Flattening the curve before it flattens us: hospital critical care capacity limits and mortality from novel coronavirus (SARS-CoV2) cases in US counties - 3 and 6 week projections from April 2, 2020

Charles C. Branas, PhD, Gelman Professor of Epidemiology and Chair, Department of Epidemiology, Mailman School of Public Health, Columbia University, NY, NY

Andrew Rundle, DrPH, Associate Professor of Epidemiology, Department of Epidemiology, Mailman School of Public Health, Columbia University, NY, NY

Sen Pei, PhD, Associate Research Scientist, Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, NY, NY

Wan Yang, PhD, Assistant Professor of Epidemiology, Department of Epidemiology, Mailman School of Public Health, Columbia University, NY, NY

Brendan G. Carr, MD, MS, Chair, Department of Emergency Medicine, Icahn School of Medicine, Mount Sinai Health System, NY, NY; Senior Advisor and Director, Emergency Care Coordination Center, Office of the Assistant Secretary for Preparedness and Response, US Department of Health and Human Services, Washington, DC, as of January 31, 2020

Sarah Sims, BS, CEO, Patient Insight, Santa Monica, CA; Research Contractor, Office of the Assistant Secretary for Preparedness and Response, US Department of Health and Human Services, Washington, DC

Alexis Zebrowski, PhD, Assistant Professor of Emergency Medicine, Department of Emergency Medicine, Icahn School of Medicine, Mount Sinai Health System, NY, NY

Ronan Doorley, PhD, Research Contractor, Media Lab, Massachusetts Institute of Technology, Cambridge, MA

Neil Schluger, MD, Chief, Division of Pulmonary, Allergy and Critical Care Medicine, Professor of Medicine, Epidemiology and Environmental Health Sciences, Columbia University Irving Medical Center, Columbia University, NY, NY

James W. Quinn, MA, Staff Associate, Department of Epidemiology, Mailman School of Public Health, Columbia University, NY, NY

Jeffrey Shaman, PhD, Professor, Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, NY, NY

ABSTRACT

Background

As of March 26, 2020, the United States had the highest number of confirmed cases of Novel Coronavirus (COVID-19) of any country in the world. Hospital critical care is perhaps the most important medical system choke point in terms of preventing deaths in crises such as the current COVID-19 pandemic. We therefore brought together previously established disease modeling estimates of the growth of the COVID-19 epidemic in the US under various social distancing contact reduction assumptions, with local estimates of the potential critical care surge response across all US counties.

Methods

Estimates of spatio-temporal COVID-19 demand and medical system critical care supply were calculated for all continental US counties. These estimates were statistically summarized and mapped for US counties, regions and urban versus non-urban areas. Estimates of COVID-19 infections and patients needing critical care were calculated for 21-day and 42-day time periods starting from April 2, 2020 to May 13, 2020 for four different reactive patterns – 0%, 20%, 30%, and 40% – of contact reduction (through actions such as social distancing). Multiple national public and private datasets were linked and harmonized in order to calculate county-level hospital critical care bed counts that include currently available beds and those that could be made available under four surge response scenarios – very low, low, medium, and high – as well as deaths in counties that had exceeded their hospital critical care capacity limits.

Results

An estimated 77,588-278,850 total critical care beds were available in the US, depending on the level of hospital surge response preparations. Maps of the US showed differences between the 21-day and 42-day projections as more counties outside the Northeast and urban areas, such as in the South, began to exceed their critical care bed capacity limits. From 185,192 deaths in the Northeast to 33,986 deaths in the Midwest could be averted by reducing contact with actions such as social distancing. As many as 104,120 deaths could be averted through an aggressive critical care surge response, including roughly 55% through high clearance and preparation of ICU and non-ICU critical care beds and roughly 45% through extraordinary measures like using a single ventilator for multiple patients.

Conclusions

Contact reduction and social distancing measures have been implemented to flatten the epidemic curve of COVID-19 cases in counties across the US. The benefit of these actions is just beginning to be realized and our findings suggest that their impact in lives saved could continue to be substantial. Moreover, heroic medical care providers are aggressively preparing for or actively attending to surges of severely ill COVID-19 patients in their counties, another significant lifesaving action as indicated by our findings. Maintenance of both stringent social distancing measures and aggressive hospital preparations and response will be critical over the coming weeks to avoid overwhelming the healthcare system in many US counties and greatly minimizing preventable deaths.

INTRODUCTION

The World Health Organization declared the novel coronavirus SARS-CoV2 a public health emergency of international concern on January 30, 2020 and a pandemic on March 12, 2020.¹ Nations around the world are increasingly experiencing case clusters or community transmission. As of March 26, 2020, the United States had the highest number of confirmed cases of COVID-19, the disease caused by SARS-CoV2, of any country in the world.²

Multiple areas in the US are seeing dramatic increases in cases of COVID-19 and concerns are mounting that local medical system response capacities will be quickly exceeded. Hospital critical care is perhaps the most important medical system choke point in terms of preventing deaths in a disaster scenario such as with the current COVID-19 pandemic.^{3,4} A spectrum of critical care, from intensive care units to other serviceable hospital critical care structures, can be drafted in the event of mass disasters, potentially doubling hospital capacity in a crisis care surge situation.^{5,6,7,8}

However, whether the nation's potential hospital surge capacity is exactly double, or perhaps more or less than that, in the context of rapidly growing cases of COVID-19 in the US, remains unclear. We therefore brought together previously established disease modeling estimates⁹ of the growth of the COVID-19 epidemic in the US under various social distancing contact reduction assumptions, with local estimates of the potential critical care surge response¹⁰ across all US counties. Our objectives in doing this was to highlight US counties that are at risk of exceeding their critical care surge capacity limits within six weeks, indicate the time it would take these counties to exceed their critical care surge capacity limits, and estimate the mortality that would potentially result from exceeding critical care surge capacity limits in these counties. These objectives speak to the capabilities of the US medical system under disaster conditions and the usefulness of social distancing and other prevention strategies for slowing the presentation rate of severe COVID-19 cases to a point where the US critical care system can adapt in minimizing preventable mortality.^{11,12}

METHODS

Study setting and units of analysis

All US counties were included as our primary units of analysis. Aside from states, counties (equivalently known as parishes, boroughs, and independent cities in some states) are the major legally defined political and administrative units of the United States. As primary governmental divisions, county boundaries and names rarely change.¹³ Our county list included the District of Columbia as a county equivalent and we also tracked and accounted for any county names or Federal Information Processing Standards (FIPS) county codes that had changed over time across our various datasets.

All US counties were further aggregated into US regions and urban/non-urban classifications. US regions were defined using Census Bureau standards as Northeast, Midwest, South, and West.¹⁴ Counties were defined as urban or non-urban using the 2013 US Department of Agriculture rural-urban continuum classification (RUCC) scheme. Urban counties had RUCC codes 1-3 in this scheme and listed as metropolitan; non-urban counties had RUCC codes 4-9 and listed as non-metropolitan. This ordinal RUCC variable distinguishes counties by considering both their population size and proximity to metropolitan areas. In doing this it provides useful added information over and above simple categorizing of counties on the basis

of population size, land area, proximity to metropolitan areas, or population density, as singular variables.^{15,16}

Various estimated parameters of spatio-temporal COVID-19 demand and medical system critical care supply were then calculated for all continental US counties. These estimates were then statistically summarized and mapped for US counties, regions and urban versus non-urban areas. Geographic Information Systems software, ArcGIS Pro 2.5 (ESRI Inc., 2020, Redlands, CA), was used to manage analytic polygons and create maps.

Estimates of spatio-temporal COVID-19 demand

A mathematical model was developed that simulates the spatiotemporal dynamics of infections. The details of this model are reported elsewhere.¹⁷ The model divides infections into two classes with separate rates of transmission: documented infected individuals and undocumented infected individuals. The spatial spread of COVID-19 is captured using Census Bureau commuting data to estimate the daily number of people traveling between counties and an estimated multiplicative factor. To reflect the reduced movement across counties due to interventions implemented in March, inter-county commuting in the model is reduced by 50% starting from March 14, 2020.

Transmission dynamics were simulated for all US study counties over the period from February 21, 2020 to April 2, 2020 using an iterated filter-ensemble adjustment Kalman filter framework.^{18,19,20} This combined model-inference system estimated the trajectories of susceptible, exposed, documented infected, and undocumented infected populations in each county while simultaneously inferring model parameters for the average latent period, the average duration of infection, the transmission reduction factor for undocumented infections, the transmission rate for documented infections, the fraction of documented infections, and the previously mentioned travel multiplicative factor. To account for delays in infection confirmation, a time-to-event observation model using a Gamma distribution with a range of reporting delays and different maximum seeding was employed. Log-likelihood was used to identify the best fitting model-inference posterior.^{8,16}

As in prior work²¹, the transmission of SARS-CoV2 under increasing reductions in population physical contact via control measures and behavior change was projected forward in time using the optimized model parameter estimates for a 21-day period from April 2, 2020 to April 22, 2020, and a 42-day period from April 2, 2020 to May 13, 2020. Due to a roughly 2-week lag between infection acquisition and case confirmation, the projections were initiated on March 19, 2020 using the parameter estimates made with confirmed case data through April 2, 2020. Note that because of this lag the effects of interventions in place between March 19 and April 2 have not yet been observed. Control measures included travel restrictions between areas, self-quarantine and contact precautions that were publicly advocated or imposed, and greater availability of rapid testing for infection. Behavior changes in medical care-seeking due to increased awareness of COVID-19 and increased personal protective behavior (e.g., use of facemasks, social distancing, self-isolation when sick) were also considered.

Four different adaptive scenarios of contact reduction were projected, 0% (no contact reduction via social distancing controls and behavior change), 20%, 30%, and 40% contact reduction. These scenarios are meant to mimic adaptive adjustments in contact imposed both by government regulations (e.g. school closures, restrictions on mass gatherings) and population self-regulation (e.g. isolation, mask wearing, social distancing). Upon initiation of projections on March 19, 2020, all counties with 10 or more confirmed cases impose a 0%, 20%, 30% or 40%

contact rate reduction, depending on the projection scenario; all other counties implement no contact reduction. Each week following if a county newly exceeds 10 confirmed cases a 0%, 20%, 30% or 40% contact rate reduction is imposed, depending on the projection scenario. Counties that had previously exceeded 10 confirmed cases and also experience an increase in the number of weekly reported confirmed cases impose a further, multiplicative 0%, 20%, 30% or 40% contact rate reduction, depending on the projection scenario. Counties with fewer than 10 confirmed cases implement continue not to implement control. This multiplicative ratcheting of contact reduction levels is continued until the end of simulations and is meant to represent increasing reactive social distancing imposed within counties as long as confirmed weekly cases of COVID-19 continue to rise. This adaptive control measures are more realistic and intended to better reflect what is currently known in terms of county-level reactions and adaptations to the introduction of COVID-19.

Estimates of spatio-temporal medical system critical care supply

Data on the counts and availability of various hospital beds that could be used for critical care were derived from the linkage and harmonization of different datasets for all US counties in the study. Several datasets, including four primary sources of data were used: (1) the 2020 Centers for Medicare & Medicaid Services (CMS), Health Care Information System (HCRIS) Data File, Sub-System Hospital Cost Report (CMS-2552-96 and CMS-2552-10), Section S-3, Part 1, Column 2; (2) the 2018 American Hospital Association (AHA) Annual Survey; (3) the 2020 US DHHS Health Resources and Services Administration, Area Health Resources Files (AHRF); and (4) the 2017-2019 CMS Medicare Provider of Services file, Medicare Cost Report, Hospital Compare Files.

The various types of hospital beds that could be used for critical care included intensive care unit (ICU) beds, as well as redirected operating room (OR) beds, post-anesthesia care unit (PACU) beds, and step-down beds. Critical care beds from all civilian US general medical-surgical, pediatric medical-surgical, and long-term acute care (LTAC) hospitals were included. No Veterans Affairs or military medical hospital facilities were included. Counts of ICU bed per hospital were summed as any reported: (a) general medical-surgical ICU beds, (b) surgical ICU beds, (c) coronary ICU beds, (d) burn care ICU beds, (e) pediatric ICU beds, and (f) other ICU beds. Neonatal ICU beds were excluded. Counts of ICU beds were the highest number of ICU beds reported by each US hospital across the four primary sources of data listed above.

A baseline critical care bed availability, in the absence of surge clearances, was established as 30% of existing ICU beds in each county being unoccupied and available. From this baseline, additional critical care bed counts were created for each county in our dataset that included beds that could be made available under four critical care surge response scenarios – very low, low, medium, and high (Table 1). Broadly, these four scenarios assumed the baseline that 30% of a hospital's critical beds are unoccupied and available, that some currently occupied critical care beds can be cleared, that other specialized non-ICU beds can be redeployed as critical care beds, and, in the high scenario, that two critical care patients can be serviced using a single ventilator. In this way, existing critical care bed availability rates and occupied critical care bed clearance rates for purposes of meeting high-volume patient surges in disasters were incorporated into our estimates. Step-down bed counts were used where reported by hospitals in the four primary data sources; if hospitals did not report step-down beds, a 1:4 step-down-to-ICU bed ratio was assumed and ICU bed counts were multiplied by 1.25. One bed per OR was assumed. For hospitals that did not report PACU beds, a 1.5:1 PACU beds-to-OR ratio was assumed and ORs were multiplied by 1.5. One ventilator was assumed per critical care bed.

The ability to put multiple patients on a single ventilator in order to meet demands in a high-volume disaster was also incorporated into our estimates.^{22,23,24,25,26,27,28,29,30,31}

Counties with zero beds were not included in calculating the mean numbers of days prior to exceeding critical care surge limits for each county. A typical ICU length of stay for COVID-19 patients was used to calculate the daily discharge rate from hospital critical care beds to recalculate critical care bed need for each day of the study period.³² Once a hospital's critical care bed minus critical care bed discharges – were aggregated to estimate deaths due to lack of critical care access. Prior reports of the hospital course of care for COVID-19 patients showed that the vast majority of those admitted to the ICU were critical and only one-in-five of those who were critical survived, mostly because of ICU care. Thus, the percentage of critically ill patients that should have gone to the ICU but did not and survived should be much lower, likely only 5%; we therefore assumed a 95% mortality for patients that would have been placed in a critical care bed but did not because their local critical care bed capacity had been exceeded.³³

RESULTS

Of the 3,142 US counties included in our analysis, 217 (6.9%) were in the Northeast, 1,055 (33.6%) were in the Midwest, 1,422 (45.3%) were in the South, and 448 (14.2%) were in the West. Additionally, 1166 (37.1%) were urban, and 1976 (57.9%) were non-urban.

The very low critical care surge response scenario had a total of 77,588 available critical beds and a mean +/- standard deviation (SD) of 24.0 +/- 88.8 available critical beds per county. The low critical care surge response scenario had a total of 131,542 available critical beds and a mean +/- SD of 40.7 +/- 143.1 available critical beds per county. The medium critical care surge response scenario had a total of 174,891 available critical beds and a mean +/- SD of 54.1 +/- 190.9 available critical beds per county. The high critical care surge response scenario had a total of 278,850 available critical beds, and a mean +/- SD of 86.2 +/- 307.7 available critical beds per county.

The numbers of urban counties exceeding their critical care bed capacity limits were consistently higher than for non-urban counties across both the 21-day and 42-day time periods. However, this urban/non-urban disparity was greatly diminished in the high critical care surge response scenario. Over both 21-day and 42-day time periods, the Northeast and the South most consistently had the highest number of counties with critical care beds exceeding their capacity across all 16 surge response and contact reduction scenarios. (Tables 2 and 3) Maps of US counties showed marked differences between the 21-day and the 42-day time periods, as more counties outside the Northeast, which contains many of the nation's smallest counties in terms of land area, began to exceed their critical care bed capacity limits. (Figures 1 and 2)

Over the 42-day period, a 40% contact reduction could decrease the number of counties exceeding their critical care bed limits between 81.5% - 87.3%, and a high intensity patient surge response could decrease the number of counties exceeding their critical care bed limits between 24.6% - 48.0%. The percentages of lives saved from high levels of contact reduction were 1.9 - 4.2 times greater than high levels of hospital surge response. As a measure of actions to flatten the epidemic curve over the 42-day period, the difference between a 0% and a 40% contact reduction ranged from an estimated 33,986 deaths averted in Midwest counties to 185,192 deaths averted in Northeast counties that implement a medium-level hospital surge response. As a measure of the impact of aggressive critical care surge actions, the difference between the high and the very low critical care surge response scenarios ranged from an

estimated 4,507-104,120 deaths averted over the 42-day period across the US. As a measure of the impact of redeploying non-ICU beds for critical care surge response, the difference between the medium and the very low critical care surge response scenarios ranged from an estimated 2,807 – 57,662 deaths averted over the 42-day period across the US. As a measure of the additional impact of putting two patients on a single ventilator, the difference between the high and the medium critical care surge response scenarios ranged from an estimated 1,700 – 46,458 deaths averted over the 42-day period across the US. (Table 3)

The increase in critical care beds that could be achieved under the various surge response scenarios was highly correlated with the number of beds estimated under the baseline critical care bed availability model. Focusing on the medium critical care surge capacity scenario, the gain in critical care beds under this scenario was highly correlated with the estimated beds available under baseline critical care bed availability (r=0.97). Regression analyses found that for each baseline critical care bed, 4.61 (95% CI 4.57, 4.65) additional critical care beds could be gained under the medium critical care surge capacity scenario. The counties that could generate the largest gains in beds under these surge capacity scenarios were counties that already had substantial hospital infrastructure and these counties were typically in large urban areas.

DISCUSSION

An inversely proportional relationship is evident between available critical care beds and deaths that would occur when critical care surge bed limits are exceeded. The value of "flattening the curve" – that is, the difference between having none and achieving even an adaptive 20% contact reduction – is potentially sizeable in terms of affording the US medical system, especially the choke point of hospital critical care, the necessary time to prepare and be able to handle a manageable throughput volume of severely ill COVID-19 cases.

Over the full 42-day study period, deaths averted from high levels of contact reduction were up to 4 times more than those averted from high levels of critical care surge response. Actions such travel restrictions, social distancing, and self-isolation for sick individuals should be first-line policies, followed by increased hospital capacity, in not exceeding hospital critical care bed limits and minimizing preventable deaths.

As many as 185,000 deaths could be averted by reducing person-to-person contact with actions such as travel restrictions, social distancing, and self-isolation for sick individuals. As many as 100,000 deaths could be averted through aggressive critical care surge response and preparations, including high clearance of ICU and non-ICU critical care beds and extraordinary measures like using a single ventilator for multiple patients. Of these roughly 100,000 deaths, 55% could be averted by redeploying appropriate non-ICU beds to function in a critical care capacity and 45% could be averted by adding the capability of putting two patients on a single ventilator in order to meet critically ill COVID-19 patient surge demands.³⁴

The highest proportion of COVID-19 deaths and counties exceeding their critical care capacity limits are shown to occur in the Northeast US and in urban counties, such as New York City, during the first 21 days we studied. The full 42-day study period showed clusters of counties that had exceeded their critical care capacity limits extending beyond the Northeast to other US regions, such as the South.

Urban counties, as opposed to non-urban counties, remained higher in terms of death and counties exceeding their critical care capacity limits over the full 42-day period. While large

urban areas generally have the largest capacity to generate additional critical care beds under our surge capacity models, these same urban counties currently, or in the near future, are predicted to have the largest numbers of COVID-19 cases. A major concern is thus whether the critical care surge capacity in urban counties is sufficient to care for the projected numbers of COVID-19 cases.

As a matching concern, the differences between urban and non-urban counties was greatly diminished in the high critical care surge response scenarios indicating that less extensive hospital resources in non-urban counties may not be able to keep pace with the growth in severe COVID-19 cases. The relocation or travel of urban residents with undetected COVID-19 infection to non-urban areas that appear to be relatively unaffected may exacerbate this and overwhelm the relatively limited critical care capacity in otherwise isolated non-urban regions. A potential example of this in the current dataset is the Colorado cluster that includes major winter vacation resorts that may have had visitors in from major cities in the US and internationally soon before public notification of the current COVID-19 crisis.

Several qualifications with respect to the mathematical model projections of disease burden must be noted and considered during interpretation of our findings. Firstly, the 21-day and 42day model projections were optimized using observations of confirmed cases by county, and represent infections that were acquired by individuals approximately 2 weeks earlier potentially during a time prior to the implementation of many of the social distancing and isolation measures that had been put in place by the end of March 2020. Because of this long delay between infection acquisition and case confirmation, any flattening of the curve due to these effects may not yet be apparent in our observations nor communicated to the model during optimization. As many new control policies were effected after mid-March, the 20%-40% contact reduction projections likely depict paths that multiple counties are already following. These contact reduction scenarios provide references against which the effectiveness of control measures already enacted can be assessed. Secondly, the landscape to which this model has been optimized is highly variable in space and time, due to differences in contact behavior, population density, control measures and testing practices. These differences in space and time add uncertainty to both model optimization and projections.

The estimates of medical system capacity presented here are based on long-established federal and professional agency databases of hospitals and hospital beds across the US. However, a limitation is that these data on healthcare infrastructure but do not account for staffing or ventilator supplies. Healthcare workers, especially those involved in critical care, are at high risk for COVID-19 infection and thus there may be staffing shortages that reduce the utility of the critical care beds that could be gained under surge responses. There have already been reports of hospitals being unable to accept patients, not because of lack of beds but due to lack of staff to cover those beds. However, our models also cannot account for the innovation, ingenuity and perseverance of medical staff, many of whom are trained to work in crisis situations. It is likely that medical staff will find solutions that are unanticipated by our models, that can subsequently be included as they become known and more widely applied across healthcare systems.

Future analyses should incorporate counts of mechanical ventilators in addition to critical care beds. Accurate, geographically-specific counts of mechanical ventilators have, however, been difficult to assemble on a national scale.³⁵ Our models also did not account for heterogeneities arising from specific high-risk communities in different counties. For instance, places with large elderly populations or high levels of pre-existing respiratory, cardiovascular, or immunocompromised conditions may have even higher mortality rates than anticipated here.

Finally, our mortality estimates are for COVID-19 infection, but do not account for collateral deaths for other critically ill or injured patients who could not get appropriate care in a suddenly overwhelmed healthcare system.^{36,37}

Contact reduction and social distancing measures have been implemented to flatten the epidemic curve of COVID-19 cases in counties across the US. The benefit of these actions is just beginning to be realized and our findings suggest that their impact in lives saved could continue to be substantial. Moreover, heroic medical care providers are aggressively preparing for or actively attending to surges of severely ill COVID-19 patients in their counties, another significant lifesaving action as indicated by our findings. Maintenance of both stringent social distancing measures and aggressive hospital preparations and response will be critical over the coming weeks to avoid overwhelming the healthcare system in many US counties and greatly minimizing preventable deaths.

Table 1. Calculated parameters underlying four critical care surge response scenarios

- (1) Very low intensity patient surge response:
 - a. 30% of existing ICU beds are unoccupied and available
 - b. 50% of existing ICU beds can be cleared and made available
- (2) **Low** intensity patient surge response:
 - a. 30% of existing ICU beds, step-down beds, OR beds, and PACU beds are unoccupied and available
 - b. 30% of existing ICU beds, step-down beds, OR beds, and PACU beds can be cleared and made available
- (3) **Medium** intensity patient surge response:
 - a. 30% of existing ICU beds, step-down beds, OR beds, and PACU beds are unoccupied and available
 - b. 50% of existing ICU beds, step-down beds, OR beds, and PACU beds can be cleared and made available
- (4) **High** intensity patient surge response:
 - a. 30% of existing ICU beds, step-down beds, OR beds, and PACU beds are unoccupied and available
 - b. 50% of existing ICU beds, step-down beds, OR beds, and PACU beds can be cleared and made available
 - c. All available ICU and step-down beds can be modified to service two patients per ventilator

<u>Table 2</u>. Projected mortality from inaccessible critical care in counties that exceed critical care bed surge limits within a 21-day time period (April 2, 2020 to April 22, 2020) under different surge response and contact reduction scenarios, by US region and urbanicity

		Very low		Low		Medium		High	
		Counties	Deaths	Counties	Deaths	Counties	Deaths	Counties	Deaths
	0%								
	US Total	205	32,979	144	26,780	117	23,233	84	18,128
	Northeast Midwest South West	65 29 62 49	27,941 194 1,653 3,191	51 13 43 37	23,952 82 1,005 1,741	43 9 37 28	21,330 54 730 1,119	31 7 29 17	16,991 34 431 672
	Urban Non-urban	148 57	32,005 974	103 41	26,040 740	86 31	22,573 660	60 24	17,609 519
	20%								
	US Total	117	8,501	77	5,980	55	4,955	39	3,324
	Northeast Midwest South West	40 13 32 32	7,480 63 332 626	30 5 22 20	5,417 14 175 374	21 4 18 12	4,498 9 142 306	13 4 14 8	2,990 9 99 226
	Urban Non-urban	82 35	8,062 439	53 24	5,677 303	38 17	4,695 260	26 13	3,111 213
	30%								
	US Total	121	3,844	71	2,753	57	2,259	43	1,388
Weekly contact reduction	Northeast Midwest South West	33 23 34 31	3,480 32 102 230	20 9 23 19	2,539 9 61 144	17 7 20 13	2,082 7 48 122	11 7 15 10	1,254 7 34 93
	Urban Non-urban	78 43	3,675 169	44 27	2,630 123	35 22	2,151 108	25 18	1,302 86
	40%								
	US Total	97	2,955	65	2,088	50	1,558	39	830
	Northeast Midwest South West	24 18 31 24	2,654 24 91 186	15 9 22 19	1,892 11 60 125	12 7 18 13	1,393 7 50 108	8 7 14 10	695 7 36 92
	Urban Non-urban	57 40	2,792 163	36 29	1,964 124	28 22	1,455 103	22 17	746 84

Critical care surge response

<u>Table 3</u>. Projected mortality from inaccessible critical care in counties that exceed critical care bed surge limits within a 42-day time period (April 2, 2020 to May 13, 2020) under different surge response and contact reduction scenarios, by US region and urbanicity

		Marrielaus			•		Maaliaaa			
		Very IOW		LOW Counties Deaths		Medium Counties Deaths		FIIGN Counties Deaths		
		counties	Deaths	Counties	Deaths	Counties	Deaths	Counties	Deatins	
	0%									
	US Total	1104	447,272	976	413,028	926	389,610	832	343,152	
	Northeast	156	200,702	145	192,730	137	187,287	126	175,621	
	Midwest	285	48,420	226	39,519	211	34,639	188	26,469	
	South	494	89,292	447	78,107	425	70,749	373	57,702	
	West	169	108,858	158	102,672	153	96,935	145	83,360	
	Urban Non-urban	740 364	427,648 19,624	678 298	395,156 17,872	640 286	372,617 16,993	573 259	327,767 15,385	
	20%									
	US Total	301	21,955	214	16,535	182	14,133	137	10,371	
	Northeast	83	14,725	55	11,458	49	9,993	37	7,500	
	Midwest	51	1,317	35	886	31	672	21	355	
	South	105	3,074	78	2,142	65	1,749	53	1,284	
	West	62	2,839	46	2,049	37	1,719	26	1,232	
	Urban	235	19,607	162	14,653	137	12,465	102	9.046	
	Non-urban	66	2,348	52	1,882	45	1,668	35	1,325	
	30%									
	US Total	256	12,223	197	9,688	170	8,380	143	6,078	
Weekly	Northeast	54	6,344	33	4,846	27	4,110	19	2,625	
contact	Midwest	51	1,175	42	950	41	841	35	597	
reduction	South	97	2,412	81	1,980	66	1,710	61	1,363	
	West	54	2,292	41	1,912	36	1,719	28	1,493	
	Urban	175	9 859	128	7 510	107	6 352	89	4 261	
	Non-urban	81	2,364	69	2,178	63	2,028	54	1,817	
	40%									
	US Total	204	8,499	155	6,736	140	5,692	106	3,992	
	Northeast	36	3,764	23	2,756	20	2,095	17	1,153	
	Midwest	50	994	40	796	35	653	24	435	
	South	74	1,872	58	1,587	56	1,461	42	1,111	
	West	44	1,869	34	1,597	29	1,483	23	1,293	
	Urban	126	6.325	91	4.723	79	3,784	56	2.310	
	Non-urban	78	2,174	64	2,013	61	1,908	50	1,682	

Critical care surge response

<u>Figure 1</u>. US counties exceeding hospital critical care surge limits within a 21-day time period (April 2, 2020 to April 22, 2020) under different surge response and contact reduction scenarios, shown in red



Hospital critical care surge response

<u>Figure 2</u>. US counties exceeding hospital critical care surge limits within 42-day time period (April 2, 2020 to May 13, 2020) under different surge response and contact reduction scenarios, shown in red



Hospital critical care surge response

References

1 Kluge HHP. WHO announces COVID-19 outbreak a pandemic. March 12, 2020. URL: <u>http://www.euro.who.int/en/health-topics/health-emergencies/coronavirus-covid-</u>

<u>19/news/news/2020/3/who-announces-covid-19-outbreak-a-pandemic</u>. Last accessed: March 29, 2020.

2 Soucheray S. US COVID-19 cases surge past 82,000, highest total in world. University of Minnesota Center for Infectious Disease Research and Policy. March 26, 2020. URL: <u>http://www.cidrap.umn.edu/news-perspective/2020/03/us-covid-19-cases-surge-past-82000-highest-total-world</u>. Last accessed: March 29, 2020.

3 Carr, B. G., Addyson, D. K., & Kahn, J. M. (2010). Variation in critical care beds per capita in the United States: implications for pandemic and disaster planning. JAMA, Journal of the American Medical Association, 303(14), 1371-1372.

4 Carr, B.G., Walsh, L., Williams, J.C., Pryor, J.P. and Branas, C.C., 2016. A geographic simulation model for the treatment of trauma patients in disasters. Prehospital and Disaster Medicine, 31(4), 413-421.

5 Hossain, T., Ghazipura, M., & Dichter, J. R. (2019). Intensive Care Role in Disaster Management Critical Care Clinics. Critical Care Clinics, 35(4), 535-550.

6 Corcoran, S. P., Niven, A. S., & Reese, J. M. (2012). Critical care management of major disasters: a practical guide to disaster preparation in the intensive care unit. Journal of Intensive Care Medicine, 27(1), 3-10.

7 Society for Critical Care Medicine. U.S. ICU Resource Availability for COVID-19. Version 2, 3/19/2020 1:49pm

8 Hick, J.L., Einav, S., Hanfling, D., Kissoon, N., Dichter, J.R., Devereaux, A.V., Christian, M.D. and Task Force for Mass Critical Care, 2014. Surge capacity principles: care of the critically ill and injured during pandemics and disasters: CHEST consensus statement. Chest, 146(4), e1S-e16S.

9 Li R, Pei S, Chen B, Song Y, Zhang T, Yang W, Shaman J. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (COVID-19). Science. 2020 Mar 16.

10 Carr, B.G., Walsh, L., Williams, J.C., Pryor, J.P. and Branas, C.C., 2016. A geographic simulation model for the treatment of trauma patients in disasters. Prehospital and disaster medicine, 31(4), 413-421.

11 Emanuel, Ezekiel J., Govind Persad, Ross Upshur, Beatriz Thome, Michael Parker, Aaron Glickman, Cathy Zhang, Connor Boyle, Maxwell Smith, and James P. Phillips. "Fair allocation of scarce medical resources in the time of Covid-19." NEJM (2020).

12 Klarevas L, Rajan S, Branas C, Keyes K. Experts chide Trump on coronavirus, the economy and depression. New York Daily News. March 25, 2020.

13 Geographic Areas Reference Manual. Washington (DC): Census Bureau (US); 2001. Available at: http:// www.census.gov/geo/www/garm.html. Accessed September 2, 2004.

14 US Census Bureau. Census Regions and Divisions of the Unites States. URL: https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf . Last accessed:

March 29, 2020.

15 Cromartie J. United States Department of Agriculture, Economic Research Service. Rural-Urban Continuum Codes Documentation. 2019. URL: <u>https://www.ers.usda.gov/data-</u>

products/rural-urban-continuum-codes/documentation/ . Last accessed: March 30, 2020. 16 Branas CC, Nance ML, Elliott MR, Richmond TS, Schwab CW. Urban–rural shifts in intentional firearm death: different causes, same results. American journal of public health. 2004 Oct:94(10):1750-5.

17 Pei S, Shaman J. Simulation of SARS-CoV2 Spread and Intervention Effects in the Continental US with Variable Contact Rates, March 24 2020. March 26, 2020. Available at https://github.com/shaman-lab/COVID-19Projection_0324.

18 E. L. Ionides, C. Bretó, A. A. King, Inference for nonlinear dynamical systems. Proc. Natl. Acad. Sci. U.S.A. 103, 18438–18443 (2006).

19 A. A. King, E. L. Ionides, M. Pascual, M. J. Bouma, Inapparent infections and cholera dynamics. Nature 454, 877–880 (2008).

20 S. Pei, F. Morone, F. Liljeros, H. Makse, J. L. Shaman, Inference and control of the nosocomial transmission of methicillin-resistant Staphylococcus aureus. eLife 7, e40977 (2018). 21 Glanz J, Leatherby L, Bloch M, Smith M, Buchanan L, Wu J, Bogel-Burroughs N. Coronavirus Could Overwhelm U.S. Without Urgent Action, Estimates Say. New York Times, March 20, 2020. URL: <u>https://www.nytimes.com/interactive/2020/03/20/us/coronavirus-model-us-outbreak.html</u>, Last accessed: March 31, 2020.

22 Hossain, T., Ghazipura, M., & Dichter, J. R. (2019). Intensive Care Role in Disaster Management Critical Care Clinics. Critical Care Clinics, 35(4), 535-550.

23 Corcoran, S. P., Niven, A. S., & Reese, J. M. (2012). Critical care management of major disasters: a practical guide to disaster preparation in the intensive care unit. Journal of intensive care medicine, 27(1), 3-10.

24 Marcon, E., Kharraja, S., Smolski, N., Luquet, B. and Viale, J.P., 2003. Determining the number of beds in the postanesthesia care unit: a computer simulation flow approach. Anesthesia & Analgesia, 96(5), 1415-1423.

25 Neyman, G., & Irvin, C. B. (2006). A single ventilator for multiple simulated patients to meet disaster surge. Academic Emergency Medicine, 13(11), 1246-1249.

26 Hossain, T., Ghazipura, M., & Dichter, J. R. (2019). Intensive Care Role in Disaster Management Critical Care Clinics. Critical Care Clinics, 35(4), 535-550.

27 Corcoran, S. P., Niven, A. S., & Reese, J. M. (2012). Critical care management of major disasters: a practical guide to disaster preparation in the intensive care unit. Journal of Intensive Care Medicine, 27(1), 3-10.

28 Society for Critical Care Medicine. U.S. ICU Resource Availability for COVID-19. Version 2, 3/19/2020 1:49pm

29 Hick, J.L., Einav, S., Hanfling, D., Kissoon, N., Dichter, J.R., Devereaux, A.V., Christian, M.D. and Task Force for Mass Critical Care, 2014. Surge capacity principles: care of the critically ill and injured during pandemics and disasters: CHEST consensus statement. Chest, 146(4), e1S-e16S.

30 Carr, B.G., Walsh, L., Williams, J.C., Pryor, J.P. and Branas, C.C., 2016. A geographic simulation model for the treatment of trauma patients in disasters. Prehospital and Disaster Medicine, 31(4), 413-421.

31 Giroir BP, Adama J. Optimizing ventilator use during the COVID-19 pandemic. US Public Health Service Commissioned Corps. March 31, 2020.

32 Pei S, Shaman J. Simulation of SARS-CoV2 Spread and Intervention Effects in the Continental US with Variable Contact Rates, March 24 2020. March 26, 2020. Available at https://github.com/shaman-lab/COVID-19Projection_0324.

33 Zhou, Fei, Ting Yu, Ronghui Du, Guohui Fan, Ying Liu, Zhibo Liu, Jie Xiang et al. Clinical course and risk factors for mortality of adult inpatients with COVID-19 in Wuhan, China: a retrospective cohort study. Lancet (2020).

34 Giroir BP, Adama J. Optimizing ventilator use during the COVID-19 pandemic. US Public Health Service Commissioned Corps. March 31, 2020.

35 Rubinson, L., Vaughn, F., Nelson, S., Giordano, S., Kallstrom, T., Buckley, T., ... & Yeskey, K. (2010). Mechanical ventilators in US acute care hospitals. Disaster medicine and public health preparedness, 4(3), 199-206.

36 Carr, B. G., Reilly, P. M., Schwab, C. W., Branas, C. C., Geiger, J., & Wiebe, D. J. (2011). Weekend and night outcomes in a statewide trauma system. Archives of Surgery, 146(7), 810-817.

37 Emanuel, Ezekiel J., Govind Persad, Ross Upshur, Beatriz Thome, Michael Parker, Aaron Glickman, Cathy Zhang, Connor Boyle, Maxwell Smith, and James P. Phillips. Fair allocation of scarce medical resources in the time of Covid-19. New England Journal of Medicine (2020).