Potential Demand for Respirators and Surgical Masks During a Hypothetical Influenza Pandemic in the United States

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Background. To inform planning for an influenza pandemic, we estimated US demand for N95 filtering facepiece respirators (respirators) by healthcare and emergency services personnel and need for surgical masks by pandemic patients seeking care.

Methods. We used a spreadsheet-based model to estimate demand for 3 scenarios of respirator use: base case (usage approximately follows epidemic curve), intermediate demand (usage rises to epidemic peak and then remains constant), and maximum demand (all healthcare workers use respirators from pandemic onset). We assumed that in the base case scenario, up to 16 respirators would be required per day per intensive care unit patient and 8 per day per general ward patient. Outpatient healthcare workers and emergency services personnel would require 4 respirators per day. Patients would require 1.2 surgical masks per day.

Results and Conclusions. Assuming that 20% to 30% of the population would become ill, 1.7 to 3.5 billion respirators would be needed in the base case scenario, 2.6 to 4.3 billion in the intermediate demand scenario, and up to 7.3 billion in the maximum demand scenario (for all scenarios, between 0.1 and 0.4 billion surgical masks would be required for patients). For pandemics with a lower attack rate and fewer cases (eg, 2009-like pandemic), the number of respirators needed would be higher because the pandemic would have longer duration. Providing these numbers of respirators and surgical masks represents a logistic challenge for US public health agencies. Public health officials must urgently consider alternative use strategies for respirators and surgical masks during a pandemic that may vary from current practices.

Keywords. influenza pandemic; respiratory protective devices.

From April 2013 to June 2014, there have been 450 cases and 165 deaths attributed to influenza A (variant H7N9), a virus not previously reported in humans [1]. The US Centers for Disease Control and Prevention (CDC) examined the potential effect on public health should sustained human to human transmission of this novel influenza strain be observed and determined the options for mitigating its spread domestically under this scenario. As part of this effort, we estimated the potential demand for N95 filtering facepiece respirators (N95 FFRs, hereby called respirators) and surgical masks by healthcare personnel, critical first responders—such as emergency medical services (EMS), police, and fire personnel, and for surgical masks for suspected pandemic influenza patients, in a variety of potential pandemic scenarios, and under various utilization behaviors. N95 Filtering Facepiece Respirators are one of the most commonly used respiratory devices available and are so named because they are intended to prevent the user from exposure to pathogens by filtering at least 95% of airborne particles that pass through the filter media. There are other types of respirators that may

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be used for personal protection. Besides disposable N95 FFRs, there are reusable elastic or rubber respirators (often called elastomeric respirators) and powered air-purifying respirators (PAPRs).

Respirators, in conjunction with environmental and administrative controls, are considered to be an important component of infection control strategy for healthcare and response workers during an influenza pandemic. During the 2009 H1N1 pandemic, CDC recommended respirators to healthcare workers (HCWs) and first responders when "caring for persons with known, probable or suspected 2009 H1N1 or influenza-like illness (ILI)" [2]. Similar recommendations are likely to be made during the next pandemic.

To date, the few studies that have quantified the potential demand for respirators and surgical masks in the event of an influenza pandemic have either assumed constant respirator and surgical mask use or use proportional to the epidemiologic curve of the pandemic [3–7] (see Supplementary Appendix I for a review). We present a model that provides estimates of the potential demand for respirators and surgical masks during a pandemic for a variety of severity and attack rate scenarios. These estimates will aid public health officials to plan how many respirators and surgical masks to stockpile and provide the basis for plans to quickly dispense them.

METHODS

Modeling Approach Overview

We developed a spreadsheet model (Microsoft Excel, Microsoft Corp., Redmond, Washington) to estimate the demand during an influenza pandemic for respirators and surgical masks. We used 4 standardized pandemic scenarios [8], with 2 attack rates (20%, 30%) and 2 levels of severity (defined by hospitalization, emergency department [ED] visits, and EMS transportation rates, see Table 1). To estimate the number of pandemic cases, the 4 scenarios (standard across all influenza modeling activities) were characterized as follows: (1) high clinical severity, 30% (high) attack rate, (2) low clinical severity, 20% (low) attack rate, (3) high clinical severity, 20% attack rate, and (4) low clinical severity 30% attack rate (Table 1) [8]. The resulting estimated epidemiologic curves did not take into account any mitigation efforts, such as vaccine or nonpharmaceutical control measures, and were 41–45 weeks in duration for the low attack rate scenario (peak: 20–23 weeks) and 26–29 weeks in duration for the high attack rate scenario (peak: 12–14 weeks).

Our model estimated need for respirators by personnel working in hospital intensive care units (ICU), hospital general wards (GW), EDs, outpatient care settings, nursing homes, and by first responders (eg, EMS, police officers, and firefighters). We also calculated surgical mask demand used in an attempt to slow onward disease transmission, for patients with suspected infection with the pandemic strain ("source control").

For each of the 4 pandemic scenarios, we modeled 3 respirator distribution scenarios: base case, intermediate demand, and maximum demand scenarios (Figure 1). In the base case distribution scenario, overall demand for respirators was proportionate to the number of patients over time until shortly after the pandemic peaked and then constant afterward. This relayed the fact that, in some sectors (ICU, GW, and nursing homes), testing patients for infection with the pandemic strain would be possible, whereas, in others (ED, first responders, and in outpatient care settings), testing would not be available or feasible on-site. In the latter, supply of respirators for HCWs was assumed to grow with the epidemic curve until it peaked, and to remain stable once there was a perception of need (after the peak). Total respirator need was the sum of the demand in all sectors (see Supplementary Appendix II for details).

For our intermediate demand model, we assumed the demand for respirators would start with the pandemic and would increase proportionally to the epidemic curve until peak usage. Thereafter, and until the end of the pandemic, demand among all healthcare, ED workers, and first responders remained equal to peak demand (Figure 1, Supplementary Appendix II). This is different from the base case model, which considered that, for the ICU, GW, and nursing homes, need was proportional to pandemic patients throughout the pandemic. We assumed, for the maximum demand scenario, that all eligible healthcare and emergency response workers would use respirators from the beginning of the pandemic until its end, regardless of how many contacts they had with patients who were clinically ill with pandemic influenza (ie, maximum precaution scenario; Figure 1). We assumed that usage rates remained the same throughout the pandemic by HCWs and patients (Table 2).

Finally, we conducted sensitivity analyses in which we analyzed the effect of demand reduction strategies, such as using respirators by HCWs for more than 1 patient contact.

Base Case

For the base case scenario, we estimated demand for respirators among ICU, GW, and nursing home workers by multiplying predicted number of pandemic patients per day by the number of times patients had contact with providers (Supplementary Appendix II). As a result, in the ICU, GW, and nursing homes, total demand was proportional to the total number of patient-provider encounters. We assumed that patients in ICUs had contact with 12 to 16 HCWs per day (Table 2), and so 12–16 respirators would be needed in the ICU per patient per day (each provider is assumed to need one respirator per patient encounter). We assumed patients in GWs had contact with 8 HCWs per day (Table 2). We used a range of length-of-stay

Table 1. Input Parameters Used to Calculate the Number of Patients With ILI Interacting With Healthcare Personnel in Different Settings and Usage by Scenario

Input	Lower Bound	Upper Bound	Source
Low severity scenario			
% cases, hospitalized	0.8	1.5	[9]
% cases, visit ED[a]	6	12	[10]
% cases, transported by EMS[b]	1	2	[11]
High severity scenario			
% cases, hospitalized	3	5	[9]
% cases, visit ED[a]	24	39	[10]
% cases, transported by EMS[b]	2	4	[11]
All scenarios			
Pandemic case to ILI case multiplier[c]	1.39	1.70	[12]
% cases, seek outpatient care	40	56	[13]
% of hospitalizations requiring ICU	20	26	[14–16]
Length of stay (days)			
ED	1		
ICU	8	10	Adapted from [17]
General ward	7	11	Adapted from [17]
Workforce			
Police officers in US (millions)[d]/% with public contact	0.45/90	0.58/90	[18, 19]
Firefighters in US (millions)[e]/% with public contact	0.34/90	1.10/90	[19, 20]
Hospital Workers[f]/% with patient contact	6 053 103/33		[19, 21]
Outpatient healthcare workers[g]/% with patient contact	3 205 399/67		[19, 21]
ED workers/% with patient contact	131 588/100		[22, 23] (as)
EMS workers[h]/% with patient contact	296 937/90		[21] (as)
Nursing home workers[i]/% with patient contact	3 426 571/25		[19, 21]
Demographics			
United States population (millions)	316		[24]
% United States population 65+, in nursing homes	4		[25, 26]

Abbreviations: (as), assumed; ED, emergency department; EMS, emergency medical service; ICU, intensive care unit; ILI, influenza-like illness.

[a] The number of ED visits was considered to be 7.8 greater than the number of Hospital Visits.

[b] Approximately 12% of ED patients were transported by EMS.

[c] At peak, 72% of specimens tested positive for influenza. 20% reduction assumed for upper bound of multiplier. For the sensitivity analysis, we considered a time varying pandemic case to ILI multiplier between 5.00 (in the beginning and end of the pandemic most cases are ILI, values adapted from [12, 17]), and 1.39 at peak.

[d] Police officers: lower bound = # of sworn officers; higher bound = # of sworn officers and civilian police officers.

[e] Firefighters: lower bound = # of professional firefighters; higher bound = # of professional firefighters and volunteer firefighters.

[f] Includes workers in NAICS 622 (Hospitals). Includes Federal, State, Local, and Private Institutions, for 2013. (NAICS: North American Industry Classification System).

[g] Includes workers in NAICS 6211 (Office of Physicians) and NAICS 6214 (Outpatient care centers). Includes Federal, State, Local, and Private Institutions, for 2013.

[h] Includes workers in NAICS 621 493 (Freestanding emergency medical centers) and NAICS 62 191 (Ambulance Services). Includes Federal, State, Local, and Private Institutions, for 2013.

[i] Includes workers in NAICS 623 (Nursing and residential care facilities). Includes Federal, State, Local, and Private Institutions, for 2013.

of 8–10 days for ICU patients, and 7–11 days for GW patients (Table 1).

We assumed that HCWs in EDs, outpatients settings, as well as first responders, used 4 respirators per day at the beginning of the pandemic (Table 2). We further assumed that the number of workers having contact with pandemic patients would proportionally increase as the number of pandemic patients increased (ie, follow the epidemic curve upward). After the pandemic peaked, the number of workers using respirators would remain fixed. Finally, we considered that only 90% of first responders, 67% of HCWs in outpatient settings, 25% of nursing home workers, and 100% of ED workers would have contact with patients (Tables 1 and 2).

HCWs in EDs, nursing homes, and outpatients settings, as well as first responders are likely to deal with patients with influenza-like illness (ILI), in addition to those with confirmed

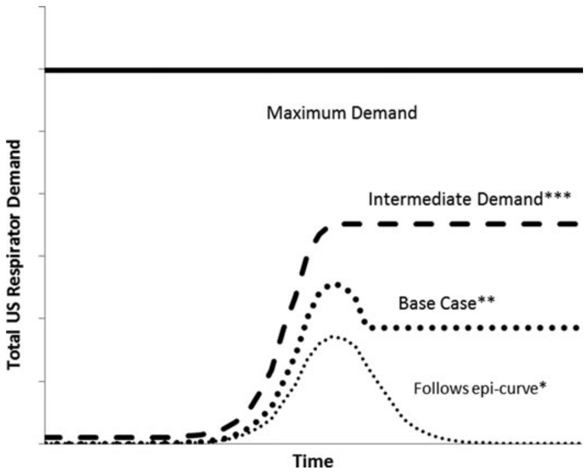

Figure 1. Schematic of alternative structures to modeling total N95 filtering facepiece respirators (respirators) use. *Example of demand that follows the epidemic curve. **In the Base Case, demand for respirators among intensive care unit, general ward, and nursing home workers was assumed to follow the epidemic curve; demand for respirators among first responders and those working in outpatient settings was assumed to follow the Intermediate Demand model. ***All sectors assumed to follow the Intermediate Demand model.

influenza. We used data from the 2009 H1N1 pandemic and assumed that there were 1.39 to 1.7 patients with ILI for each case of pandemic influenza (Table 1; [12]). We also assumed, for the same calculations, that 40%–56% of all pandemic patients would seek medical care [13]. We supposed, for all 3 scenarios, that changes in pandemic severity affected hospitalization, ED, and transportation by EMS rates but did not affect the proportion of ILI patients interacting in outpatient settings.

Intermediate Demand

For this scenario, we assumed respirator use among all HCWs and first responders increased proportionally to the epidemic curve until the pandemic peaked. Thereafter, and until the end of the pandemic, demand remained equal to peak demand. HCWs in nursing homes were assumed to use 1 respirator per day, all others were assumed to use 4 respirators per day (Table 2).

Maximum Demand

For the Maximum Demand scenario, we assumed the need for respirators across all HCWs and first responders was constant throughout the pandemic. As in the Intermediate Demand scenario, all HCWs (but workers in nursing homes) were assumed to need 4 respirators per day (Table 2).

Demand for Surgical Masks

For all scenarios, we estimated the number of surgical masks required for source control in all settings (hospital, nursing

Table 2. Input Respirator and Surgical Mask Usage Parameters by Setting[a]

	Respirators		Surgical Masks		
Variable (Unit)	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Source
Base case					
ICU (per patient/day)	12	16	2	2	CDC Task Force
GW (per patient/day)	8	8	2	2	
ED (per worker/day; per patient/day)	4	4	1.2[b]	1.2[b]	
Outpatient (per worker/day; per patient visit)	4	4	1.2[b]	1.2[b]	
Nursing homes (per patient)	3	4	1.2[b]	1.2[b]	
EMS (per worker/day; per patient/day)	4	4	1.2[b]	1.2[b]	
Police (per worker/day)	4	4	0	0	
Fire personnel (per worker/day)	4	4	0	0	
Maximum demand and intermediate demand					[19], CDC Taskforce
ICU (per worker/day)	4	4			
GW (per worker/day)	4	4			
ED (per worker/day)	4	4			
Outpatient (per worker/day)	4	4			
Nursing homes (per worker/day)	1	1			
EMS (per worker/day)	4	4			
Police (per worker/day)	4	4			
Fire personnel (per worker/day)	4	4			

Abbreviations: CDC, Centers for Disease Control and Prevention; ED, emergency department; EMS, emergency medical service; GW, general ward; ICU, intensive care unit.

[a] All values held constant throughout the pandemic.

[b] Not a whole number on account of patients being accompanied by additional persons (eg, family members) who would be provided masks as well.

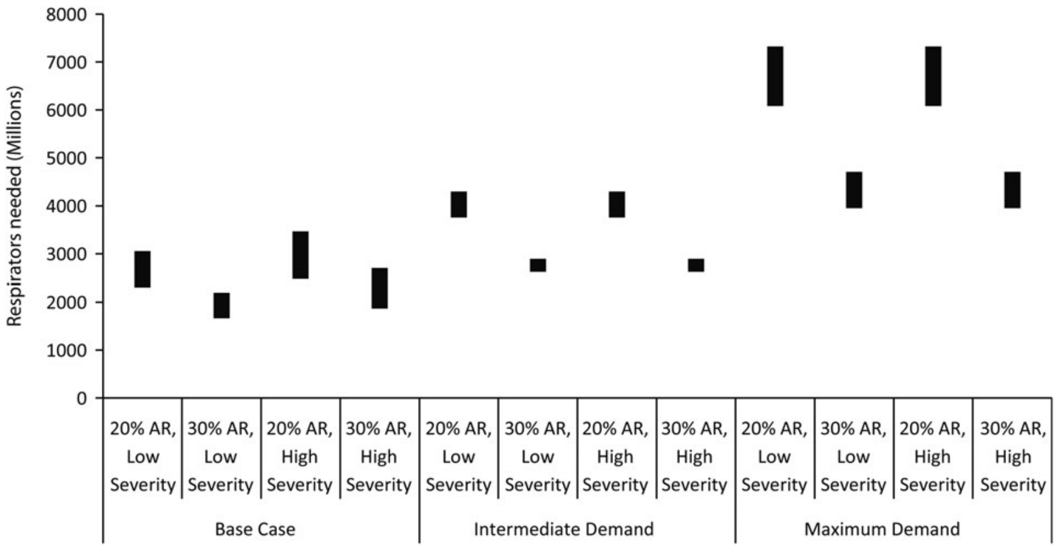

Figure 2. Demand for N95 filtering facepiece respirators (respirators) for different models and scenarios. For each scenario and distribution model, ranges result from variations in respirator use rates and epidemiologic and healthcare use parameters. Abbreviation: AR, attack rate.

homes, outpatient settings, and EMS) by multiplying the weekly number of ILI patients by the number of masks per patient per day and by the number of days patients would spend in each setting (Table 1).

Sensitivity Analysis

Demand Reduction Strategies for Respirators in the Base Case

To characterize the lowest bound of needed supply of respirators, we chose the base case distribution scenario to evaluate 3 additional strategies designed to potentially reduce respirator demand. Demand reduction strategy 1 included using the same respirator to attend to several patients in different settings such as the ICU, GW, ED, nursing homes, outpatient clinics, and police and fire (Supplementary Appendix III: Table AIII-1), donning (putting on), and doffing (removing) the respirator in between patients (limited FFR reuse [27–29]). Demand reduction strategy 2 consisted of limited respirator reuse by personnel in the hospital settings (ICU, GW, ED) and nursing homes; and use of surgical masks instead of respirators in outpatient clinics and by EMS, fire, and police responders, with removing and putting on the same surgical mask for different suspected pandemic patients in these settings. Surgical mask use was also included for source control in all settings. Finally, demand reduction strategy 3 consisted of substituting respirators with elastomeric respirators (a reusable respirator that can provide N95 or higher level of protection and that could be issued to an individual HCW for use throughout a pandemic or shared between HCWs after following the manufacturer's recommendations for disinfection) in the ICU and ED settings, limited reuse of respirators in hospital GWs, in nursing homes, and EMS settings, and use of surgical masks in outpatient clinics and by fire and police responders, with removing and putting on the same surgical mask for different suspected pandemic patients in these settings. Again, use of surgical masks was included for source control, as in the second demand reduction strategy (Supplementary Appendix III: Table AIII-1).

Respirator and Surgical Mask Usage Rates

We conducted a univariate sensitivity analysis to examine the effect of respirator usage rates on total demand in the base case scenario. We chose the high severity and low attack rate scenario for this analysis and decreased/increased the lower bound of usage rates in each setting by a factor of 50%. We also compared results obtained with the assumed rates of usage with results found using rates adapted from the literature (Supplementary Appendix III: Table AIII-2, Appendix I). Separately, we analyzed the impact of assuming a time varying ILI to case ratio on the estimates and varied this ratio between a maximum of 5.00 in the beginning and end of the pandemic (20% of all cases seen are pandemic cases) and minimum of 1.39 during the peak (72% of all cases are pandemic cases).

RESULTS

In the low attack rate/low severity scenario, the pandemic caused around 63 million symptomatic cases, 0.5–1.0 million hospitalizations, and 0.1–0.3 million ICU admissions. In the high attack rate/high severity scenario, the pandemic caused approximately 94 million symptomatic cases, 2.8–4.7 million hospitalizations, and 0.6–1.2 million ICU admissions [8].

Base Case, Intermediate, and Maximum Demand Scenarios

In the base case, the estimated total demand for respirators ranged from 1.7 billion (lower bound) in the high attack rate/low severity scenario to 3.5 billion (higher bound) in the low attack rate/high severity scenario (Figure 2). The estimated need for respirators was higher for the low attack rate/low severity scenario than for the high attack rate/high severity scenario because of differences in pandemic duration: 41–45 weeks for the low attack rate and 26–29 weeks for the high attack rate scenario. For all scenarios, 0.1–0.4 billion surgical masks would be needed for source control (Figure 3).

In all scenarios, the demand for respirators by personnel in outpatient settings exceeded demand in other settings and comprised approximately one-half of total demand in the low severity scenario. In the low severity scenarios, the hospital settings accounted for the least use, with only approximately one-tenth of total use. For the high severity scenario, police, fire services, EMS, and nursing home settings comprised approximately one-third of the total respirator demand. The remaining respirators were used in the outpatient setting (from one-third to approximately one-half), and a smaller portion in the hospital setting (up to almost one-third in the high severity/high attack rate scenario).

Results were especially sensitive to assumptions regarding use behavior in different settings, as relayed by different use models (Figure 2). In particular, the base case scenario assumption that ILI recognition is possible in some healthcare settings (and that only HCWs interfacing with ILI patients would require respirators) results in a reduction of up to 1.5 billion respirators, when compared with the intermediate demand scenario (where respirator use surges with the pandemic but then remains constant from the peak until the pandemic resolves) among low and high attack rate scenarios. If comparing the base case distribution scenario with the maximum demand distribution scenario, the difference is up to 4.3 billion for the low attack rate and higher duration scenarios and up to 2.5 billion respirators for the high attack rate and lower duration scenarios.

The difference between estimates obtained with the intermediate demand model and the maximum demand model is also substantial for the low attack rate scenarios (Figure 2). The difference between the two models is up to 3.0 billion for the low attack rate scenario; the maximum demand model always yields higher estimates. The primary factor driving the different respirator estimates among these two models is the duration of the pandemic. Therefore, the largest differences in demand estimates between these two models are observed among the pandemic scenarios of greater duration (low attack rate scenarios).

The estimated number of surgical masks required for source control varied from 0.1 billion in the low attack rate/low severity scenario to 0.4 billion in the high attack rate/high severity scenario (Figure 3). Between approximately one and two-thirds of required surgical masks would be used by patients in the hospital, in the low and high severity scenarios. The remaining

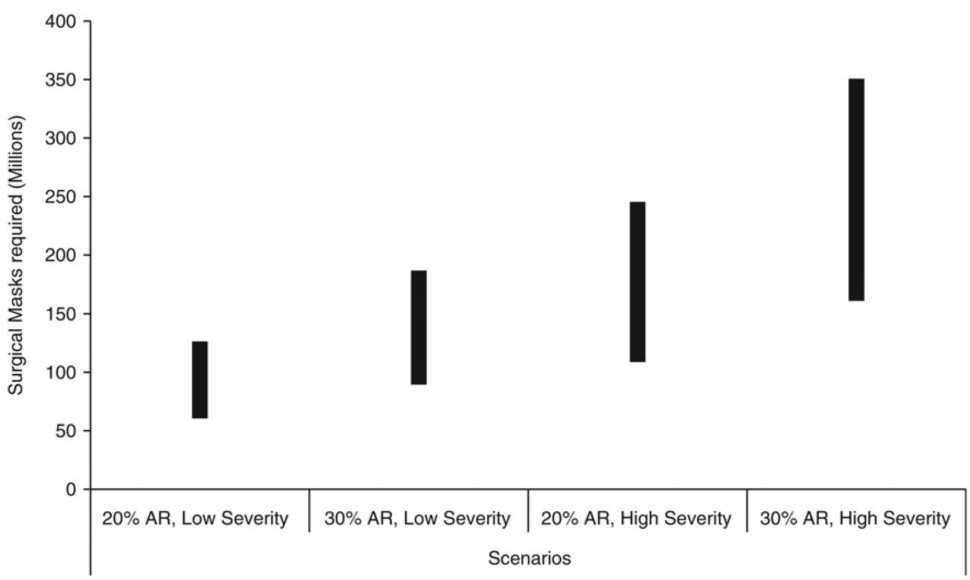

Figure 3. Surgical mask demand by pandemic scenario. For each scenario, ranges result from variations in surgical mask use rates and epidemiologic and healthcare use parameters. Surgical mask demand is the same for the base, intermediate, and maximum scenario, as it is meant for source control and the number of patients is proportional to the epidemic curve. Abbreviation: AR, attack rate.

Table 3. Total Demand for N95 Filtering Facepiece Respirators (Respirators) and Effect of Demand Reduction Strategies 1–3 on Total Demand for Respirators (in Millions)

Model	Pandemic Scenario	Lower Bound	Upper Bound
Base case	20% AR, low severity	2302	3053
	30% AR, low severity	1662	2194
	20% AR, high severity	2476	3467
	30% AR, high severity	1867	2703
Demand reduction strategy 1	20% AR, low severity	573	754
	30% AR, low severity	412	536
	20% AR, high severity	610	838
	30% AR, high severity	454	638
Demand reduction strategy 2	20% AR, low severity	20	56
	30% AR, low severity	25	66
	20% AR, high severity	57	139
	30% AR, high severity	67	169
Demand reduction strategy 3	20% AR, low severity	61	80
	30% AR, low severity	48	74
	20% AR, high severity	83	138
	30% AR, high severity	78	154

Effect of demand reduction strategies was calculated assuming the base case distribution scenario. Description of demand reduction strategies: Demand reduction strategy 1: limited reuse of respirators across all settings; Demand reduction strategy 2: limited reuse of respirators in intensive care unit (ICU), general ward (GW), emergency department (ED), and nursing homes, and substitution of surgical masks for respirators in outpatient clinics, emergency medical service (EMS), and for fire and police responders, with removing and putting on the same surgical masks for different patients in these settings; Demand reduction strategy 3: partial substitution of respirators by elastomeric respirators in the ICU and ED settings; limited reuse of respirators in GWs, nursing homes, and EMS settings, with use of surgical masks in outpatient clinics and by fire and police responders (removing and putting on the same surgical masks for different patients).

Abbreviation: AR, attack rate.

surgical masks would be used by ill persons mainly in outpatient settings. Estimates of surgical mask use in nursing homes and by patients transported by EMS ranged from 2 to 9 million (2%–3% of total demand), across all scenarios.

Sensitivity Analysis

Effect of Demand Reduction Strategies

Our analyses indicated that demand reduction strategies can have a substantial effect on projected total respirator use, especially if surgical masks or elastomeric respirators are used to substitute for respirators (Table 3). For demand reduction strategy 1 (using the same respirator to attend to several patients in different settings such as the ICU, GW, ED, nursing homes, outpatient clinics, and police and fire), limited reuse of respirators across all settings in the base case demand model reduced demand by approximately 76% across all scenarios.

For demand reduction strategy 2 (limited respirator reuse by personnel in the hospital settings and nursing homes; and use of surgical masks instead of respirators in outpatient clinics and by EMS, fire, and police responders), demand for respirators was <7% of original demand across all scenarios, requiring a minimum of 20 million of these respirators in the low attack rate/low severity scenario and a maximum of 169 million respirators in the high attack rate/high severity scenario (Table 3). This reduction was largely the result of eliminating demand for respirators among police, fire, outpatient, and EMS.

Demand reduction strategy 3 (substituting respirators with reusable, elastomeric respirators in hospital ICUs and EDs, limited reuse of respirators in hospital GWs, in nursing homes, and EMS settings, and use of surgical masks in outpatient clinics and by fire and police responders) had slightly less of an effect than demand reduction strategy 2, mainly because demand for respirators by EMS (a setting where an intermediate demand behavior was assumed) was not eliminated. Demand for respirators varied between 48 million in the high attack rate/low severity scenario and 154 million in the high attack rate/high severity scenario (Table 3).

However, demand reduction strategies 2 and 3 required a substantially higher number of surgical masks to replace respirators. Across all scenarios and courses of action, total demand for surgical masks increased to 894 million for the low attack rate (and higher duration)/ high severity scenario, and to 787 million for the high attack rate (and smaller duration)/high severity scenario.

Respirator and Surgical Mask Use Parameters

Demand estimates were sensitive to respirator use parameters, especially to respirator use in the outpatient setting. A 50% decrease in the use of respirators in the outpatient setting resulted in approximately 700 million fewer respirators being required (Figure 4). The sectors in which respirator use parameters had the next greatest effect were police, fire services, and EMS, where use was modeled with an intermediate demand approach. The lesser influence of respirator use parameters in these sectors, if compared with the outpatient sector, was due to the fewer number of HCWs working in these sectors. There were approximately 6 times the number of HCWs in outpatient settings compared with the number of police officers, and there were 9 times more HCWs in outpatient settings than professional firefighters.

Variations in the demand for respirators in the ICU and nursing home settings had decreasing influence on the demand for respirators because we assumed that patients with ILI would be recognized in these settings and demand was driven by the number of people with ILI seeking care. In particular, by varying the respirator use rate in ICU to 50% of the original value, demand for respirators decreased by 26 million (it would conversely increase by 26 million if the use rate would increase to 150% of the original value; Figure 4).

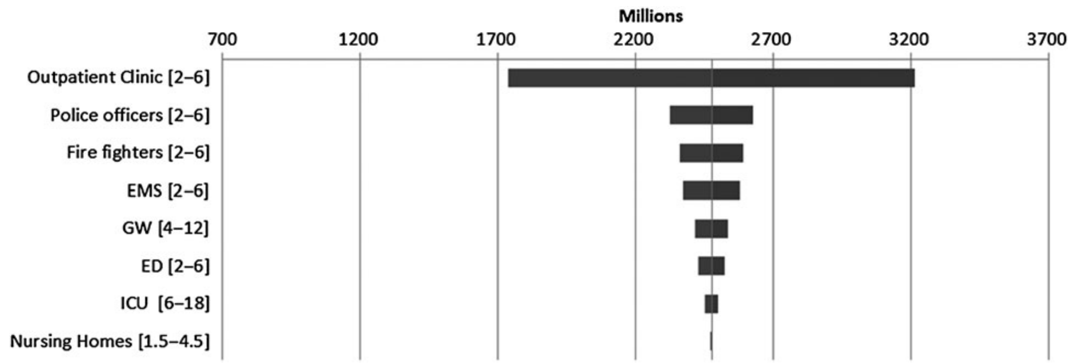

Figure 4. Variation of demand for N95 filtering facepiece respirators (respirators) with usage rates for different settings; for the base case (bars are centered around approximately 2.5B, the estimated demand for respirators for the 20% Attack Rate; high severity scenario; each bar shows the minimum and maximum demand obtained when varying the parameters in the interval featured on the left axis). Interpretation: if respirator use rate in the outpatient sector changes to 2/day/healthcare worker (50% reduction), total demand for respirators reduces to 1.7 billion). Abbreviations: ED, emergency department; EMS, emergency medical service; GW, general ward; ICU, intensive care unit.

We also abstracted respirator use multipliers from the literature (Supplementary Appendix III: Table AIII-2; Appendix I) and used these values to compute respirators required by healthcare providers. Using these multipliers, without use of any reduction strategies, the number of respirators required varied from1.6 billion to 3.4 billion across all scenarios; similar to results obtained in the base case demand scenario.

Finally, assuming a time varying ILI to case ratio did not impact the base case results significantly but had a slightly greater impact on the lower bound estimated for demand reduction strategies 2 and 3. Base case estimates increased by a maximum of only 5%; however, the lower bound of need for demand reduction strategies 2 and 3 increased by <26% and <15%, respectively.

DISCUSSION

We calculated that, in the base case scenario (base case model) from 1.7 billion to 3.5 billion respirators will be required for HCWs and first responders in the hospital, outpatient, nursing home, EMS, and the fire and police sector in the event of an influenza pandemic. In addition, 0.1–0.4 billion surgical masks will be required for source control. Estimates were sensitive to respirator use rates, especially in the outpatient setting, followed by police and fire (other settings in which demand was proportional to the size of the workforce). Projected demand was especially sensitive to assumptions regarding use in different sectors. For instance, assuming constant respirator use throughout the pandemic resulted in an estimated demand for respirators of up to 7.3 billion.

We have used conservative assumptions regarding patient-provider contacts. In our base case scenario, we assumed ICU patients would have 12–16 contacts with HCWs and so 12–16 respirators would be needed per patient per day. In comparison, Murray et al [17] estimated, in Vancouver, Canada, that during the 2009 pandemic, ". . . 498 respirators and 494 masks . . . were used per patient with laboratory-confirmed H1N1 influenza infection." Although we have made several sensitivity analyses to respirator usage rates, the possibility of pandemic cases generating excessive demand remains open, given the few data points available, and underscoring the great need of planning for respirator and surgical mask during a pandemic. To note, demand for respirators and surgical masks for household use and by groups of workers that have routine contact with the public and may desire protection may further decrease available supplies.

Another limitation of our calculations is that they were based on a hypothetical, unmitigated influenza pandemic and limitless care capacity by healthcare providers. Interventions, such as school closings, prompt treatment of ill persons, and mass vaccination campaigns, may reduce the spread of the pandemic and, hence, the need for respirators and masks. Capacity constraints could prevent delivery of care to all persons and also the number of required respirators and surgical masks. However, we do not know by what percentage these other interventions would reduce potential demand for respirator and surgical masks. Vaccines could, as in 2009, be delivered in notable amounts only after the pandemic peak [30].

Additionally, respirators are just one component of infection control recommendations for mitigation of influenza risk and this paper does not attempt to model the use of other resources (such as administrative and engineering controls as well as the use of face shields, eye shields, and airborne isolation rooms), which may be in limited supply during a pandemic. We also did not attempt to model other strategies that could have an impact on total demand, such as chemoprophylaxis (medication for the purposes of preventing disease), or other use strategies for respirators, such as extended use (not removing the respirator between patients). We expect that extended use could further diminish total need, however, the amount by which it would do so depends on rate of contact with patients by HCW and setting, a quantity difficult to estimate. We did model the impact of limited reuse on total demand. However, such estimates were obtained under the assumption of complete compliance by healthcare providers, which may be problematic [31, 32].

Our study suggests that, during a pandemic, usual standards of care for workers in contact with the ill from respiratory diseases such as influenza may not be feasible as it would involve an impractical demand for respirators and surgical masks. The domestic respiratory protective device industry currently manufactures product needed to meet anticipated normal market demands with minimal room for instant ability ramping up of production (surge). Surge capacity may increase over time (6 weeks to 4 months) but ability to surge is contingent on multiple factors including availability of manufacturing capacity and raw materials, and sustained demand for products [Personal communication, A. Patel, CDC, Atlanta]. Thus, although guidance for crisis standards of care exist [33, 34], the predicted gap between needed facial protective equipment and existent capacity may become so large as to warrant further exploration of alternative strategies. In our model, the use of durable elastomeric respirators that can be issued to a healthcare provider and reused repeatedly over the course of a pandemic could substantially reduce the supply-demand gap. However, elastomeric respirators have not been widely used in healthcare settings, and we cannot predict how well they will be accepted and if healthcare providers will adhere to recommendations for these devices.

These findings underscore the need for policy makers, leaders of healthcare organizations, and ethicists, to urgently consider strategies for use of respirators during a pandemic that may vary from current practices, including incorporating other types of respirators such as elastomerics and PAPRs, extended and limited reuse strategies for respirators, and other mitigation strategies, such as source, administrative, and environmental control measures, in order to optimize HCW protection.

Supplementary Data

Supplementary materials are available at *Clinical Infectious Diseases* online (http://cid.oxfordjournals.org). Supplementary materials consist of data provided by the author that are published to benefit the reader. The posted materials are not copyedited. The contents of all supplementary data are the sole responsibility of the authors. Questions or messages regarding errors should be addressed to the author.

Notes

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