ventilator demand. The impact of ICU shortages may also extend to the care of patients with diseases unrelated to the pandemic as resources would no longer be available for other intensive care.

In addition, our data demonstrate that an aggressive vaccination strategy reduces the overall attack rate and substantially eliminates the possibility of breaching ICU and ventilator capacity during the peak of the national epidemic. The addition of vaccination to the model (with 50% population penetration at a rate of two million doses per week) results in a sufficient reduction in attack rates that ICU resources should easily suffice to handle the anticipated surge of soH1N1-infected critically ill patients.

Recent studies from Australia and New Zealand (11) and the United States (12) have closely examined the profiles of hospitalized and critical care H1N1 patients. The focus of these studies primarily focused upon the comorbidity risks for severe complications – an aspect of the disease not considered in the present study. While the study of patients from the United States does provide the number of patients hospitalized and in ICU, it does

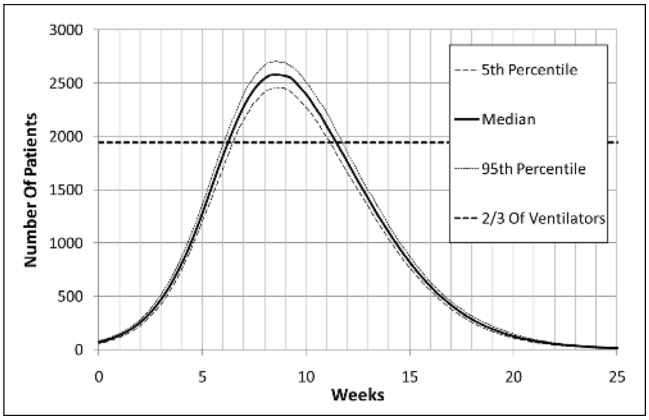

Figure 4) *Number of patients on ventilation as a function of time for a pandemic across Canada with 35% attack rate and a duration of 10 weeks. The horizontal line corresponds to the number of ventilators available in Canada for H1N1 patients under the assumption that two-thirds of the total ventilators could be made available*

not provide any data on the duration of stays in ICU or on ventilation. However, the Australian and New Zealand study do report median (interquartile range) ICU and ventilation durations of 7 (2.7 to 13.4) and 8 (4 to 16) days, respectively. These values are somewhat smaller than the values based on the Winnipeg data (2) of 12 (5 to 20) days in ICU and 12 (6 to 20) days on ventilation. The reasons for the discrepancies are not clear. Given that the virus is unchanged, it is likely related to differences in risk factors, possibly both individual and environmental, between the populations. As we are interested in investigating the impact of soH1N1 upon the Canadian critical care system, using the Canadian data would provide the most relevant scenarios as it implicitly incorporates any Canada-specific risks. An interesting result of the Australian and New Zealand studies is that the attack rates are estimated to be less than 10%. In such situations, the critical care capacity would not be breached. However, the expectation for the second wave in North America would have been for the attack rate to be significantly higher in the absence of antiviral and vaccination interventions.

It is important to note that ICU bed and ventilator availability are not the sole factors to consider when determining whether capacity problems may exist. Highly trained staff are required to operate and monitor ICU beds. Prolonged requirement for isolation of symptomatic, infected patients in the ICU can substantially add to nursing and support staff demands beyond what may be anticipated due to the severity of illness alone further restricting capacity. In addition, staffing may also be highly stressed by the occurrence of soH1N1 infection among the care-givers. Apart from staffing issues, sedatives are required for the patients, and other equipment such as infusion pumps and monitors are also needed. A shortfall in any one of these would also result in ICU demand exceeding what the healthcare system can provide.

Another limitation of the study arises from the fact that Manitoba has a relatively large proportion of First Nation and Inuit patients. This may not be representative of other regions in Canada and could introduce some bias in the collected ICU data. In particular, if First Nation or Inuit patients tend to have a higher incidence of severe disease (whether on a genetic basis or on the basis of a greater proportion of patients with delayed treatment and therefore more severe disease presentation), the estimates presented here may lead to an overestimation of the ICU demand. Public knowledge of the risk may alter behaviour so that patients seek out medical assistance (and antiviral therapy) earlier so that case severity is diminished even if total numbers of cases are not. On the other end of the equation, the number of available ventilator-capable ICU beds may be relatively dynamic. We considered the possibility that ICUs may be able to empty two-thirds of ventilator-capable beds during an anticipated surge event; however, this may depend on the speed of the evolving epidemic with greater ability to empty beds with a slower epidemic wave affording greater time. Further, total ICU ventilator capacity may be able to be augmented to some extent through use of other available resources (federal emergency response stores, local 'mothballed' stored ventilators, operating room ventilators). Given the limited capability of some such machines, their utility may be limited.

Despite the uncertainty regarding both available resources and the specific level of demand, our analysis across a variety of attack rates and pandemic durations suggest a very high level of ICU ventilator bed demand is possible during the anticipated fall influenza epidemic, with the probability of significant regions of the country experiencing shortfalls in capacity if the current vaccination strategy is not effectively implemented. The primary surge capacity efforts to date have been local contingency nursing/physician/support staff planning efforts and supplementation of the federal emergency ventilator stores. As a complement to the development of ventilator-capable bed surge capacity within regions, provinces and nationally, other national strategies should have been considered in case of a failure of the vaccine strategy. These approaches include mitigation efforts involving aggressive community antiviral strategies and contingency planning for shifting of necessary staff and equipment resources as required nationally.

APPENDIX A

The equations governing the SEIR model are

$$\frac{dS^{ag}}{dt} = -S^{ag}\sum_b C^{ab}\rho^{ab}\frac{I^b}{P^b} - v(t)S^{ag}$$

$$\frac{di^{ag}}{dt} = S^{ag}\sum_b C^{ab}\rho^{ab}\frac{I^b}{P^b} - \lambda_{i\to I}i^{ag}$$

$$\frac{dI^{ag}}{dt} = \lambda_{i\to I}i^{ag} - \lambda_{I\to R}I^{ag} - \lambda_{I\to D}I^{ag}$$

$$\frac{dR^{ag}}{dt} = \lambda_{I\to R}I^{ag}$$

$$\frac{dV^{ag}}{dt} = v(t)S^{ag}$$

where S^{ag}, i^{ag}, I^{ag} and R^{ag} are the susceptible, infected, infectious, and recovered populations respectively in age group *a,* and of gender *g*. V^{ag} is the vaccinated population, and $v(t)$ is the vaccination rate. The rates of recovery, death and transition from infected to infectious are $\lambda_{I\to R}$, $\lambda_{I\to D}$, and $\lambda_{i\to I}$ respectively. ρ^{ab} is the probability of infection given that a person in age group *a* has come into contact with an infectious individual of age group *b*. C^{ab} is the rate that people age *a* contact people of age *b*. The cumulative number of infections, Q^{ag}, is

$$\frac{dQ^{ag}}{dt} = S^{ag}\sum_b C^{ab}\rho^{ab}\frac{I^b}{P^b}$$

The contact rates used are from Mossong[13], while the probability of infection is adopted from Haber et al[14]. By scaling the probability of infection (but maintaining the relative likelihood between age groups), and adjusting the recovery rate, the attack rate and the duration of the pandemic were calibrated to the required values.

SEIR Susceptible, Exposed, Infectious, Recovered

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