Strategies to improve pediatric disaster surge response: Potential mortality reduction and tradeoffs

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Objective: To estimate the potential for disaster mortality reduction with two surge response strategies: 1) control distribution of disaster victims to avoid hospital overcrowding near the scene, and 2) expand capacity by altering standards of care to only "essential" interventions.

Design: Quantitative model of hospital mortality.

Setting: New York City pediatric intensive care unit and non–intensive care unit pediatric hospital capacity and population.

Measurements and Main Results: Mortality was calculated for a hypothetical sudden disaster, of unspecified mechanism, assuming 500 children per million population need hospitalization, including 30% severely ill/injured warranting pediatric intensive care unit care, with high (76%) predisaster hospital occupancy. Triage rules accommodated patients at lower levels of care if capacity was exhausted. Specified higher relative mortality risks were assumed with reduced levels of care. In a pessimistic baseline scenario, hospitals near the disaster scene, considered to have 20% of regional capacity, were overcrowded with 80% of the surge patients. Exhausted capacity at overcrowded hospitals near the scene would account for most of the 45 deaths. Unused capacity would remain at remote facilities. If regional surge distribution were controlled to avoid overcrowding near the scene, then mortality would be reduced by 11%. However, limited pediatric intensive care unit capacity would still require triage of many severe patients to non–intensive care unit care. Instead, if altered standards of care quadrupled pediatric intensive care unit and non–intensive care unit capacity, then mortality would fall 24% below baseline. Strategies 1 and 2 in combination would improve mortality 47% below baseline. If standards of care were altered prematurely, preventable deaths would occur. However, additional simulations varying surge size, patient severity, and predisaster occupancy numbers found that mortality tradeoffs would generally favor altering care for individuals to improve population outcomes within the range of federal planning targets (500 new patients/million population).

Conclusion: Quantitative simulations suggest that response strategies controlling patient distribution and expanding capacity by altering standards of care may lower mortality rates in large disasters. (Crit Care Med 2007; 35:2837–2842)

KEY WORDS: disaster; pediatric intensive care; public health; standards of care; surge capacity; triage

Disasters may overwhelm hospital services (1–4). The imbalance between needs and resources would be exacerbated if uncontrolled overcrowding occurs at facilities near the scene of an emergency (5) or if many children are involved (6). The transition from individual to population-based care in disaster surges is a research priority (7, 8).

One proposed surge response strategy involves controlling the distribution of disaster victims evenly across a region in proportion to hospital capacity (5). Another proposal involves altering standards of care, providing only "essential" interventions, to accommodate larger numbers of patients (2, 9–15). Preliminary analysis suggests that altering standards of care to extend resources would usually meet federal targets for surge capacity (14), but premature alteration of standards would worsen mortality by unnecessary withholding of care.

This quantitative modeling study investigated these two proposed strategies for their potential to improve surge response capability. Estimated mortality in a hypothetical sudden-impact disaster involving children was evaluated for these strategies, alone or in combination, compared with a baseline scenario of uncontrolled patient distribution and normal standards of care. Mortality tradeoffs were analyzed to determine how large a surge of patients would be needed to justify altering standards of care, balancing the population benefit of expanded capacity against the adverse effect of restricting interventions for individuals.

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METHODS

Design. Postdisaster mortality of pediatric hospital inpatients was estimated in quantitative models for response strategies in the New York City region. The analysis was performed in Excel (2004 version, Microsoft, Redmond, WA). Numbers of patients accommodated for care at each level would be dependent on hospital capacity, predisaster occupancy, triage rules, and the response strategy. Numbers of deaths were estimated as a function of patient numbers with each severity and level of care and with the mortality risk for each:

$$\text{Number of deaths} = (\text{number of severe patients} \times \text{mortality risk}) + (\text{number of less severe patients} \times \text{mortality risk}) \quad [1]$$

Mortality risks are dependent on the level of care. Definitions, values, and varying assumptions are detailed below.

No actual patients or interventions were involved in this study of publicly available data. The Institutional Review Board for the

Table 1. Assumptions for all scenarios in Table 2

	Standards of Care		
	Normal, n	Altered, n	No.
Regional maximum capacity			
PICU	108	432	
Non-ICU	1390	5560	
Total	1498	5992	
Patients			
Predisaster inpatients[a]			
Severely ill/injured			75
Less severely ill/injured			895
Total			970
Disaster surge of 500 children/million population			
30% severely ill/injured			240
70% less severely ill/injured			560
Total			800
Patients needing hospital care[b]			
Severely ill/injured			315
Less severely ill/injured			1455
Total			1770

PICU, pediatric intensive care unit; non-ICU, non-intensive care unit.

[a]Predisaster occupancy (76% of peak capacity) − discretionary discharges + non-disaster admissions; [b]predisaster inpatients + disaster victims.

Protection of Human Subjects at SUNY Upstate Medical University considered that the study did not constitute human experimentation.

Capacity at Each Level of Care. Hospital capacity for predisaster inpatients and new disaster victims was expressed as the number of patients who could be accommodated at each level of care. Values for normal capacity were based on historical observations. The five-borough New York City region has a population of 1.6 million children (0–14 yrs) (16) served by 71 hospitals (14). The usual regional peak capacity was 1,498 pediatric hospital inpatients, with 108 in pediatric intensive care units (PICUs) (68/million) and 1,390 in non-ICU care (869/million) (6, 14). Total capacity with altered standards of care was assumed to increase four-fold over the historical peak (Table 1).

Predisaster Inpatients. Predisaster inpatients were defined as:

$$\text{Predisaster inpatients} = \text{baseline occupancy} - \text{discretionary discharges} + \text{daily non-disaster-related unscheduled admissions} \quad [2]$$

Numbers of predisaster inpatients are shown (Tables 1 and 2), assuming high baseline percentage occupancy before the disaster (76% of capacity; historical 95th percentile for New York City, 1996–2002) (6). Outcomes were also estimated for lower baseline occupancy (61% and 48% of capacity; historical mean and fifth percentile, respectively, for New York City, 1996–2002) (6). Baseline occupancy was considered to be the same across ICU and non-ICU areas of all hospitals. It was assumed that baseline occupancy could be decreased by 20% as a result of discretionary discharges and cancelled elective admissions, with no resulting mortality (6, 17, 18). It was also assumed that unscheduled admissions on the day of the disaster, but unrelated to the disaster, were reduced to half the usual number (nine per day for ICU and 50 per day for non-ICU patients) (19, 20).

Disaster Patients. For purposes of this study, patients meeting usual criteria for ICU care were considered to be severely ill/injured, and those meeting usual criteria for non-ICU hospital care were considered to constitute the less severe group of patients. No mechanism of illness/injury was specified. For evaluation of disaster response strategies, federal planning targets of 500 new pediatric inpatients per million population were assumed (4, 9), with 30% severely ill/injured (21–23) (Tables 1 and 2). In exploring the size of disasters necessary to justify altering standards of care, a range of smaller surges and smaller proportions of severe children were also considered.

Numbers of Patients at Each Level of Care: Triage Rules. The following triage rules were postulated. Severe patients would receive care in PICUs until capacity was exhausted, and then they would be triaged to receive non-ICU hospital care in preference over the less severe patients. Less severe patients would receive hospital care until hospital capacity was exhausted, and then they would be excluded from care. It was assumed that predisaster inpatients and hospitalized disaster victims were triaged without distinction. Any decisions to withhold care from "hopelessly" ill/injured patients would have been made before the activity modeled in this study.

Thus, numbers of patients receiving care at ICU or non-ICU levels would be the sum of predisaster inpatients and new disaster patients at each level, up to peak capacity (normal or expanded). After exhausting capacity, additional patients would be excluded from care.

Baseline Disaster Scenario and Surge Response Strategies. A hypothetical sudden-impact event of unspecified mechanism was considered. An all-hazards approach to disaster response planning may gain the most generalizable insights (2, 9, 11). A pessimistic baseline scenario assumed that uncontrolled distribution of patients resulted in crowding at hospitals near the disaster scene. Quantitative assumptions about patient distribution are arbitrary but consistent in concept with historical observations (5). Hospitals near the disaster scene, with only 20% of the regional pediatric capacity, would serve 80% of the surge patients. Those remote from the disaster, with 80% of the regional pediatric capacity, would serve the remaining 20% of the disaster patients. Neither individual hospitals nor the location of the hypothetical disaster was specified. Hospital activity and outcomes were considered as aggregates for all nearby and remote hospitals. In the baseline scenario, normal standards of care would be attempted. Thus, hospital capacity would be the same as under normal circumstances.

In strategy 1, patients would be evenly distributed according to hospital capacity (5), implying an intact transport system and appropriate emergency medical service controls. As a result, resources throughout the region would be used, minimizing unused capacity at remote locations. In strategy 2, standards of care would be altered to accommodate four times the usual capacity by providing only essential interventions (2, 9–13, 15). If strategies 1 and 2 were implemented in combination, a larger number of patients could be accommodated for essential care at the appropriate ICU or non-ICU level.

Mortality Estimates. To calculate numbers of hospital deaths, it was assumed that the mortality risk for the severe children receiving normal care in a PICU equaled the national PICU mortality rate of 2.9% (19). No published mortality risk is available for less severe children receiving normal non-ICU hospital care. Therefore, a 0.19% mortality risk was estimated (Appendix 1). Historical reports of mortality rates for hospitalized disaster trauma victims receiving normal standards of care are generally well below 10% (21, 23). It was assumed that predisaster inpatients and hospitalized disaster victims had the same mortality risks for each severity and corresponding level of care. Calculated fractional numbers of deaths were rounded off to the nearest whole number. In some cases (Table 2), sums are in error by one patient as a result of rounding off.

Altered standards of care with interventions limited to essential measures would increase mortality risk for each patient, even as

Table 2. Scenarios: Baseline and strategies for disaster response

	No. of Patients			No. of Patients and Deaths at Each Level of Care						
				ICU		Non-ICU		Excluded		
	Predisaster	Surge	Total	Pts	Deaths	Pts	Deaths	Pts	Deaths	Total Deaths
a) Baseline scenario: Uncontrolled uneven distribution of surge, receiving normal standards of care										
Hospitals near disaster scene (20% of capacity = 22 PICU, 278 non-PICU beds; 20% of predisaster patients; 80% of surge)										
Severe	15	192	208	22	1	186	27	0	0	28
Less severe	179	448	627	NA	NA	92	0	535	10	10
Hospitals remote from disaster scene (80% of capacity = 86 PICU, 1112 non-ICU beds; 80% of predisaster patients; 20% of surge)										
Severe	60	48	108	86	2	21	3	0	0	5
Less severe	716	112	828	NA	NA	828	2	0	0	2
Total deaths all hospitals										45
b) Strategy 1: Controlled, even distribution of surge, receiving normal standards of care										
Hospitals near disaster scene (20% of capacity = 22 PICU, 278 non-PICU beds; 20% of predisaster patients; 20% of surge)										
Severe	15	48	63	22	1	41	6	0	0	7
Less severe	179	112	291	NA	NA	237	0	54	1	1
Hospitals remote from disaster scene (80% of capacity = 86 PICU, 1112 non-ICU beds; 80% of predisaster patients; 80% of surge)										
Severe	60	192	252	86	2	166	24	0	0	26
Less severe	716	448	1164	NA	NA	946	2	218	4	6
Total deaths all hospitals										40
Mortality reduction below baseline										11%
c) Strategy 2: Uncontrolled, uneven distribution of surge, receiving altered standards of care										
Hospitals near disaster scene (20% of capacity = 88 PICU, 1112 non-PICU beds; 20% of predisaster patients; 80% of surge)										
Severe	15	192	208	88	5	120	18	0	0	23
Less severe	179	448	627	NA	NA	627	2	0	0	2
Hospitals remote from disaster scene (80% of capacity = 344 PICU, 4448 non-ICU beds; 80% of predisaster patients; 20% of surge)										
Severe	60	48	108	108	6	0	0	0	0	6
Less severe	716	112	828	NA	NA	828	3	0	0	3
Total deaths all hospitals										34
Mortality reduction below baseline										24%
d) Combined strategies 1 and 2: Controlled even distribution of surge, receiving altered standards of care										
Hospitals near disaster scene (20% of capacity = 88 PICU, 1112 non-PICU beds; 20% of predisaster patients; 20% of surge)										
Severe	15	48	63	63	4	0	0	0	0	4
Less severe	179	112	291	NA	NA	291	1	0	0	1
Hospitals remote from disaster scene (80% of capacity = 344 PICU, 4448 non-ICU beds; 80% of predisaster patients; 80% of surge)										
Severe	60	192	252	252	14	0	0	0	0	14
Less severe	716	448	1164	NA	NA	1164	5	0	0	5
Total deaths all hospitals										24
Mortality reduction below baseline										47%

ICU, intensive care unit; Pts, patients; PICU, pediatric intensive care unit; NA, not applicable.

larger capacity reduces overall numbers of deaths. However, no evidence is available regarding the increased risk for individuals. In addition, no evidence is available regarding the mortality consequences of triage decisions to reduce patients' level of care from ICU to hospital care, or to completely exclude patients from care when capacity is exhausted. For purposes of modeling the mortality consequences of proposed disaster response strategies, the following assumptions were made.

If severe children received only altered standards of PICU care, limited to essential interventions, it was assumed that mortality risk would increase modestly (doubling to 5.8%); if severe patients were triaged to non-ICU hospital care, mortality risk would be substantially higher (five-fold increase to 14.5%); if severe patients were excluded from any hospital care, mortality risk would be much greater still (ten-fold increase to 29%). Likewise, if less severe children received altered standards of non-ICU hospital care limited to essential interventions, it is assumed that mortality risk would modestly increase (doubling to 0.38%); if excluded from care, mortality risk would be much higher (ten-fold increase to 1.9%).

For these assumptions that are unsupported by evidence, sensitivity analyses were performed to evaluate the effect of varying the assumed relative mortality risks on calculated numbers of deaths. Relative mortality risks for severe and less severe patients as assumed above are: normal care/altered standards of essential care/ICU triaged to non-ICU care/exclusion from care = 1/2/5/10–fold increases. In the sensitivity analysis, other sets of assumed relative mortality risks were considered, including a set with a "lower risk range" (1/1.5/3.75/7.5–fold increases) and a set with a "higher risk range" (1/4/10/20–fold increases), each having the same ratio of increased risk at successively reduced levels of care. A third alternative set of assumptions was considered, having a "narrower risk range" with high risk for altered care compared with normal care, but only slightly worse risk for triage from ICU to the non-ICU setting, or exclusion from care (1/4/5/7.5–fold increases).

RESULTS

Baseline Scenario: Uncontrolled Distribution, Normal Standards of Care. Table 1 summarizes patient numbers and capacity in each location, at each level of care. A total of 45 deaths would occur in this scenario (mortality rate of 11% among severe patients and <1% among less severe patients) (Table 2a). At overcrowded hospitals near the disaster, numbers of severe patients would greatly exceed PICU capacity, with 186 of 208 severe patients triaged to non-ICU hospital care, accounting for most of the 45 deaths. At remote hospitals, ICU capacity would almost accommodate severe patients. Among less severe children, 535 at hospitals near the disaster would be excluded from any care, with 10 deaths resulting in the excluded group. None of the less severe patients would be excluded from care in the remote hospitals, where there would be a large unused capacity.

Strategy 1: Control the Regional Distribution of Patients Evenly in Proportion to Hospital Capacity. If all variables were the same as in the baseline scenario, but controls prevented overcrowding near the disaster, then a small reduction in mortality to 40 deaths would be achieved, 11% below baseline (mortality rate of 11% among severe patients and <1% among less severe patients) (Table 2b). Despite using the entire normal regional PICU capacity, only approximately one third of severe children could be accommodated for ICU care. Severe patients triaged to non-ICU hospital care would still account for most of the deaths. However, the more even distribution of less severe patients would result in fewer being excluded from care, accounting for a small reduction in mortality.

Strategy 2: Altered Standards of Care to Quadruple Capacity. In this scenario, it was assumed that patients were distributed unevenly, with all variables as in the baseline scenario, but standards of care were altered so that capacity would expand four-fold (Table 1). A substantial increase in patients receiving essential ICU care would reduce total deaths to 34, a 24% reduction below baseline (mortality rate of 9% among severe patients and <1% among less severe patients) (Table 2c). However, at overcrowded hospitals near the disaster scene, ICU capacity would still be exhausted, despite altering standards.

Strategies 1 and 2 Combined: Controlled Patient Distribution and Altered Standards of Care. Combining both strategies to control patient distribution and alter standards of care would reduce mortality by 47% below the baseline scenario to only 24 deaths (mortality rate of 5% among severe patients and <1% among less severe patients) (Table 2d). With the combination of strategies 1 and 2, no patients would be excluded from care or even triaged to a lower level of care, although care of all patients would be limited to essential interventions.

Sensitivity Analysis for Relative Mortality Assumptions. Sensitivity analyses were performed to evaluate the effect of varying the assumed relative mortality risks (Table 3). For a set of lower and higher ranges of relative mortality risks, each having the same ratios of increased risk at successively reduced levels of care, mortality improvement would be similar to the original estimates detailed above. For a set of mortality risks having a narrower ratio among the relative risks, the adverse effect of altering levels of care on individual mortality would outweigh expanded capacity, worsening mortality outcomes.

Mortality Tradeoffs Between Individual and Population-Based Care. Surge size was varied to determine how many disaster patients would be necessary for expanded capacity to balance the adverse effect of limiting care to essential interventions. It was assumed that strategy 1 was already implemented (there is no disadvantage of controlling distribution of patients at any size surge). With small surges, altering standards of care would worsen the overall mortality rate (Fig. 1). Tradeoffs between worse outcome for individuals with altered care would only be balanced by better outcome associated with expanded capacity if the number of disaster victims exceeded 192/million. As seen in Figure 1, the slope of increasing mortality with normal standards of care becomes steeper at surges exceeding 100/million because ICU capacity becomes exhausted. With altered standards of care, all those requiring essential ICU interventions would be accommodated. A variety of other scenarios were explored in which predisaster occupancy varied from low levels of 48%, average levels of 61%, to high levels of 76% and in which the proportion of severely ill/injured patients varied from 5%, to 15%, to 30%. The size of disaster surge for which mortality reductions would justify altered standards of care is shown in Table 4 for each scenario. If ≥15% of the hospitalized disaster victims were severe, alteration of care to extend capacity would improve hospital survival within the range of surge planning targets of 500/million.

DISCUSSION

Quantitative modeling of the hospital system in New York City shows that two strategies to manage regional surge responses in disasters both have the potential to reduce mortality. The benefit would be greater if both approaches are used in combination.

Controlling even distribution of patients would improve survival by taking advantage of all existing resources. To optimize distribution, it would be useful to determine in advance what proportion of a disaster surge could be accommodated at each hospital (5). Controlling patient distribution implies that timely information on moment-by-moment hospital capacity can be obtained (24), that decision makers have authority to act on this information, and that transportation throughout the region is possible (5).

Table 3. Sensitivity analysis: Effect of variation in assumptions about relative mortality risks on percentage of mortality reduction[a]

Response Strategy[b]	Starting Assumptions on Relative Mortality, %[c]	Lower Relative Range, %	Higher Relative Range, %	Narrower Relative Range, %
Strategy 1	−11	−14	−13	−7
Strategy 2	−24	−28	−21	+21
Strategies 1 and 2 combined	−47	−50	−44	+14

[a]Mortality improvement (negative percentages) or worsening (positive percentages) relative to baseline scenario with varying relative mortality risk (see text for definitions of relative mortality ranges); [b]strategy 1 controls even regional distribution of disaster surge, and strategy 2 extends care by altering standards of care; [c]starting assumptions on relative mortality are defined in Table 2.

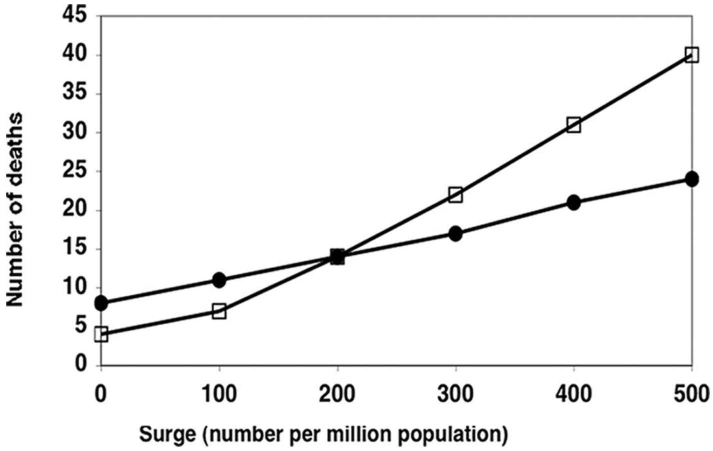

Figure 1. Calculated numbers of deaths in a hypothetical disaster involving varying surges of patients needing hospital care (in number per million of regional population). Outcome was compared for normal standards of care (*squares*) vs. altered standards of care (*circles*). In each case, the hypothetical event involved 30% of disaster victims having severe illness/injury warranting intensive care, even distribution of disaster victims to regional hospitals (consistent with strategy 1), and predisaster hospital occupancy at 76% of peak capacity. The results correspond to scenarios detailed in Table 2, panels b and d, in which a surge of 500/million was specified.

Table 4. No. of surge patients above which altering standards of care would improve mortality assuming even regional distribution of surge patients

Predisaster Occupancy (% of Peak Capacity)	Percentage of Surge Patients with Severe Illness/Injury, %	Size Surge Justifying Altered Standards of Care (No. of Patients per Million Population)
High (76%)		
	5	533
	15	359
	30	192
Average (61%)		
	5	646
	15	434
	30	213
Low (48%)		
	5	764
	15	499
	30	231

Federal agencies and professional organizations have suggested general approaches to accommodate larger numbers of patients by altering standards of care. Proposed measures include templates for standing orders to standardize treatment, simplifying the medical record, increased reliance on clinical judgment with less radiographic or lab testing, reuse of some disposable supplies, and reduction of privacy and confidentiality (2, 9–13). A consensus panel of physicians and nurses (15) has suggested that essential interventions in quadrupling ICU capacity should include mechanical ventilation, vascular volume resuscitation, and multiple intravenous medications, but might not include vasoactive drug infusions, invasive hemodynamic or intracranial pressure monitoring, or dialysis. Essential non-ICU hospital interventions would include oxygen, intravenous hydration, and scheduled medications.

This quantitative modeling study was based on historical evidence and plausible assumptions. Analysis of simulations is necessary to understand system behavior in rare or unprecedented events. Simulation of system responses in New York City may reasonably represent response capabilities in other large metropolitan areas. PICU capacity, a major determinant of surge response capability, in the New York City region is similar to the national average of 65/million children (for populations 0–14 yrs old) (19, 25). Distinct issues might be encountered in rural, suburban, or smaller urban settings. It is possible to imagine worse outcomes if hospitals were disrupted in a disorderly environment or if hospitals became inaccessible. To provide insight about a wide range of hypothetical situations, no particular disaster mechanism was modeled in this study. Certain conditions would have disorder-specific implications for clinical management and outcome. Pandemics evolving over a long period of time raise logistic complexity beyond the scope of this study.

Most assumptions used in the study were evidence-based. No published observations are available to estimate increased relative mortality risks associated with essential care or reductions in level of care. A sensitivity analysis shows how varying these assumptions would affect outcome. If the increased relative risk of altering standards to essential care are substantially smaller than added risks of triage to a lower level of care, then regardless of exact assumptions, altered essential care generally would be beneficial for large surges. On the other hand, if the increased risk of altering to essential care is large compared with small additional risks in triage from ICU to non-ICU care, or exclusion from care, then altering to essential care might worsen mortality for any surge size. Thus, the reported results are not intended to recommend particular response strategies. Rather, the results should heighten awareness that choice of disaster management strategies may have a substantial effect on mortality within the range of surge planning targets. Future planning will benefit from better evidence obtained in actual disaster responses. Data unique to each region would improve the application of quantitative models for planning purposes.

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APPENDIX 1

Appendix: Non–Intensive Care Unit Hospital Mortality Risk. Because no published data are available, the following method was used to estimate usual non–intensive care unit (ICU) hospital mortality risk with normal care. Published data provide the annual number of patients per pediatric ICU (PICU) bed (60/bed/year) (19), mortality risk (2.9%) (19), and the number of PICU beds in New York City (108 PICU beds) (14).

Thus, it is estimated that 60 patients/PICU bed/year × 108 PICU beds × 2.9% mortality risk = 188 annual PICU deaths occurred in New York City. If the total annual number of hospital deaths of children in New York City in one recent year was 320 (26), then 320 − 188 = 132 deaths are assumed to have occurred in the non-ICU hospital setting. A total of 75,815 children (0–14 yrs) were hospitalized annually in New York City (20). Of these, 60/PICU bed/year × 108 PICU beds = 6,480 were assumed to have been PICU admissions, based on the above data. Thus, 75,815 − 6,480 = 69,335 children were hospitalized in the non-ICU hospital setting. Therefore, 132 non-ICU deaths/69,335 non-ICU patients = 0.19% mortality risk.