Ambulances Required to Relieve Overcapacity Hospitals: A Novel Measure of Hospital Strain During the COVID-19 Pandemic in the United States

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Study objective: One in 4 deaths from COVID-19 has been attributed to hospital crowding. We simulated how many ambulances would be required to rebalance hospital load through systematic interhospital transfers. We assessed the potential feasibility of such a strategy and explored whether transfer requirement was a helpful measure and visualization of regional hospital crowding during COVID-19 surges.

Methods: Using data from the United States hospitals reporting occupancy to the Department of Health and Human Services from July 2020 to March 2022 and road network driving times, we estimated the number of ambulances required weekly to relieve overcapacity hospitals.

Results: During the peak week, which ended on January 8, 2021, approximately 1,563 ambulances would be needed for 15,389 simulated patient transports, of which 6,530 (42%) transports involved a 1-way driving time of more than 3 hours. Transfer demands were dramatically lower during most other weeks, with the median week requiring only 134 ambulances (interquartile range, 84 to 295) and involving only 116 transports with 1-way driving times above 3 hours (interquartile range, 4 to 548). On average, receiving hospitals were larger and located in more rural areas than sending hospitals.

Conclusion: This simulation demonstrated that for most weeks during the pandemic, ambulance availability and bed capacity were unlikely to have been the main impediments to rebalancing hospital loads. Our metric provided an immediately available and much more complete measure of hospital system strain than counts of hospital admissions alone. [Ann Emerg Med. 2022;80:301-313.]

Please see page 302 for the Editor's Capsule Summary of this article.

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INTRODUCTION

The COVID-19 pandemic has been associated with at least half a million excess deaths in the United States,[1] with potentially 1 in 4 of these deaths attributable to the overloading of hospitals.[2,3] Deep and pervasive disparities among hospitals, both at regional and neighborhood levels, have been well documented during the pandemic and have complex causes rooted in both regional surges in infections and demographic inequalities and segregation.[4-7] However, adequate load balancing schemes among hospitals to prevent excess deaths at overloaded hospitals have remained rare throughout the pandemic in the United States.[8-11] Despite some public calls that transfers may have been able to save lives,[12,13] rationing of care away from patients with a poor prognosis has received far more attention, even though crisis standards of care in most jurisdictions call for transfers to first be exhausted before any rationing. Could the roughly 58,000 operating American ambulances have been underutilized during the COVID-19 pandemic?[14-16]

We estimated the approximate number of ambulances required each week from July 2020 to March 2022 to transfer patients such that no hospital experienced a load (proportion of available beds occupied by a patient) more than 90% of their standard capacity.[17,18] This simulation had 2 primary purposes. First, we sought to determine whether, in a hypothetical coordinated health care system, sufficient ambulances and beds existed to balance hospital load completely. Second, we explored transfer requirements as a measure of hospital strain and a helpful visualization of the geographical distribution of hospital strain.

Editor's Capsule Summary

What is already known on this topic

Hospital crowding impacts care, and intrahospital transfer is one method to address needs.

What question this study addressed

During the COVID-19 peak demand, how many staffed transfer vehicles could ease US overcapacity concerns?

What this study adds to our knowledge

In a simulation informed by 20 months of recent federal data, 1,563 staffed ambulances could move 15,389 patients in the peak COVID-19 demand week, 42% of which would be a trip of >3 hours. Other observed transfer time intervals required fewer resources.

How this is relevant to clinical practice

The national and local transfer capability is unknown, limiting the use of this measure to a strain assessment at peak demand.

MATERIALS AND METHODS

This was a retrospective simulation combining weekly reported bed capacity and patient load data from the United States Department of Health and Human Services (HHS) with calculated driving times to estimate the resources required to transport patients from overcapacity hospitals to nearby facilities with capacity. We modeled a hypothetical intervention allowing the hospital with the highest excess occupancy to immediately transfer patients to the nearest hospital with available patient beds, followed by the hospital with the next highest excess occupancy, until all hospitals operate within capacity.

Outcomes

The primary outcome was the number of ambulances, operating 24 hours per day for 7 days needed to transport any patients at hospitals operating at more than 90% capacity to the closest hospital operating at less than 90% capacity within 1 week. We estimated ambulance time for each transport with a fixed and variable component. The fixed component was 2 hours to account for patient pickup and drop off as well as ambulance cleaning and resupply; the variable component was 3 times the estimated driving time from the sending to receiving hospital to account conservatively for ambulance movements to and from a dispatch base. For example, a transport requiring 12 minutes driving time would require 2 hours and 36 minutes of ambulance time. Each transport was assumed to require a single ambulance (1 patient per ambulance). Hospital loads were recomputed after each simulated transfer, 1 patient at a time. A sensitivity analysis incorporated the impact of simulated transfers from previous weeks under varying assumptions about the duration of inpatient admission. Secondary outcomes included the number of patients transferred, heatmaps illustrating the geography of patient transports, the driving time of the longest required transfer, and the number of transfers requiring more than 1 hour of 1-way driving time (and thus 5 hours of ambulance time) or more than 3 hours 1-way driving time (and thus 11 hours of ambulance time).

Bed Capacity and Hospital Load

In available HHS data, bed capacity reporting was often inconsistent and frequently included spurious values that required additional data cleaning. Missing values (which were often reported by very small hospitals) were censored to 0, whereas single-week outlier values of 0 or those approaching 7 times baseline (which was a frequent error because of misreporting of weekly numbers as daily) were imputed from prior and subsequent weeks and loads were also winsorized at 1000%.

Using a random selection of hospitals stratified by region and size, Figure E1 (available at http://www.annemergmed.com) illustrates how, even after preprocessing, reported capacity can vary widely, potentially because of changes in staffing. Hospitals are directed to report "all staffed adult inpatient beds … currently set-up, staffed and able to be used for a patient [including] all overflow, observation, and active surge/expansion beds used for inpatients, ICU beds, [and] any surge/hallway/overflow beds that are open for use for a patient, regardless of whether they are occupied or available."[19] However, the observed bed range complicated our analysis, and inconsistent data were especially apparent at facilities that increased capacity to accommodate COVID-19 surges. In practice, it seems some hospitals reported these beds as an increase in their capacity, whereas others did not and therefore reported loads above 100%. To overcome this inconsistency in reporting, we used a modified mode of each hospital's weekly reported capacity that discounted small differences in integer values.

After performing an extensive review of the reported data for hundreds of outlier and typical hospitals, we conducted personal correspondence with the leadership of many hospitals publicly reported to be over or undercapacity and did or did not create surge capacity. In

Box. Key assumptions in simulation model.

Patient prioritization	**Hospitals with the greatest excess occupancy have top priority to send patients to the nearest hospital with available beds**
Goal hospital load	90% of all beds are occupied by patients (in primary analysis), which applies to sending and receiving hospitals This reflects the minimum unused capacity necessary for the safe functioning of a hospital (or the maximum hospital capacity that can safely be used)
ICU transfers	Since some ICU patients may be too critically ill to safely transfer, ICUs were partly decompressed indirectly by the transfer of multiple non-ICU patients (some of whom may later require ICU care) and by freeing non-ICU beds for recovered ICU patients (see "ICU overcapacity multiplier" below)
ICU overcapacity multiplier	2× (in primary analysis) In addition to transferring patients to meet the *goal hospital load*, in our primary analysis, 2 non-ICU patients were transferred per overcapacity ICU bed The ICU overcapacity multiplier served as a combined estimate of several simultaneous dynamics: how many floor patients might need to be transferred to prevent a subsequent decompensation on the floor, the need for available floor beds to accommodate recovered ICU patients who no longer required ICU level care, and the fact that many ICU patients were likely to be too sick or too complex to be transferred. In addition, this multiplier was intended to mitigate overall resource demands on a hospital by transferring more non-ICU patients
Number of patients transported from sending hospitals	(Actual Hospital Load - Goal Hospital Load) × (non-ICU Beds + [ICU Beds · ICU overcapacity multiplier]) Eg, in the primary analysis (goal hospital load of 90% and ICU overcapacity multiplier of 2×), a 100% full, 150-bed hospital with 100 non-ICU beds and 50 ICU beds would be scheduled for a total of 20 transfers: 10 transfers to reduce non-ICU beds to 90% capacity, plus 10 patients to 2× decompress the ICU to 90% as well (or alternatively, 15 to reduce the overall hospital load to 90%, plus 5 more to 2× decompress the ICU to 90% as well)
Time window to complete transfer	Within 7 days*
Patients per ambulance	1
Transport time ("*ambulance time*")	Fixed component + variable component Fixed component: 2 hours (1 for loading, and 1 for unloading) Variable component: 3 times driving time (the duration required to drive from the origin to the destination hospital along street networks at posted speed limits) (to account for driving from an operational base to the sending hospital, then to the receiving hospital, and finally back to an operational base)
Sending hospital requirements	Overall capacity at least 90%[†] *and* ICU capacity at least 90%[†,‡]
Receiving hospital requirements	Not a critical access hospital *and* Overall capacity below 90%[††] *and* ICU capability with at least 1 open ICU bed *and* ICU capacity below 90%[†]
Existing transfers	In areas with existing transfer programs to partially relieve overcapacity hospitals, resources required for these transfers not included in this tally, but resources required to fully unburden to 90% goal capacity were included

*We modeled in isolation the most challenging first week of transfers that must address all accumulated overloads without assuming any transfers performed in previous weeks.
[†]In sensitivity analyses, this 90% threshold changed along with the goal hospital load.
[‡]Or, for small hospitals with less than 10 ICU beds (or no ICU capacity), this requirement would also be satisfied if only 1 free ICU bed was available.

all the cases that we reviewed, we achieved a reasonable approximation of hospital capacity using the "10% functional mode," which is the reported weekly bed capacity (or a number of currently admitted patients, if this was greater), with the most other weeks reporting a value within 10% of itself. Figure E1 shows how this metric

Table 1. Characteristics of all hospitals included in simulation study.*

Median (IQR)	All Hospitals n=4,531	Hospitals by Senders vs Receivers of Patients			
		Never Transfer n=1,449 (32%)	Only Send n=824 (18%)	Only Receive n=1,225 (27%)	Send and Receive n=1,033 (23%)
Weeks with simulated outgoing transfers†,‡	0(0, 6)	-	9 (3, 27)	-	11 (4, 26)
Weeks with simulated incoming transfers†,§	0(0, 11)	-	-	14 (5, 29)	9 (3, 17)
Maximum simulated weekly outgoing transfers	0(0, 9)	-	5 (2, 21)	-	24 (11, 47)
Maximum simulated weekly incoming transfers	0 (0, 19)	-	-	25 (12, 44)	14 (7, 26)
Hospital size (count of all beds)‖	58 (23, 181)	25 (17, 42)	24 (12, 96)	120 (54, 256)	144 (67, 253)
Range in reported count of all beds¶	14 (2, 42)	6(0, 19)	9 (2, 27)	20 (3, 61)	34 (14, 75)
ICU size (count of ICU beds)‖	8 (0, 26)	1(0, 6)	0 (0, 12)	16 (7, 41)	19 (9, 39)
Range in reported count of ICU beds¶	0 (0, 7)	0 (0, 0)	0 (0, 3)	1 (0, 9)	6 (1, 15)
Hospital count by size:‖					
Small (0-50 beds, 8% of all beds)	n=2,150 (47%)	n=1,128 (78%)	n=553 (67%)	n=288 (24%)	n=181 (18%)
Midsize (51-250, 35%)	1,621 (36%)	221 (15%)	191 (23%)	617 (50%)	592 (57%)
Large (251-500, 31%)	545 (12%)	68 (5%)	55 (7%)	237 (19%)	185 (18%)
Very large (501-2,500, 27%)	215 (5%)	32 (2%)	25 (3%)	83 (7%)	75 (7%)
Hospital count by region:#					
Midwest	n=1,361 (30%)	n=632 (44%)	n=255 (31%)	n=298 (24%)	n=176 (17%)
Northeast	560 (12%)	183 (13%)	85 (10%)	176 (14%)	116 (11%)
South	1,739 (39%)	406 (28%)	317 (38%)	495 (40%)	521 (50%)
West	871 (19%)	228 (16%)	167 (20%)	256 (21%)	220 (21%)
Surrounding zip codes:					
Rural**	0% (0, 60)	50% (0, 100)	0% (0, 100)	0% (0, 0)	0% (0, 0)
Poverty	9% (6, 13)	9% (6, 13)	9% (6, 14)	9% (6, 14)	10% (6, 14)
Race					
White, non-Hispanic	76% (55, 91)	86% (67, 94)	79% (60, 92)	71% (53, 87)	63% (46, 80)
White, Hispanic	4% (2, 10)	3% (1, 7)	3% (1, 9)	5% (2, 11)	6% (3, 16)
Black	4% (1, 13)	1% (0.4, 6)	2% (1, 11)	5% (2, 16)	8% (3, 19)
Asian	1% (0.4, 3)	0.6% (0.2, 2)	1% (0.2, 2)	2% (0.6, 4)	2% (0.8, 6)
Native American	0.3% (0.1, 0.7)	0.3% (0.1, 0.8)	0.4% (0.2, 0.9)	0.3% (0.2, 0.6)	0.3% (0.2, 0.6)
Other	1% (0.4, 4)	1% (0.2, 2)	1% (0.3, 3)	2% (0.6, 4)	2% (0.9, 5)

IQR, Interquartile range.

*Median and interquartile range among hospitals, unless noted otherwise, with all hospitals given equal weight, regardless of size (unweighted). Here, hospitals are classed as sending or receiving based on whether they ever had outgoing or incoming simulated transfers during any week of our study.

†Out of 86 weeks from July 31, 2020, to March 18, 2022.

‡Equivalent to the count of weeks out when a hospital was overcapacity.

§Equivalent to the count of weeks when a hospital was the closest undercapacity hospital to another overcapacity hospital (accounting for all other higher-priority transfers from even more overcapacity hospitals).

‖By 10% functional mode of the daily count.

¶Median (and interquartile range) of the difference between the highest and lowest reported weekly hospital bed capacity for each hospital.

#By standard US Census Regions of the United States.

Midwest: IA, IL, IN, KS, MI, MN, MO, ND, NE, OH, SD, WI (12 states).

Northeast: CT, MA, ME, NJ, NH, NY, PA, RI, VT (9 states).

South: AL, AR, DC, DE, FL, GA, KY, LA, MD, MS, NC, OK, SC, TN, TX, VA, WV (16 states, DC).

West: AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, WY (11 states).

**Percentage of surrounding zip codes identified by Rural-Urban Commuting Area Codes provided by the US Department of Agriculture as “small town” or “rural” (file updated 2020, August 17).

Table 2. Characteristics of simulated sending versus receiving hospitals.*

Median (IQR)	Difference: Destination Minus Origin	Origin: Sending Hospital	Destination: Receiving Hospital	All Hospitals†
Marginal Hospital Load‡ (immediately after each patient transfer)	-38% (-61, -23)	100% (94, 108)	67% (50, 77)	§
Hospital Load‖ (before any transfers)	-45% (-74, -28)	103% (97, 114)	64% (45, 75)	75% (62, 85)
ICU Load‖ (before any transfers)	-45% (-79, -27)	102% (96, 119)	64% (45, 77)	64% (45, 77)
Hospital size (beds)	-21 (-210, 166)	253 (143, 423)	213 (91, 388)	292 (156, 518)
ICU size (beds)	-3 (-39, 28)	38 (19, 81)	29 (11, 75)	46 (19, 100)
Surrounding zip codes:				
Rural¶	2.3% (mean)¶	2.6% (mean)¶	4.9% (mean)¶	5.0% (mean)¶
Poverty	0.0% (-4.1, 3.5)	10.3% (6.9, 14.9)	10.0% (6.2, 14.5)	9.7% (6.2, 14.5)
Race				
White, non-Hispanic	0.0% (-3.5, 2.1)	56.5% (40.8, 67.9)	58.2% (43.5, 74.6)	62.9% (46.1, 78.4)
White, Hispanic	0.0% (-3.5, 2.0)	8.9% (3.4, 18.9)	7.8% (3.0, 17.7)	6.2% (2.8, 13.6)
Black	-0.3% (-7.0, 2.9)	10.5% (4.8, 20.7)	8.8% (3.6, 19.0)	8.8% (3.4, 20.4)
Asian	0.0% (-2.1, 1.7)	4.1% (1.5, 8.3)	3.1% (1.2, 8.2)	3.0% (1.3, 6.6)
Native American	0.0% (-0.2, 0.2)	0.4% (0.2, 0.6)	0.4% (0.2, 0.7)	0.3% (0.2, 0.6)
Other	0.0% (-1.7, 1.0)	2.8% (1.2, 6.3)	2.5% (1.0, 5.1)	2.2% (1.0, 4.9)

IQR, Interquartile range.

*Weighted median and interquartile range (according to a number of transfers across all weeks, n=611,807 transfers in total), with the difference representing the median change, experienced among all transfers. Here, statistics are computed at the patient level based on the median change experienced from the sending to the receiving hospital (effectively, weighted by the number of transfers), with data provided for comparison on all hospitals, weighted by their number of beds.

†Included all hospitals in our study, regardless of whether they did or did not send or receive any transfers, weighted by the number of beds in each hospital, based on the 10% functional mode. In contrast, all other columns in this table are weighted by the number of transfers. Values in this column differed from those previously provided in Table 1, which are unweighted (hospitals are all given equal weight, regardless of size).

‡As percentage of full capacity, based on 10% functional mode, taking into account on an ongoing basis any prior (higher-priority) transfers from even more overcapacity hospitals and their patient-by-patient effects on both sending and receiving hospitals, as well as any effects of the ICU overcapacity multiplier.

§Not meaningfully calculable since marginal load varied with every transfer (and thus by week as well).

‖As a percentage of full capacity, based on 10% functional mode, before any transfers at all, and not including any effects of ICU overcapacity multiplier.

¶Since 93% of hospitals had no surrounding zip codes classified as "rural" or "small town," all median and IQR values were 0, so means have been included in their place.

approximates capacity for hospitals that reported their capacity in response to surges in different ways.

Critical Care Transports

Although critically ill patients (and overcapacity critical care units) accounted for a large share of the morbidity and mortality associated with COVID-19,[20] transporting critically ill patients would be fraught with issues of specialized equipment availability, provider safety, and the possibility of patient decompensation during transport.[21-23] Although these challenges may be surmountable in many cases, our simulated intervention avoided transferring ICU patients. Instead, we transferred non-ICU patients, anticipating that some will need ICU care later in their hospital course, and, after transfer, would now be at a hospital with available ICU capacity. We accounted for ICU patients in several different ways. First, receiving hospitals were required to report an ICU load of no more than 90%. Second, sending hospitals were required to have an ICU load of at least 90%. Finally, non-ICU patients equaling 2 times (designated as "2×") the number of ICU patients required to reduce the ICU load to below 90% were allocated for transfer; in a sensitivity analysis, this "ICU overcapacity multiplier" was changed to 1×, 5×, and 10×. Another sensitivity analysis examined how changing the "goal hospital load" and ambulance turnaround time would affect ambulance requirements (Box).

Data Sources

We drew occupancy from the HHS database of Reported Patient Impact and Hospital Capacity,[24-26] which provided weekly load estimates (as an average of the previous 7 days) from almost all hospitals nationwide, except some federally operated facilities such as the Defense Department, Veterans Affairs, and Indian Health systems). We included all adult acute care and

Table 3. Simulated transport resources required to relieve overcapacity hospitals during exemplar weeks, in addition to daily ambulance requirements.*

Week Ending On:	Ambulances Required (24h for 7d):†	Individual Patient Transports:‡	Transports by Driving Time: <1h	1-3h	>3h	Longest Transport (Hours):	Notes:
July 31, 2020	106	4,893	4,006 (82%)	826 (17%)	61 (1%)	4.3	First week of available data (relatively low resource utilization)
January 8, 2021	1,563	15,389	5,884 (38%)	2,975 (19%)	6,530 (42%)	24.5	Peak of winter 2020-2021 surge (overall highest resource utilization week)
August 20, 2021	731	13,738	7,592 (55%)	3,292 (24%)	2,854 (21%)	22.5	Peak of summer and fall 2021 surge (delta variant)
January 21, 2022	478	14,488	9,082 (63%)	4,408 (30%)	998 (7%)	8.4	Peak of winter 2021-2022 surge (omicron variant)

*Results of simulated patient transfer intervention.
†For context, roughly 58,000 civilian ambulances operate in the 48 states, and around 4,000 classed for interhospital transport.
‡For context, prepandemic hospital-to-ED transfers averaged roughly 20,000 per week.

critical access hospitals in the contiguous mainland United States (48 states and the District of Columbia) that reported any data from July 31, 2020, to March 18, 2022. We did not include children's hospitals or long-term care facilities.

Demographic characteristics of areas surrounding hospitals were assembled from the American Community Survey[27] using means from each hospital's zip code and the 5 closest zip codes within 10 miles and compared using Student's t test.[28] Hospitals with missing geographic coordinate data were assigned the coordinates of their street address (or their ZIP code's centroid[29]), and driving times between hospital pairs were computed using ArcGIS Pro software[30] traveling on standard roads at posted speed limits (or, alternatively, at 50 kilometers per hour, as the crow flies, if a street network path was not calculable). The primary analysis was conducted using Stata 13.1 software,[31] with simulation programming performed in Perl using the Text::CSV, Math::Trig, and Statistics::Descriptive packages (source code available upon request).[32]

RESULTS

Of the 4,531 hospitals included in the primary analysis of simulated transfers (Table 1), 1,449 (32%) never sent or received a simulated patient transfer (and thus were always under capacity). Over the study period, 1,857 hospitals (41%) sent at least 1 patient (and thus, at some point, were overcapacity), 1,077 (24%) sent more than 10 patients in a single week, and 105 (2%) sent more than 100 patients in a single week. Two thousand two hundred fifty-eight hospitals (50%) received at least 1 patient (and thus were under capacity whereas nearby hospitals were overcapacity), 1,604 (35%) received more than 10 patients in a single week, and 92 (2%) received more than 100 patients in a single week. Thousand thirty-three hospitals (23%), during different weeks, both sent and received at least 1 patient, 486 (11%) sent and received at least 10 patients, and 4 (0.1%) sent and received at least 100 patients. Overall, sending hospitals were markedly larger and less rural than receiving hospitals (Table 2).

The week with the highest simulated demand for ambulance resources during our study period was that ending on January 8, 2021. During that peak week, we estimated that relieving all overburdened hospitals by the week's end would require 1,563 ambulances to transport 15,389 individual patients, in addition to any patient transports already in place external to our simulation (Table 3). Six thousand five hundred thirty (42%) of these transfers had 1-way driving times more than 3 hours (and hence ambulance time more than 11 hours). Subsequent peaks during the Delta wave (August 20, 2021) and Omicron wave (January 21, 2021) required fewer ambulances (731 and 478, respectively) for almost as many transfers overall (13,738 and 14,488, respectively) but fewer transfers longer than 3 hours (2,854 [21%] and 998 [7%], respectively). Transfers from the most overcapacity hospitals, which are prioritized in our algorithm, were generally shorter in length, except during the January 8, 2021 peak (Figure 1).

The demand for transfer during other weeks was far smaller, with the median week requiring only 134 ambulances (interquartile range, 84 to 295 ambulances, Figure 2A) and involving only 116 transports with 1-way

Sending Hospital Load[b]:	One-way Driving Time:		
	Less than 1 hour	1 to 3 hours	More than 3 hours
July 31, 2020 (first week of available data from HHS)			
All Sending Hospitals:	4,006 (82%) *42 ambulances*	826 (17%) *19 ambulances*	61 (1%) *2 ambulances*
90% to 100%: (minimally overcapacity hospitals)	1,498 (79%) *0 ambulances*	356 (19%) *0 ambulances*	35 (2%) *0 ambulances*
100% to 110%:	897 (81%) *15 ambulances*	190 (17%) *8 ambulances*	26 (2%) *2 ambulances*
110% to 150%:	1,180 (81%) *20 ambulances*	269 (19%) *10 ambulances*	0 (0%) *0 ambulances*
More than 150% (most overcapacity hospitals)	431 (98%) *7 ambulances*	11 (2%) *1 ambulances*	0 (0%) *0 ambulances*
January 8, 2021 (overall peak, during winter 2020-2021 surge)			
All Sending Hospitals:	5,884 (38%) *117 ambulances*	2,975 (19%) *128 ambulances*	6,530 (42%) *1,318 ambulances*
90% to 100%: (minimally overcapacity hospitals)	3,138 (47%) *63 ambulances*	1,399 (21%) *61 ambulances*	2,176 (32%) *453 ambulances*
100% to 110%:	1,669 (39%) *32 ambulances*	639 (15%) *28 ambulances*	2,031 (47%) *445 ambulances*
110% to 150%:	904 (23%) *18 ambulances*	703 (18%) *30 ambulances*	2,257 (58%) *406 ambulances*
More than 150% (most overcapacity hospitals)	173 (37%) *4 ambulances*	234 (50%) *9 ambulances*	66 (14%) *14 ambulances*
August 20, 2021 (delta variant surge during summer 2021)			
All Sending Hospitals:	7,592 (55%) *142 ambulances*	3,292 (24%) *149 ambulances*	2,854 (21%) *440 ambulances*
90% to 100%: (minimally overcapacity hospitals)	3,430 (49%) *64 ambulances*	2,094 (30%) *94 ambulances*	1,541 (22%) *256 ambulances*
100% to 110%:	2,666 (61%) *49 ambulances*	968 (22%) *44 ambulances*	739 (17%) *116 ambulances*
110% to 150%:	1,270 (65%) *25 ambulances*	188 (10%) *9 ambulances*	487 (25%) *60 ambulances*

Figure 1. Weekly simulated national patient transports, stratified by driving time and hospital load. Number of transfers for exemplar weeks, shaded by absolute number (>3,000, >2,000, >1,000, >100), with percentages by row, in addition to any baseline transports external to our simulation.[a] *Annotated, in italics, with the number of ambulances required to complete simulated transports.*

driving times above 3 hours (interquartile range, 4 to 548, Figure 2C). A few states had particularly high absolute and per capita ambulance requirements (Figure 2B). Transfer distances varied widely from week to week (Figure 2C), with the longest transfers concentrated in the southwest in January 2021 and the southeast in August 2021 (Figure 3). Our sensitivity analyses showed the varying impact of changing underlying assumptions on simulated ambulance demands during the peak week (January 8, 2021): eg, 18,242 ambulances would be required assuming an ICU overcapacity multiplier of 10×, whereas only 197 ambulances would be required assuming a goal hospital load of 100% (Figure 4).

LIMITATIONS

Our methodology had several significant limitations. First, our results should be positioned as point estimates within a broad range defined by our sensitivity analyses. The challenge of assessing actual hospital capacity from imperfect data that reflect an imperfect definition is perhaps the most important contributor to these uncertainties. Ultimately, we use hospital inpatient beds as a proxy for hospital capacity to treat COVID-19 patients, and hospital beds differ significantly in available resources and expertise, although care for COVID-19 is likely to be more standardized across facilities than other conditions. However, beds are at least indirectly correlated with necessary items such as staffing, personal protective

More than 150% (most overcapacity hospitals)	226 (64%) *4 ambulances*	42 (12%) *2 ambulances*	87 (25%) *8 ambulances*
January 21, 2022 (omicron variant surge during winter 2021-2022)			
All Sending Hospitals:	9,082 (63%) *174 ambulances*	4,408 (30%) *188 ambulances*	998 (7%) *115 ambulances*
90% to 100%: (minimally overcapacity hospitals)	3,854 (60%) *73 ambulances*	2,105 (33%) *92 ambulances*	483 (8%) *56 ambulances*
100% to 110%:	2,245 (56%) *45 ambulances*	1,439 (36%) *59 ambulances*	312 (8%) *35 ambulances*
110% to 150%:	2,385 (70%) *45 ambulances*	834 (24%) *35 ambulances*	203 (6%) *24 ambulances*
More than 150% (most overcapacity hospitals)	598 (95%) *11 ambulances*	30 (5%) *2 ambulances*	0 (0%) *0 ambulances*

[a] For context, at baseline in recent years approximately 20,000 hospital-to-ED ambulance transports take place per week.

[b] Expressed as a percentage of full capacity (100% means the number of patients equals the functional mode of bed capacity), and re-computed after each transfer, so that the load for a sending hospital will incrementally decrease with each transfer. The goal capacity for receiving hospitals remains at 90%.

Figure 1. Continued.

equipment, ventilators, oxygen supplies, and other important (though potentially more mobile) resources, and we are not able to simulate the equitable distribution of these resources. Indeed, the prominence of travel nursing and other temporary health care workers suggests that staff have been far more mobile than patients during the pandemic, although this has caused instability in the nursing labor market that could have been mitigated by balancing hospital loads.[33]

Second, wide variability among hospitals in ICU admission criteria, which was only exacerbated during surges in the COVID-19 pandemic, made ICU capacity an important but unreliable indicator of hospital burden. Finally, though we chose total bed rather than ICU capacity as the main trigger for patient transfers, our findings were very sensitive to values of the ICU overcapacity multiplier.[34]

Third, our approach of prioritizing transfers of more stable non-ICU patients minimized the overall risk and complexity of transfers (eg, basic rather than advanced ambulance services could be used) but did not confer on the sickest patients the benefit of being transferred to the least burdened hospitals.

Finally, the available bed data suffered from poorly defined reporting of additional surge capacity by hospitals. In some instances, hospitals documented in the lay media to be markedly overcapacity reported open beds in the HHS data, whereas hospitals we knew to have spare capacity reported that they were full. This may have been because some hospitals included new beds in tents, outpatient areas, or rooms converted to double occupancy as part of their capacity, whereas others counted all rooms as single occupancy (citing infection control reasons) and did not include any surge spaces in their accounting. Frequently, hospitals even changed their reporting of total beds from week to week, with a median range (difference between highest and lowest reported weekly beds) of around one-fourth of the median hospital size (Table 1). Indeed, hospitals may have had financial incentives to underreport their bed availability and effectively reserve beds for elective patients. These effects may have resulted in a systematic underestimation of the potential for transfers to help overwhelmed hospitals and their patients. To prevent these distortions in future pandemics, we advocate for more consistent definitions to guide hospital reporting that explicitly incorporate staff availability and objective stratification of patient severity and the quality of surge spaces. Nevertheless, our functional mode technique may have mitigated some of these limitations by measuring the services hospitals were consistently able to provide. Future reporting should also include important daily or even hourly granularity that was not resolvable from our weekly data.

DISCUSSION

Our simulation could serve as a novel tool to help local and national leaders continuously assess the impact of ongoing COVID-19 or other disease surges. Maps of required transfers illustrate which hospitals and areas were most overwhelmed and address weaknesses of existing metrics of COVID-19 pandemic surges. Unlike positive

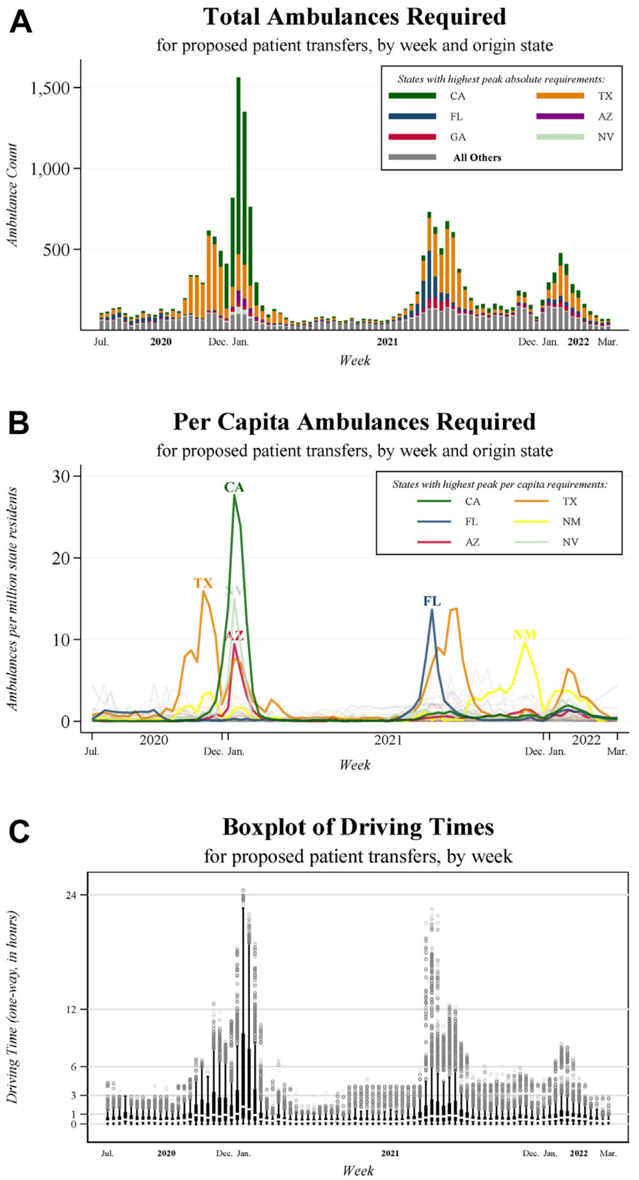

Figure 2. Simulated ambulances required and transport time by week, primary analysis. To relieve all overcapacity hospitals nationally within 7 days, simulated using parameters in the primary analysis and illustrating a sharp increase in requirements during the national surge in early 2021, peaking in January 2021, and again increasing in August 2021 and January 2022. *A*, Ambulances required for all transfers, broken down by the state of the sending hospital. *B*, Ambulances required per million population for each state. *C*, Distribution of 1-way driving times.

COVID-19 test counts and rates, our methods accounted for the clinical severity of the cases and were not affected by differential availability and use of testing.[35] Unlike simple tallies of hospital admissions, we incorporated geography to identify locally overwhelming case clusters alongside relatively nearby hospitals with potentially useful spare capacity. Moreover, unlike reported deaths, which is a trailing indicator[36] that can underestimate true mortality,[37] our method could provide real-time results to guide resources toward and patients away from the most overwhelmed hospitals.

Our results suggest that, at peak, less than 3% of nationwide civilian ambulance units might have been required weekly to rebalance hospital load and relieve overcapacity hospitals through transfers (there are around 58,000 operating civilian ambulances in the 48 states, around 4,000 of which are classed for interhospital transport, and approximately 1,500 operating air ambulances, not considering substantial military assets that are likely to be even more mobile).[38-40] Notably, staffing of ambulances may still pose a challenge, as many of the 250,000 licensed paramedics and 500,000 emergency medical technicians may be inactive. Nevertheless, our simulated transfers would represent a small fraction of all ambulances that are generally used to transport patients from the community to emergency departments (EDs) but would amount to three-fourths of the baseline hospital-to-ED ambulance transports (which are around 20,000 per week).[41] We did not cap the length of transfers, nor did we consider air ambulance assets in our primary analysis, so that maps of transfers would faithfully reflect the full geographic extent of required rebalancing. For political and logistical reasons, including local unavailability of ambulances and staff (who might have to temporarily relocate) and long transfer distances, full relief of all overcapacity hospitals may not be feasible. However, even partial implementation of a few transfers could have substantial benefits at a relatively low cost. Although our primary analysis focuses on ambulance requirements for the first week of en masse transfers, the sensitivity analyses using previously observed posttransfer admission durations suggest that managing ongoing transfer flows may not be prohibitive.[42,43]

In any case, a coordinated health care system that had the ability to transfer patients would no doubt also be able to coordinate out-of-hospital community ambulance destinations to prevent crowding in the first place. The majority of states (Table E1 [available at http://www.annemergmed.com]) already have protocols that recommend load balancing among hospitals before triaging resources away from patients unlikely to survive; our methods could help support a more ideal, coordinated public health system response that, in addition to preventing severe infections altogether, can share resources and responsibilities for patient care before reaching crisis levels.

In conclusion, our results illustrate the true severity of local COVID-19 “spikes” and visually answer the

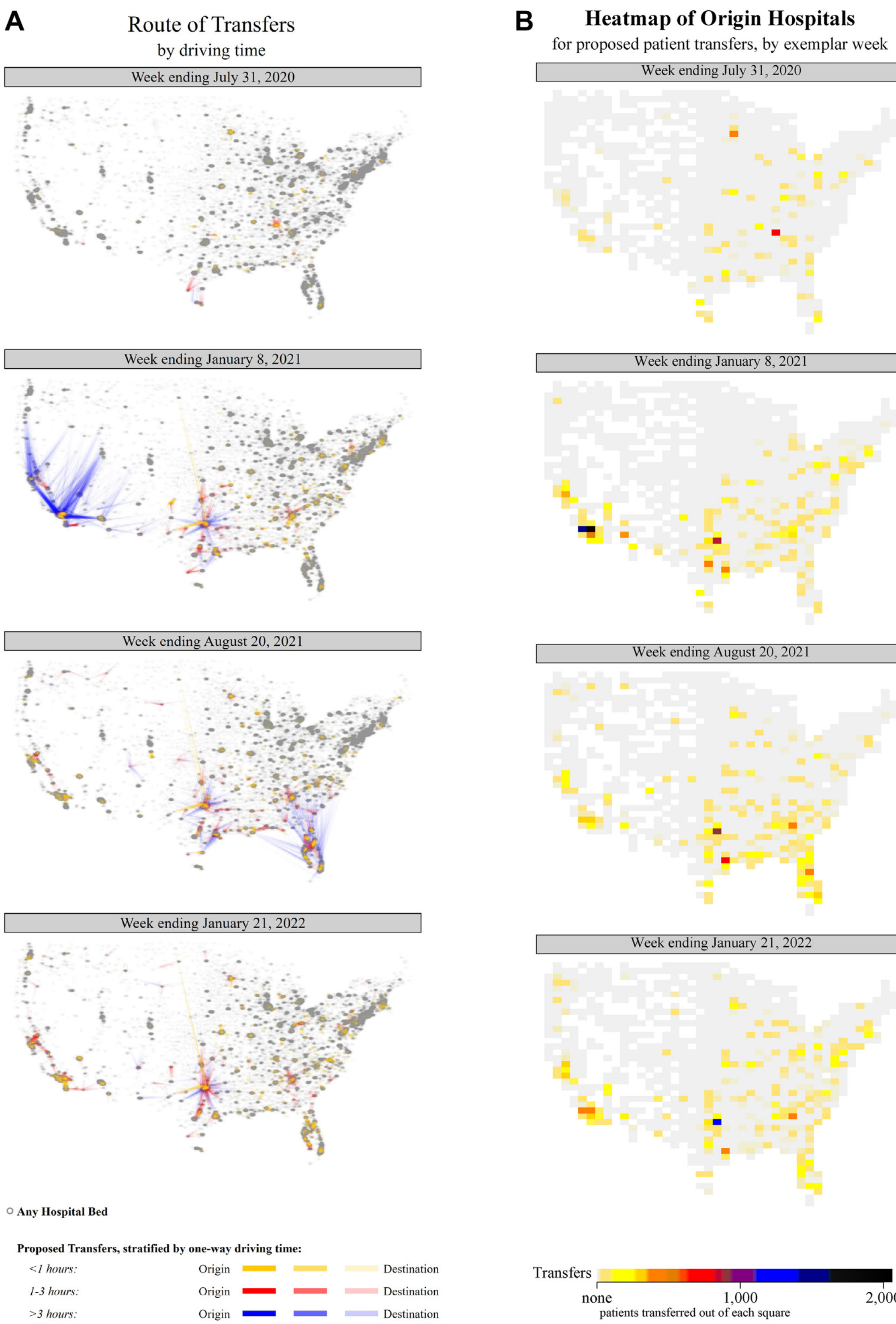

Figure 3. Geography and length of simulated patient transfers for representative weeks. *A*, Geography of simulated transfers with a degree of jitter added to show the density of hospital beds in the (gray) background and relative patient flows in short (less than 1 hour 1-way driving time in yellow), long (1 to 3 hours in red), and very long (more than 3 hours in blue) transfers. *B*, Heatmap of origin hospitals for simulated transfers, weighted by the number of transferred patients, so that each square represents the total number of transferred patients.

Ambulances Required (24h for 7d):	*Individual Patient Transports:*	***Goal Hospital and ICU Load:***	***Ambulance Turnaround Time:***	***Percent of Transfers Still Admitted in Next Week:***	***ICU Over-capacity Multiplier:***
197	6,283	100%	2 hours	None	2x
535	9,416	95%	2 hours	None	2x
1,563[a] (primary analysis)	**15,389**	**90%**	**2 hours**	**None**	**2x**
4,980	25,278	85%	2 hours	None	2x
1,470	15,389	90%	1 hour	None	2x
1,563[a] (primary analysis)	**15,389**	**90%**	**2 hours**	**None**	**2x**
1,745	15,389	90%	4 hours	None	2x
1,563[a] (primary analysis)	**15,389**	**90%**	**2 hours**	**None**	**2x**
1,831	18,731	90%	2 hours	25%[b] (0.5 week LOS[c])	2x
2,507	26,266	90%	2 hours	50%[b] (1 week LOS[c])	2x
3,868	42,303	90%	2 hours	71%[b] (2 week LOS[c])	2x
875	12,283	90%	2 hours	None	1x[d]
1,563[a] (primary analysis)	**15,389**	**90%**	**2 hours**	**None**	**2x**
5,469	27,641	90%	2 hours	None	5x
18,242	50,016	90%	2 hours	None	10x

[a] Alternatively, 291 air ambulances and 515 ground ambulances would be required. These estimates assume air assets are used only for transfers with one-way driving times greater than 12 hours, and these transports would still require at least 6 hours of ambulance time, with 24 hours of air ambulance time need per 12 hours of obviated driving time. In other words, a 12-hour block of ground ambulance

Figure 4. Sensitivity analysis of effect of model assumptions transport resources required to relieve overcapacity hospitals in simulation during the peak week (ending January 8, 2021).

question, "how far away was the nearest open hospital bed?" They also suggest that many crowded hospitals could have been decompressed during pandemic surges through interhospital transfer using a relatively modest number of ambulances. Extensive prepandemic planning and complete cooperation from multiple stakeholders would have been required for en masse transfers, and widely separating patients from community support would have far-reaching impacts on families. That said, existing discussions focused on intrahospital triage of life-saving resources have neglected interhospital transfer as a potentially life-saving intervention, perhaps because of administrative and political hurdles ingrained into the decentralized American health care system. We hope that our results can foster political will for more organized bed reporting and transfer infrastructure, create local incentives to accept patient transfers, and potentially avoid future unnecessary deaths due to crowding.

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Author contributions: KLHI coordinated the study, programmed and performed the primary data analysis, created the figures, and drafted the introduction, methods, and results sections; AMD contributed to the design of the methods, verified the analysis, and drafted the discussion section. MES performed the geospatial analyses and contributed to the design of the methods. DLS conceived and supervised the study and contributed to all portions of the manuscript. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication. KLHI takes responsibility for the paper as a whole.

All authors attest to meeting the four ICMJE.org authorship criteria:(1) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND (2) Drafting the work or revising it critically for important intellectual content; AND (3) Final approval of the version to be published; AND (4) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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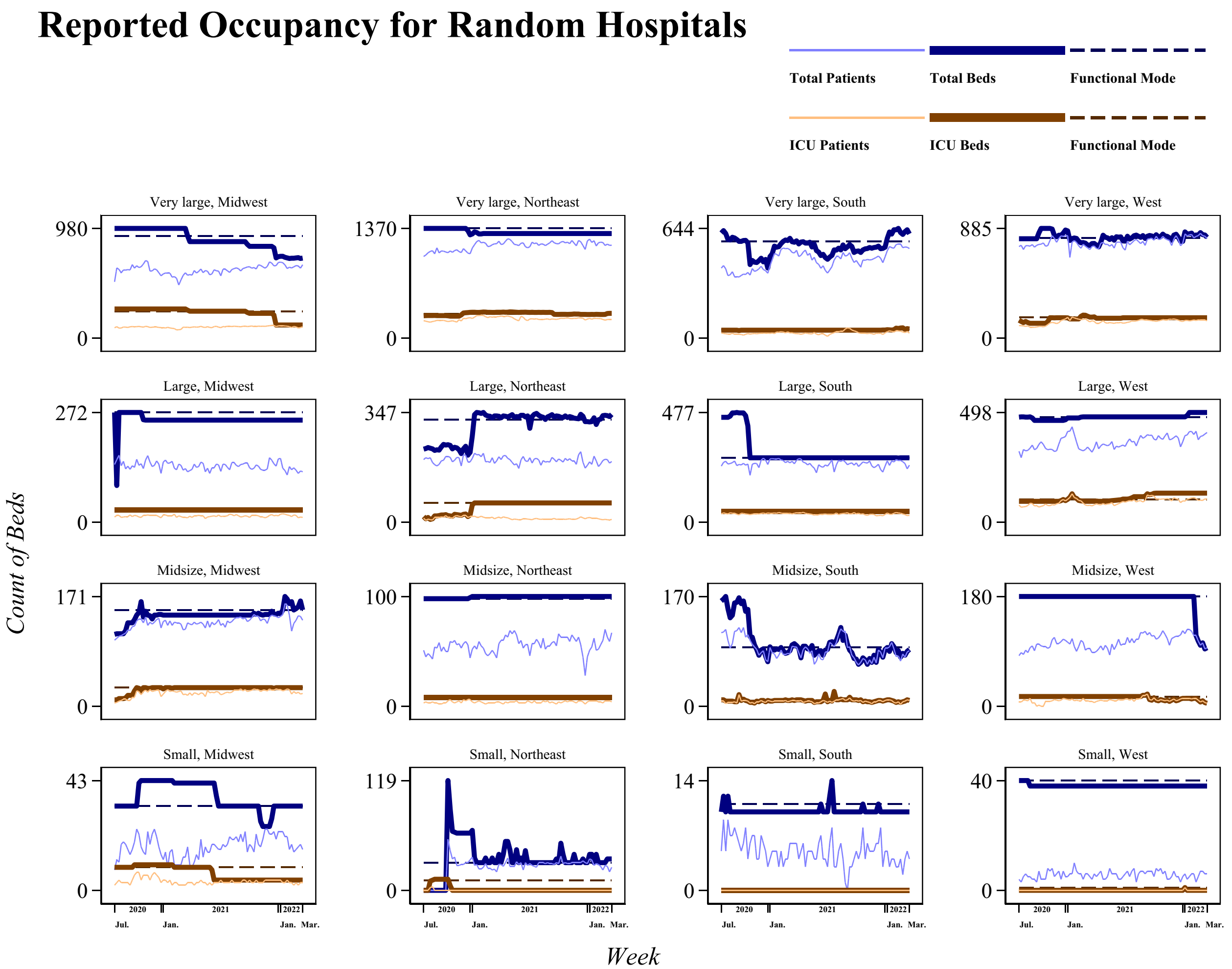

Figure E1. Examples of Reported Hospital Bed and Occupancy Data.Week-by-week hospital loads, from July 31, 2020, to March 18, 2022, annotated with the 10% functional mode of bed capacity used in our algorithm, for random hospitals selected from each region and size stratum. Most hospitals show significant variation, in some cases from week to week, or in others in large blocks; correlations with patient load are inconsistent. In most cases, the functional mode (dashed lines) provides a reasonable approximation of capacity.

Table E1. Crisis standards of care protocols, by state. In total, 47 states and the District of Columbia have published procedures.

State	Most Recent Update	Link
Alabama	02/2020	https://www.adph.org/CEPSecure/assets/alabamacscguidelines2020.pdf
Alaska	04/2020	http://dhss.alaska.gov/dph/Epi/id/SiteAssets/Pages/HumanCoV/SOA_DHSS_CrisisStandardsOfCare.pdf
Arkansas	11/2021	https://www.healthy.arkansas.gov/images/uploads/pdf/ARCOVID-19_Crisis_Standards_of_Care.pdf
Arizona	2020	https://www.azdhs.gov/documents/preparedness/emergency-preparedness/response-plans/azcsc-plan.pdf
California	06/2020	https://www.cdph.ca.gov/Programs/CID/DCDC/CDPH%20Document%20Library/COVID-19/California%20SARS-CoV-2%20Crisis%20Care%20Guidelines%20-June%208%202020.pdf
Colorado	04/2020	https://drive.google.com/file/d/1pH6RF2Wi4h0vTE6Bb5uBUzeTspUZhNhQ/view
Connecticut	10/2020	https://portal.ct.gov/-/media/Departments-and-Agencies/DPH/dph/legal/StandardsofCarefinalpdf.pdf
D.C.	06/2013	https://files.asprtracie.hhs.gov/documents/modified%20delivery%20of%20critical%20care%20services.pdf
Delaware	03/2020	https://www.centerforpublicrep.org/wp-content/uploads/2020/05/DE-CSC-ConOps-FInal-4-29-20.pdf
Florida	03/2018	http://www.floridahealth.gov/programs-and-services/emergency-preparedness-and-response/training-exercise/_documents/mytep-2019-2021.pdf
Georgia	None found	N/A
Hawaii	09/2021	https://health.hawaii.gov/coronavirusdisease2019/files/2021/09/Hawaii-Crisis-Standards-of-Care-Triage-Allocation-Plan-and-FAQs.pdf
Idaho	2020	https://publicdocuments.dhw.idaho.gov/WebLink/DocView.aspx?id=11746&dbid=0&repo=PUBLIC-DOCUMENTS&cr=1
Illinois	06/2020	https://www.dph.illinois.gov/sites/default/files/Guidelines%20on%20Emergency%20Preparedness.pdf
Indiana	04/2014	https://emeraldcoasthcc.org/sites/emeraldcoasthcc.site/files/indiana-crisis-standards-of-care-2014.pdf
Iowa	09/2020	http://publications.iowa.gov/17889/1/panflu_ehtical_guidelines_manual.pdf
Kansas	09/2013	https://www.kdheks.gov/cphp/download/Crisis_Protocols.pdf
Kentucky	03/2020	https://www.kyha.com/assets/docs/COVID19/Update/CrisisStandardsofCareFinal.pdf
Louisiana	09/2011	https://cdn.ymaws.com/www.lhaonline.org/resource/resmgr/imported/Louisiana%20CSOC%20Guidelines%20in%20Disasters.pdf
Maine	06/2015	https://www.maine.gov/dhhs/mecdc/public-health-systems/phep/documents/mainecdcallhazeop.pdf
Maryland	08/2017	http://www.bioethics.net/wp-content/uploads/2020/03/Daugherty-Maryland-framework-PH-emergency-2017.pdf?x41592
Massachusetts	04/2020	https://d279m997dpfwgl.cloudfront.net/wp/2020/04/CSC_April-7_2020.pdf
Michigan	11/2012	http://www.mimedicalethics.org/Documentation/Michigan%20DCH%20Ethical%20Scarce%20Resources%20Guidelines%20v2%20rev%20Nov%202012.0.pdf
Minnesota	05/2020	https://www.health.state.mn.us/communities/ep/surge/crisis/index.html
Mississippi	02/2017	http://www.msdh.state.ms.us/msdhsite/index.cfm/44,7221,122,pdf/CrisisStandardsOfCare2017.pdf
Missouri	04/2020	https://www.mhanet.com/mhaimages/COVID-19/A%20Framework%20for%20Managing%20the%202020%20COVID.pdf
Montana	2020	https://mtha.org/wp-content/uploads/2020/04/Montana-Crisis-Care-Guidance-Final.pdf
Nebraska	05/2021	https://www.unmc.edu/healthsecurity/_documents/NE-Crisis-Protocol.pdf

Table E1. Continued.

State	Most Recent Update	Link
Nevada	04/2020	http://nrhp.org/wp-content/uploads/2020/04/NV-Crisis-Standards-of-Care-COVID-040220.pdf
New Hampshire	04/2020	https://www.dhhs.nh.gov/documents/nh-csc-plan.pdf
New Jersey	04/2020	https://nj.gov/health/legal/covid19/FinalAllocationPolicy4.11.20v2%20.pdf
New Mexico	06/2018	https://www.nmhealth.org/publication/view/plan/4877/
New York	08/2018	https://www.urmc.rochester.edu/MediaLibraries/URMCMedia/flrtc/preparedness-response-tools/documents/HANYS-healthcare_emergency_guidebook_regs.pdf
North Carolina	03/2020	https://nciom.org/wp-content/uploads/2020/04/North-Carolina-Protocol-for-Allocating-Scarce-Inpatient-Critical-Care-Resources-in-a-Pandemic_FINAL-4-6-2020_rev.pdf
North Dakota	01/2015	https://web.archive.org/web/20210509153514/https://www.health.nd.gov/epr/redacted-response-plans/
Ohio	04/2020	https://ohiohospitals.org/OHA/media/OHA-Media/Documents/Patient%20Safety%20and%20Quality/COVID19/Ohio-Guidelines-for-Allocation-of-Scarce-Medical-Resources-CLEAN-FINAL.pdf
Oklahoma	04/2020	https://www.ok.gov/health2/documents/Hospital%20Crisis%20Standards%20of%20Care.pdf
Oregon	06/2018	https://www.oregon.gov/oha/PH/DISEASESCONDITIONS/COMMUNICABLEDISEASE/PREPAREDNESSSURVEILLANCEEPIDEMIOLOGY/Pages/crisis-care.aspx
Pennsylvania	04/2020	https://www.health.pa.gov/topics/Documents/Diseases%20and%20Conditions/COVID-19%20Interim%20Crisis%20Standards%20of%20Care.pdf
Rhode Island	04/2020	https://health.ri.gov/publications/guidelines/crisis-standards-of-care.pdf
South Carolina	09/2009	https://www.scdhec.gov/sites/default/files/Library/CR-009538.pdf
South Dakota	11/2021	https://sdaho.org/wp-content/uploads/2021/12/SD-Crisis-Standards-of-Care-FINAL_120921.pdf
Tennessee	06/2020	https://www.tn.gov/content/dam/tn/health/documents/cedep/ep/Guidance_for_the_Ethical_Allocation_of_Scarce_Resources.pdf
Texas	None found	N/A
Utah	04/2020	https://www.scribd.com/document/455615343/Utah-COVID-19-Crisis-Standards-of-Care-Protocol#from_embed
Vermont	05/2020	https://www.healthvermont.gov/sites/default/files/documents/pdf/Vermont%20CSC%20Plan%2005.18.2020.pdf
Virginia	2020	https://www.vdh.virginia.gov/content/uploads/sites/182/2020/12/Resource-Allocation-under-Crisis-Standards-of-Care-for-COVID-112420-AP-1.pdf
Washington	2020	https://nwhrn.org/wp-content/uploads/2020/03/Scarce_Resource_Management_and_Crisis_Standards_of_Care_Overview_and_Materials-2020-3-16.pdf
West Virginia	12/2020	http://www.wvha.org/getmedia/512c19ea-ef10-448d-af3c-14594edf33d8/A-FRAMEWORK-FOR-MANAGING-THE-2020-COVID19-PANDEMIC-RESPONSE.pdf.aspx
Wisconsin	None found	N/A
Wyoming	06/2019	https://health.wyo.gov/publichealth/ems/hospital-preparedness-program/