Combined external and internal hospital disaster: Impact and response in a Houston trauma center intensive care unit*

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Objective: To increase awareness of specific risks to healthcare systems during a natural or civil disaster. We describe the catastrophic disruption of essential services and the point-by-point response to the crisis in a major medical center.

Design: Case report, review of the literature, and discussion.

Setting: A 28-bed intensive care unit in a level I trauma center in the largest medical center in the world.

Case: In June 2001, tropical storm Allison caused >3 feet of rainfall and catastrophic flooding in Houston, TX. Memorial Hermann Hospital, one of only two level I trauma centers in the community, lost electrical power, communications systems, running water, and internal transportation. All essential hospital services were rendered nonfunctional. Life-saving equipment such as ventilators, infusion pumps, and monitors became useless. Patients were triaged to other medical facilities based on acuity using ground and air ambulances. No patients died as result of the internal disaster.

Conclusion: Adequate training, teamwork, communication, coordination with other healthcare professionals, and strong leadership are essential during a crisis. Electricity is vital when delivering care in today's healthcare system, which depends on advanced technology. It is imperative that hospitals take the necessary measures to preserve electrical power at all times. Hospitals should have battery-operated internal and external communication systems readily available in the event of a widespread disaster and communication outage. Critical services such as pharmacy, laboratories, blood bank, and central supply rooms should be located at sites more secure than the ground floors, and these services should be prepared for more extensive performances. Contingency plans to maintain protected water supplies and available emergency kits with batteries, flashlights, two-way radios, and a nonelectronic emergency system for patient identification are also very important. Rapid adaptation to unexpected adverse conditions is critical to the successful implementation of any disaster plan. (Crit Care Med 2004; 32:686–690)

KEY WORDS: disaster; flood; intensive care; power failure; communications; patient safety; mass casualty

The disruption of hospital systems during a city-wide crisis that produces mass casualties can quickly overwhelm hospital emergency resources and hinder the provision of both basic and sophisticated medical care, such as that provided in the intensive care unit (ICU). Events that precipitate such an internal crisis include natural disasters, such as floods or earthquakes, and human acts, such as enemy attack during wartime. These could result in widespread loss of vital systems, including electricity; communications systems; critical services, such as pharmacy, laboratories, and blood bank; ventilation and monitoring systems; water; and evacuation systems.

Little has been published about internal disasters of medical institutions and how to cope with them, and very few case reports exist that address this aspect of disaster medicine (1–2). A few reports have addressed internal disasters caused by fire, earthquakes, flooding, lack of water supply, and short-lived power failures (3–6); only a very small number of articles have addressed the aftermath lessons (7–8). This report highlights the responses and systematically reviews these responses to help clinicians in future similar conditions.

We report the effects of a catastrophic, city-wide flood on Memorial Hermann Hospital (MHH), a major healthcare institution in Houston, TX. We describe MHH's response to this crisis, focusing on the neuroscience/trauma ICU (NTICU) and describe key points to be addressed by hospitals in meeting the challenge of such devastating internal disasters.

CASE REPORTS

In June 2001, tropical storm Allison emerged from the Gulf of Mexico and caused massive precipitation in and around Houston, TX, the fourth largest city in the United States (population, >4,000,000). More than 12 inches of rain fell from June 5 to June 7, and additional rainfall overnight surpassed 38 inches of rain by June 8. This resulted in the most damaging urban flood in an American city to date (9), causing among other disasters a major disruption in the medical services of the entire community.

By the early morning of June 9, >40 million gallons of water had inundated the MHH basements, rushing through the tunnel system that connects multiple different institutions in the Texas Medical Center (TMC; the largest medical center in the world) and rushing from adjacent streets, in which floodwater had risen to >5 feet.

The hospital's main and emergency generators, which were on the second floor, paging system, and communica-

*See also p. 884.

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tions systems (internal and external telephones and some wireless telephone systems) failed. The hospital became incommunicado and isolated; no personnel could come or leave, and many could not be reached. The plumbing system stopped functioning, and no fresh running water for basic hygiene was available. The elevators and escalators in the hospital's five buildings, which ranged from six to 12 stories, including penthouses for equipment, stopped functioning. None of the hospital's 570 patients could be immediately transferred.

By shortly after 3:00 am, the NTICU had no electricity, ICU monitoring capability, electrical mechanical ventilators, suction, computers, laboratories, local pharmacy (the Pyxis medication system was locked), medication-infusion pumps, or functional internal-tube transport system for drugs. All supplies outside the NTICU (medications and equipment) were floors away, through complex, dark corridors and stairs.

Emergency contingency plans were implemented. The house officer and nurse in charge established immediate communication with the medical and nursing directors by using personal wireless phones, as did hospital administrators with one another. At the time of the power outage, seven of the 17 patients in the NTICU were undergoing mechanical ventilation; two were on pressure-controlled ventilation requiring both high peak end-expiratory pressure and peak inspiratory pressure, three were on synchronized intermittent mechanical ventilation, and two were on pressure support ventilation. Ventilators were run using batteries until the batteries were depleted, at which time the seven patients were switched to pneumatic devices to maintain ventilation. Manual ventilation, complicated by the lack of wall suction, was used during the transition and was the only means to provide continued, adequate oxygenation in one patient. Staff took turns operating the manual ventilators, using 60-mL syringes for suctioning; manual drip calculations sustained vital intravenous infusions. Two transport monitors were used to check vital signs and electrical cardiac activity hourly until all batteries were depleted.

The central pharmacy, main laboratory, blood bank, central supply, radiology department, kitchen, and other services were evacuated and nonfunctional owing to rising flood waters. Although the Pyxis medication system was reopened, only critical medicines were provided. The medical director (physician on call) made rounds to simplify management.

During the next several hours, staff and volunteers were able to arrive at MHH (some by helicopter). Many brought flashlights, cellular phones, two-way battery-operated radios, food, and water.

Medical personnel in-house were reorganized to create a command center in the emergency department for the systematic diagnosis and management of cases and problems.

Initially, patients were triaged and those who required essential services were evacuated to other hospitals; when the extent of the internal disaster was realized, however, the chief executive officer and hospital medical director ordered the transfer of all in-house patients. The NTICU patients were evaluated and prioritized by the attending physician in the ICU and the neurosurgeons who were contacted at home. Vertical evacuation required that patients be carried out on backboards down four flights of stairs to the hospital's general transfer holding area. Patients were then triaged again and transferred by ambulance or helicopter, depending on their conditions or destinations. All in-house patients were transferred to other hospitals or discharged home within 30 hrs, and no deaths occurred as result of the evacuation.

The magnitude of the disaster was reflected by the human and economic toll. By the end of June 9, the storm had left >3 feet of rain (38.78 inches in some areas of the city), breaking records (most rain in 1 hr, 6.3 inches; most rain in 6 hrs, 21.5 inches) in the flood history of the city and the United States. In addition to the TMC, university campuses, downtown, 50,000 houses, and 70,000–100,000 vehicles were also flooded. The human and economic cost of the flood included 22 deaths (17 persons drowned, including one in an elevator, three were electrocuted, and two died during nursing home evacuations), 33,000 families requiring government assistance for temporary housing, and ≥$5 billion in damages. The structural and scientific cost in the TMC reached $2 billion, with losses by the University of Texas Health Science Center and MHH totaling $205 million and $430 million, respectively.

MHH was closed for 38 days but continued to serve the community through Memorial Hermann Healthcare System Hospitals throughout the city.

DISCUSSION

MHH effectively responded to the internal disaster owing to preparedness training, the ability to establish communication and coordination among healthcare professionals, back-up battery power for some communications systems and for ventilation systems, the successful evacuation of patients, the vast medical resources of the city, and the help of many volunteers.

Hospital preparedness for external and internal disasters is not a requirement in many developed countries; in a recent survey, Kai et al. (10) reported an alarming lack of contingency plans for external disasters in the city of Osaka, Japan. In the United States, however, the Joint Commission for the Accreditation of Healthcare Organizations requires that all hospitals prepare contingency plans for the possible scenarios in the event of systems failures such as those that occurred at MHH. MHH's preparedness, the vast medical resources of the city, and the training of the TMC personnel explain the exceptional response seen in this example. Nevertheless, medical services in the city were severely affected during the period that MHH and other major hospitals in the TMC were closed; with 30% of the beds in the TMC (25% of them ICU beds) and the largest of the only two trauma centers in town out of service, the rest of the hospitals in the area were overwhelmed despite the assistance of the medical and nursing personnel displaced because of hospital closures. The storm had flooded an area not considered at risk for the next 200 yrs.

In the weeks that followed the flooding, the Joint Commission for the Accreditation of Healthcare Organizations and several other government agencies were involved in evaluating the response to the crisis (11); they found no deficits in MHH's management of the disaster, and the National Committee for Quality Health Care later honored the Memorial Hermann Healthcare System for its performance during and after the flood.

Loss of electricity was the most significant challenge because it affected so many aspects of patients care. Numerous scenarios involving loss of electricity that were explored before the new millennium

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included hospital disasters (12). In a recent article, Wilson (13) described how an electromagnetic bomb could knock out electricity, disabling computers and telecommunications and destroying the foundation of modern society. We found no reports of hospitals with prolonged electrical outages of the magnitude experienced by MHH, but some cases describe the consequences of short power failures in hospitals or ICUs (7, 14–19). Outcomes are unpredictable, and deaths have been reported despite preparedness for power failures (8).

Mitchell (14) summarized the main problems caused by a hospital-wide power failure in an 18-bed adult ICU as follows: increased staffing needs, communication failure, electrically powered ventilator failure, electrical failure, and loss of ambient temperature regulation. In the early 1990s, O'Hara and Higgins (15) reported a 45-min power outage at the Cleveland Clinic Foundation, and Aghababian et al. (7) reported a 7-min power outage at the University of Massachusetts Medical Center. The most important problems they identified were the need for a 2:1 staffing ratio, lack of communication leading to potential panic, lack of lighting, and failure of critical care equipment (7). One solution recommended has been the use of an uninterruptible power supply or UPS (12, 16, 18, 20), a standard in ICUs today that is followed by very few in some places (12). Although MHH is equipped with a UPS, this system is time- and power-limited and provided no benefit in our case.

The loss of ventilation systems in our case caused a second emergent situation. Such a scenario is especially relevant in light of current world events, which stress that not only natural disasters but also unanticipated mass-casualty events may precipitate the need for large-scale patient ventilation. A multiple respirator system option has been considered not only by physicians exposed to civilian warfare and its effects (21, 22) but also by American physicians (23). Other alternatives to the sophisticated design of multiple respirator systems and mushroom valves are disposable respirators. One example of the latter, the VORTRAN Automatic Resuscitator (Vortran Medical Technology, Sacramento, CA), is a disposable automatic respirator that provides ventilatory support via a mask or endotracheal tube; it is an excellent alternative to hand ventilation but requires a continuous flow of gas, which can be from a wall source or a gas cylinder (24). Other, less viable alternatives among this type of ventilators are more expensive and require manual triggering; moreover, some oxygen regulators have recently been voluntarily recalled because of the risk of fire (25). In 1999, a survey of 17 ICUs in northeastern of England showed that, among the 16 respondents, seven planned to rely on only manual ventilation in case of total electrical failure; the other nine planned to use gas-driven ventilators, or a combination of these and self-reflating bags for hand ventilation (they stocked the Ambu-bags with oxygen cylinders at bedside). Norcross et al. (5) reported that staff in their ICUs (surgical, neurosurgery, burns, and cardiothoracic) hand-ventilated patients for 4 hrs during the total failure of electrical systems resulting from a hurricane.

The pneumatic ventilators were effective in our case, but the loss of medical gases could have been lethal for oxygen-dependent patients. A series of different ventilator strategies to respond to various threats is probably the best approach. Emergency kits are also important and should include flashlights and batteries for the equipment. Battery-operated suction devices and large syringes for suction should be available at all times.

The interruption of external and internal communications seriously threatens any disaster plan and is in itself a disaster. In our case, the personal mobile phones of medical personnel on call became the primary mode of external communication, and messengers on foot maintained internal communication between departments. Walkie-talkies were of limited use owing to the size of the institution. A limited number of operational cellular phones were used to maintain external communication while batteries lasted; a private company that was able to maintain services during the disaster lent new cellular telephones during the evacuation.

In contrast, the experiences of some hospitals in California have led to the development of very well-organized emergency communications system known as Hospital Disaster Support Communication System (HDSCS) in their region (26), and there are other examples at sea (27). The HDSCS is a group of 90 amateur radio operators who provide volunteer backup to 35 institutions in case of internal or external communications failure for any reason in Orange County, CA (28). Since 1980, HDSCS has been involved in 73 communications emergencies, 22% of them serious (e.g., earthquakes, firestorms, floods).

Patient evacuation is key in the event of a major internal disaster. The use of helicopters to transport trauma patients is controversial and may be harmful under certain circumstances (29–32). In our case, however, MHH's three trauma-center helicopters (Hermann Life Flight) (33), the Texas National Army Reserve Black Hawk helicopters, and the Coast Guard helicopters were vital in patient evacuation because the roadways between many hospitals were impassable. Also aiding in the evacuation of patients was the decision to use the emergency department as a command center to which patients were vertically evacuated from multiple units, triaged, and then transferred to outside facilities or discharged home.

Another problem to address during this type of crisis is the lack of documentation. A manual casualty-logging system is essential for documenting patients' transfers with the lack of computers and electronic medical records, as is a manual system for tracking and recovering equipment. It is also useful for patient follow-up as in our case, because the patients were transferred to several institutions.

On the basis of our experience, we believe the following are essential in addressing the most important factors in the solution of internal disasters of this magnitude:

1. Coordination of human response. Crisis training that includes such elements as communication, coordination with other healthcare professionals, and strong leadership is essential during a crisis. Also, the human response from the community was a decisive factor in

our evacuation. Without the help of hundreds of volunteers, it would have been impossible to carry hundreds of patients down the stairs of the hospital in darkness. The community should be invited to participate in disaster planning.

2. Electricity. Electrical power is vital in today's healthcare system, which depends on advanced technology. To prevent widespread internal electrical loss, it is imperative that hospitals take the necessary measures to preserve electrical power at all times.
3. Communications. Hospitals should have battery-operated internal and external communication systems readily available in the event of a communication outage. Cellular telephones are useful but may be limited by weather conditions and battery life. A regionalized communications center and network should be considered (34). The HDSCS seems to address these problems and may be a good model for benchmark.
4. Protection of essential services. Critical services such as pharmacy, laboratories (e.g., microbiology), blood bank, and central supply rooms should be in safer places than the ground floors in areas at risk of flooding or better protected physically in areas of high seismic activity or other threats, including terrorism. Experiences such as the 1993 attack on the World Trade Center support this approach even in areas that are not at risk of flooding but could be exposed to an enemy or terrorist attack (34). In the event a hospital becomes isolated, these services are essential to maintain continuity of care. Therefore, these services should be prepared for challenging situations, like the one experienced by MHH, and extensive performances (1).
5. Patient ventilation. Alternative modes of ventilation and monitoring, with contingency plans in the event of complete power failure, should be available. A military or a mass-casualty approach to any similar event may be necessary if a plan is not in place or does not work or if the team responding to the crisis is overwhelmed. Planning the response to mass-casualty ventilation needs in conjunction with the respiratory therapy department is recommended.
6. Water and other essential supplies. Maintenance of protected water supply; water purifiers; emergency food supplies; emergency kits with batteries, flashlights, battery-operated lamps, and two-way radios; reflecting devices or emergency lights in stairwells and corridors; telephones in elevators; and lists of telephone numbers of personnel, essential internal services, and outside facility emergency services (e.g., police, National Guard) is critical (3, 4, 7).
7. Patient-logging system. A nonelectronic emergency system for the identification of incoming or outgoing patients should be readily available. The Casualty Handling System developed in Europe in the late 1980s and used with success in some countries since the early 1990s could be used for a benchmark (35).
8. Evacuation plan. Effective design and system for vertical evacuation of patients could help to reduce evacuation time, personnel requirements, potential injuries, or deaths. This includes updated engineering and architectural design of stairwells, as well as special evacuation equipment, such as the Evacu-Trac or Evac+Chair (Garaventa Accessibility Trac, Blaine, WA) (36). More research into vertical evacuation of tall buildings is necessary, as was made apparent by 2001 attacks on the World Trade Center buildings (37).
9. Media communication. The media's report of a disaster could be of help, be distracting, or create panic (6). Therefore, these organizations should also review their performances and role during any crisis. They should organize and develop plans to respond during disasters in a more responsible and effective way. At the same time, the hospital should establish a system for communicating information through the media in a manner most likely to create a productive response.

Although the recovery phase is not a major concern during an emergency like this, proper planning is essential for a rapid recovery and return to baseline function (38). Finally, rapid adaptation to unexpected adverse conditions is critical to the successful implementation of any disaster contingency plan.

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