

# Potential ICU Ventilator Demand/Capacity Mismatch due to Novel soH1N1 in Canada

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## *Abstract*

The initial Canadian outbreak of the novel swine origin influenza A/H1N1 (soH1N1) virus in Manitoba, Canada in the spring of 2009 severely tested 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 healthcare system to handle widespread re-emergence of the soH1N1 virus.

Based on ICU data collected during the Manitoba outbreak in the spring of 2009, a Susceptible-Exposed-Infectious-Recovered (SEIR) model indicates that there could be a severe shortage of ventilated ICU beds in Canada if the fall attack rate exceeds 25%. The lengthy duration that patients remain on ventilation is a primary contributing factor behind the anticipated capacity problems. Unless intervention strategies such as vaccination or antiviral use can reduce the attack rate to well below 25%, or the critical care capacity of the Canadian healthcare system can be rapidly increased, significant shortages in ICU resources may be expected.

Key Words: Demand; Influenza; intensive care; Pandemic; Mathematical Modeling.

## *Introduction*

Intensive care units and ventilators are vital resources for the treatment of severely ill 2009 pandemic swine origin influenza A/H1N1 (soH1N1)-infected patients. Though 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, personal communication). This represents approximately ½ 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 becomes available. Therefore, rather than focussing on a single fall wave projection, a variety of data sources (including comprehensive 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.

### *Methods*

Data used to determine estimates was derived from 3 sources: Manitoba data provided from a study of soH1N1-associated ICU admissions (a subset of the data published in (2)); Canada's national surveillance system, FluWatch; and Pandemic Fit Models (3). All data from (2) was collected with the approval of the University of Manitoba Research Ethics Board under a waived consent protocol.

The Winnipeg Regional Health Authority ICUs operate as an integrated system with ongoing communication between sites. This allows for real time awareness of bed utilization and capacity. Data on all PCR-positive (n=56) and epidemiologically/clinically highly suspect (n=6; based on epidemiologic and clinical factors as determined by the attending physician of record) potential soH1N1 influenza virus infections requiring ICU care was prospectively collected using a pre-positioned data collection tool (4) during the epidemic. Additional data collection during the resolution phase of the epidemic was 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 PCR positive test results allowed for data collection on 100% of all suspected cases admitted to ICU within the region.

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 SEIR system (5; 6). The equations governing the system are

$$\begin{aligned}\frac{dS^{ag}}{dt} &= -S^{ag} \sum_b C^{ab} \rho^{ab} \frac{I^b}{P^b} \\ \frac{di^{ag}}{dt} &= S^{ag} \sum_b C^{ab} \rho^{ab} \frac{I^b}{P^b} - \lambda_{i \rightarrow i} i^{ag} \\ \frac{dI^{ag}}{dt} &= \lambda_{i \rightarrow i} i^{ag} - \lambda_{I \rightarrow R} I^{ag} - \lambda_{I \rightarrow D} I^{ag} \\ \frac{dR^{ag}}{dt} &= \lambda_{I \rightarrow R} I^{ag}\end{aligned}$$

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  $g$ . The rates of recovery, death and transition from infected to infectious are  $\lambda_{I \rightarrow R}$ ,  $\lambda_{I \rightarrow D}$ , and  $\lambda_{i \rightarrow i}$  respectively.  $\rho^{ab}$  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 (7), while the probability of infection is adopted from Haber et al (8). 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 arbitrary values.

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. 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.

Pandemics are inherently uncertain, which impedes efforts to accurately predict the course of impacts. As a result, in order 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 5, 6, 8, 10, and 15 weeks were also considered. The duration is defined as the time between 5% and 95% of total infections. Models of the current pandemic (3) indicate hospitalization rate of about 0.4% of those infected, though it should be noted that the hospitalization rate may be larger in populations with higher risk factors. This is similar to the rate reported in the Australian study (1).

In order to determine if there will be an ICU or ventilator shortage, the number of ICU beds and ventilators in Canada is required. Unfortunately, there is no Canada-wide data and the best estimate that can be obtained is an extrapolation from a recent survey from Ontario which found 8.7 mechanically ventilated beds per 100,000 population (9). The number of ICU beds is an even more ambiguous quantity since there is no clear definition as to what exactly constitutes an ICU bed. For example, some hospitals may be able to convert beds which are traditionally classified as non-ICU into an ICU bed if required. Therefore, while the demand for ICU beds is addressed in this study, the focus is on the demand for ventilators in order to identify characteristics of the pandemic that may result in ventilator shortages.

## *Results*

For each attack rate, pandemic duration and population combination, 200 stochastic trials were run to determine the ICU and ventilator demand. Figure 2 shows the typical curve of cumulative ICU admissions, ICU releases (due to recovery or death), and number of patients residing in the ICU.

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. Table 2 shows the expected ventilator demand, along with the 5<sup>th</sup> and 95<sup>th</sup> 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.

We calculated expected ventilator demand in comparison to anticipated ventilator resources for regions of differing populations. Canadian ICU's run at a normal occupancy rate of approximately 90% or higher at most times (9; 10). We assumed that fully 2/3 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, for attack rates of greater than 25%, the expected ventilator demand is predicted to exceed normal capacity in all cases except for pandemics with a duration greater than about 9 weeks. If more than 1/3 of ventilator capable beds are required for non-influenza patients or if these beds cannot be made available as quickly as the increase in demand, the mismatch worsens substantially.

As the area of a geographic region increases, the pandemic duration tends to increase. As can be seen in Table 2, 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 see if the total supply of Canadian ventilators could be exceeded. Table 3 shows the results for modelling Canada as a single region with a population of 33.5 million.

These results show that a national soH1N1 epidemic stretching over 10 to 15 week duration could result in a demand for ventilator-capable bed demand within the overall national capacity at attack rates of 25-30%. However, this assumes that the epidemic will be evenly distributed in space and time across the country. In reality, the pandemic can be expected to strike different areas at various times. As a consequence, during a national epidemic in which overall resources are sufficient, ICU ventilator capacity in some regions may still be breached at time when other areas have significant available resources. Attack rates of greater than 25 to 30% could breach national capacity overall at the peak of the epidemic depending on the duration. Figure 3 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 5 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.

Note that no interventions, such as vaccination or wide-spread use of antivirals, have been considered here. One expects that an aggressive community antiviral strategy or a timely vaccination effort would significantly reduce the attack rates and relieve the demand on ICU beds and ventilators

### *Discussion*

There are three primary factors which 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.

We have shown that a very broad distribution of ventilation duration among critically ill soH1N1 infected patients may cause a significant national demand for ICU ventilator support. If, as in the Manitoba outbreak, half on the patients on ventilation require ventilation for at least 2 weeks, while approximately 10% of those recovering require

ventilation for over 50 days, ventilator bed capacity may be highly stressed. For a rapid pandemic with a relatively high attack rate, available ICU ventilator bed capacity may be 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 be exceeded nationally. The resulting lack of ICU resources could result in a significant increase in the mortality rate. As 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. In addition, vaccination or aggressive antiviral strategies would, of course, reduce the overall attack rate and work to relieve some of the burden on the system. 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.

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, 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.

An important aspect of the data to note is 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 ICU's may be able to empty 2/3 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.

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 likely during the anticipated fall influenza epidemic with the probability of significant regions of the country experiencing shortfalls in capacity. In addition to the development of ventilator-capable bed surge capacity within regions, provinces and nationally, other strategies should be considered. These include mitigation efforts involving aggressive community antiviral strategies, early introduction of vaccine. In addition, a strategy to shift resources as required nationally may be in the public interest.

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Figure 1: Patient flow diagram from symptomatic through to recovery or death.

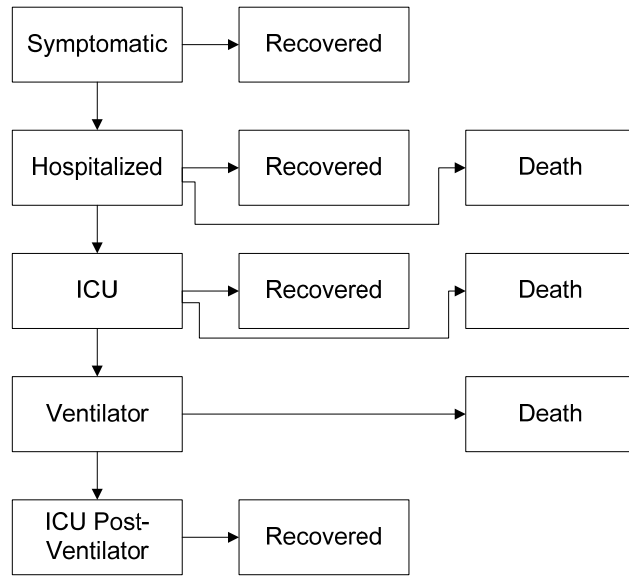


Figure 2: Typical cumulative admissions and releases from ICU for a population of 1 million, attack rate 25% and duration of 8 weeks. The number of patients in ICU is the difference between the cumulative admissions and releases.

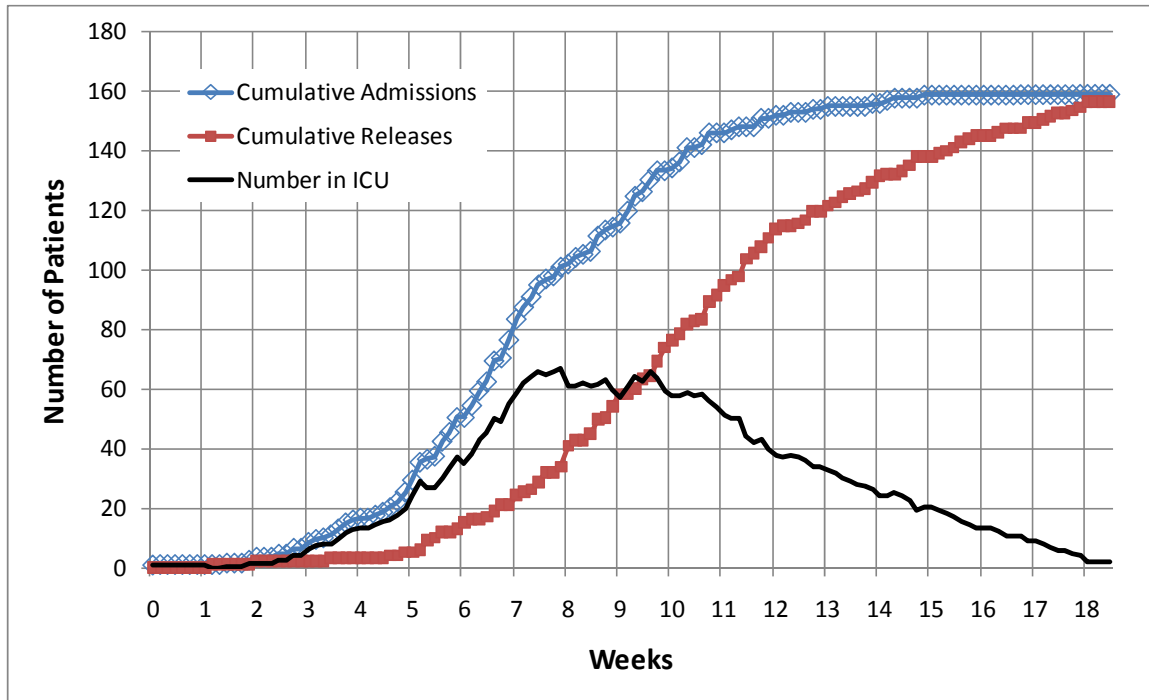


Figure 3: Ventilator demand as a function of time for a 35% attack rate and a duration of 10 weeks.

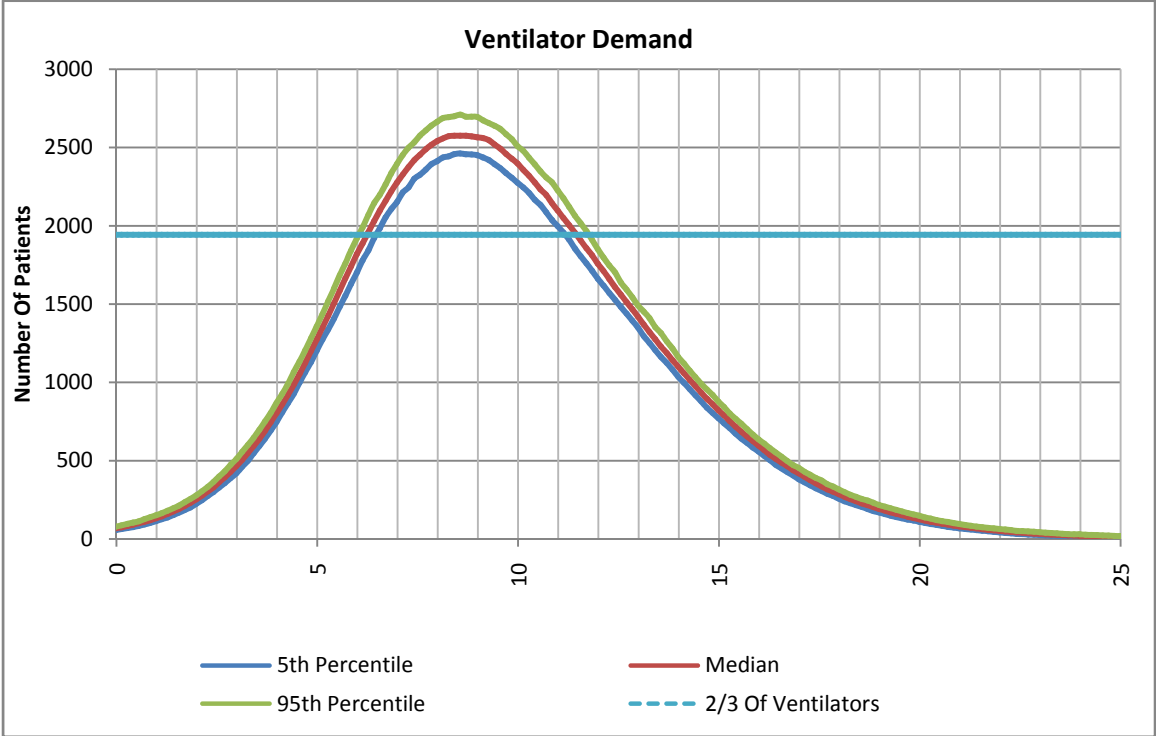


Table 1: Probabilities derived from the pandemic models, FluWatch, and the Manitoba data set.

<b>Transition</b>	<b>Probability</b>	<b>Counts</b>	<b>Source</b>
<b>Hospitalized Given Symptomatic</b>	0.4%	-	Pandemic Fit Models
<b>ICU Given Hospitalized</b>	17.6%	240/1366	FluWatch Data
<b>Direct Recovery given ICU</b>	6.8%	4/59	Manitoba Data Set
<b>Ventilation given ICU</b>	93.2%	55/59	Manitoba Data Set
<b>Recovery given Ventilation</b>	83.6%	46/55	Manitoba Data Set
<b>Death given Ventilation</b>	16.4%	9/55	Manitoba Data Set

Table 2: Peak ventilator demand assuming 1/3 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).

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)

Table 3: Ventilator demand for the entire Canadian population. Peak ventilator demand assuming 1/3 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)