SAGE-Hindawi Access to Research
International Journal of Nephrology
Volume 2011, Article ID 748053, 9 pages
doi:10.4061/2011/748053

Review Article

Renal Replacement Therapy in Austere Environments

Christina M. Yuan[1] and Robert M. Perkins[2]

[1] *Nephrology Service, Department of Medicine, Walter Reed Army Medical Center, 6900 Georgia Avenue Northwest, Washington, DC 20012, USA*
[2] *Department of Nephrology, Center for Health Research, Geisinger Medical Center, MC 44-00, 100 North Academy Avenue, Danville, PA 17822, USA*

Correspondence should be addressed to Robert M. Perkins, rmperkins@geisinger.edu

Received 7 September 2010; Revised 8 February 2011; Accepted 22 February 2011

Academic Editor: Achim Jörres

Myoglobinuric renal failure is the classically described acute renal event occurring in disaster environments—commonly after an earthquake—which most tests the ingenuity and flexibility of local and regional nephrology resources. In recent decades, several nephrology organizations have developed response teams and planning protocols to address disaster events, largely focusing on patients at risk for, or with, acute kidney injury (AKI). In this paper we briefly review the epidemiology and outcomes of patients with dialysis-requiring AKI after such events, while providing greater focus on the management of the end-stage renal disease population after a disaster which incapacitates a pre-existing nephrologic infrastructure (if it existed at all). "Austere" dialysis, as such, is defined as the provision of renal replacement therapy in any setting in which traditional, first-world therapies and resources are limited, incapacitated, or nonexistent.

1. Introduction

Austere renal replacement therapy (RRT) describes the provision of renal replacement therapy in any setting in which traditional, first-world therapies and resources are limited, incapacitated, or nonexistent. The provision of RRT in an austere environment is very different from that in a routine situation in a first-world country. In the latter case, the following apply (1) the environment is secure from violence and physical risk to the providers and patients; (2) the transportation infrastructure is functioning; (3) there are plentiful and stable sources of electricity, RRT supplies, and potable water; (4) engineering systems are in place for the production of pure water; (5) sophisticated equipment is available; (6) adequate equipment maintenance and nursing/technician staff support exist; (7) patient acuity and numbers are predictable and stable.

In an austere situation, some or all of these components may be inadequate or completely absent. If austere environment RRT is to be successful, the provider must identify the components that are lacking and attempt to offer reasonably safe and effective substitutes for them if they cannot be controlled or repaired. This requires flexibility, the ability to triage, and a thorough understanding of the engineering and physiologic principals of RRT. Moreover, specific advance planning is necessary, especially in an environment or geographic area where certain disasters are likely to occur (particularly true for storms and earthquakes). Every dialysis unit should have a disaster plan. Moreover, it is important during planning and implementation not to allow (as in Voltaire's aphorism) the "perfect" to become the enemy of the good. Ultimately, the optimal scenario for RRT provision after a disaster, or in an austere situation, is for RRT to be unnecessary or able to be delayed.

Others have provided expert opinion regarding the appropriate response to certain likely disasters (especially earthquakes and storms) for both providers and patients requiring both acute and chronic RRT [1–7]. Many recent reviews focus on the epidemiology and management of patients with acute kidney injury (AKI) due to crush injury sustained after earthquakes [2, 3, 7]. The Renal Disaster Relief Task Force (RDRTF) and European Renal Best Practice (ERBP) are currently developing comprehensive guidelines for the management of crush syndrome [8]. Therefore, in this paper, although we will discuss the situation of AKI due to crush injury as the paradigm for austere RRT, we will focus more on general practical aspects of managing patients who require RRT in austere settings, regardless of the cause of renal failure. A particularly important group is patients with ESRD receiving chronic dialysis. Many such patients are likely to be encountered where chronic dialysis units have been incapacitated or resources are otherwise severely limited due to unanticipated disaster events. Lastly, it is important to remember that an “austere” RRT situation may exist where there are only a few patients to manage, and no “disaster” has occurred, but RRT provision is limited by logistical and equipment considerations alone.

2. Earthquake-Associated Crush Syndrome as a Paradigm for AKI after a Disaster

Although crush syndrome with resultant myoglobulinuria and AKI due to acute tubular necrosis (ATN) is not the only type of renal failure requiring RRT seen under austere circumstances, it has received the most attention. Although most associated with earthquake events, it also may be seen in the setting of entrapment after building collapse due to any cause and was first described in 1941 in patients removed from beneath collapsed buildings during the aerial bombardment of London [9]. There was no RRT infrastructure in 1941 (dialysis had not yet been developed), and death due to hyperkalemia was the outcome for the patients described in this series.

Subsequently, much of the disaster nephrology literature has focused on preparing for and treating the influx of patients with ATN due to crush-related muscle injury after an earthquake event [7, 10, 11]. RRT management of such patients can be very resource intensive because of the associated muscle damage with resultant accelerated hyperkalemia, hypocalcemia, and acidosis. In addition, in situations where intravenous fluid resuscitation is available and employed, severe symptomatic “rebound” volume overload can occur in those who develop oliguria. Even with efficient, single-pass hemodialysis, RRT may be necessary more than daily, and dialysis dependence may last for weeks. Less efficient forms of RRT, such as peritoneal dialysis and continuous therapies, may not provide enough clearance to control the metabolic abnormalities (particularly hyperkalemia).

Although patients with myoglobinuric ATN require very resource-intensive RRT, the effects of the earthquake itself may significantly limit RRT delivery. After an earthquake, there may be prolonged interruptions of electricity and water delivery, transportation infrastructure and medical building may be severely damaged, and medical personnel themselves may be casualties. It is also difficult to predict the number and severity of casualties that may develop ATN and require RRT. The type of buildings in the area, the rapidity of rescue, the provision of intravenous (IV) fluid prophylaxis at the injury site, and the strength and timing of the earthquake can substantially affect the number of casualties with crush injury and subsequent ATN. For example, after the large California earthquakes of 1971, 1983, and 1989, crush injuries were small in number, but in situations where there are collapses of multistory stone or reinforced buildings (as seen in the Armenian earthquake in 1988), there may be many [12, 13]. The damage can be so great that there are paradoxically few crush injuries and cases of ATN, because few persons are rescued or are able to access medical care. They simply die at the scene, as observed after the Haitian earthquake, as well as after the collapse of the World Trade Center in New York in 2001 [8, 14]. In another scenario, where buildings are small and constructed of relatively light materials, such as brick, wood, or adobe, there are few crush injuries because rescues are very rapid, and crush syndrome does not develop [15, 16]. Despite these observations, it is important to recognize that crush syndrome remains the second most likely cause of death in earthquake disasters after direct trauma and, unlike the latter, may be medically prevented [7].

The best treatment of crush injury-associated ATN is prevention. The pathophysiology of crush syndrome and rhabdomyolysis-associated ATN is complex and beyond the scope of this paper. Direct tubular toxicity due to heme iron released from myoglobin, other toxins released from injured muscle (to include uric acid), formation of obstructing myoglobin casts, volume depletion, free radical activation, reperfusion injury, cytokine release, and acidosis all appear to contribute to renal injury and development of ATN [17–19]. It has been shown in animal models as well as in humans that volume repletion, with increased glomerular filtration and tubular flow, prevents ATN, along with (and perhaps to a lesser extent) alkalinization and administration of free radical scavengers (such as mannitol) [20]. This has been translated into the clinical practice of prophylactic isotonic IV fluid resuscitation to victims of crush injury in the field, in many cases while still entrapped—an intervention shown to be effective in preventing ATN [11, 21].

The RTRTF of the International Society of Nephrology (ISN) has developed a disaster plan and organized a response team to assist in the management of RRT for victims presenting with ATN after earthquakes [4]. They have reported extensively on their experiences with crush syndrome and management of AKI, after numerous large earthquakes [4]. It is noteworthy that crush syndrome casualties are proportionately few relative to the overall injured population, and even fewer require RRT [4]. Of those who do require RRT, mortality appears relatively low, and the majority who survive will regain renal function (Table 1). That being said, the burden of AKI requiring resource-intensive management will vary widely from one earthquake event to another, depending on a multitude of factors, only some of which are predictable prior the disaster event [22].

3. Defining the Disaster: RRT Demand and Capacity in Austere Situations

There are many other situations, besides earthquakes, when nephrologists may be called upon to manage an influx of patients requiring RRT, in an environment in which optimal physical and personnel resources are not available, or are severely compromised (Table 2). First, it is useful to summarize, in an orderly manner, the situations in which RRT may be required in an austere situation taking into consideration the capacity and demand for RRT.

(1) The most commonly described, and planned-for event is a disaster that results in an increased incidence of AKI, requiring an increased demand for RRT services. In this situation, the RRT infrastructure (capacity) may be in one of three states.

(a) *Present previously and now severely damaged.* In this scenario, not only is there an influx of patients requiring acute RRT, but also there is a population of patients with pre-existing ESRD who are receiving either chronic hemodialysis or peritoneal dialysis. Examples of events that could cause such a situation include, but are not limited to, earthquakes and urban battlefields. Damage to infrastructure may vary considerably depending on the age, design, and location of the buildings housing dialysis units, and the size and intensity of the damaging event. This would be the situation predicted for the recent Chilean earthquake. However, there appear to have been very few cases of AKI after this event, and the major impact was on the patients with ESRD who were unable to receive care because of severe damage to their dialysis units [8].

(b) *Previously nonexistant or negligible*, although other medical services may exist. In this scenario, there are few patients with pre-existing ESRD receiving chronic RRT, and the patients who require RRT largely have AKI. Events that could cause this situation include earthquakes, urban battlefields, infectious disease outbreaks associated with AKI (e.g., hantavirus-associated hemorrhagic fever, gastroenteritis-associated HUS), or wide population exposure to renal-toxins (e.g., melamine-contaminated infant formula) [38–40]. Earthquake events in third-world countries, such as the Haitian earthquake of 2010, are examples of this scenario [33]. One would presume, in this situation, that dialysis resources would have to be brought to the area, but this is not clear-cut. After the Haitian earthquake of 2010, although limited dialysis resources were "brought" to the area aboard the USNS Comfort, which had 2 standard hemodialysis machines and provided 15 treatments within the first 9 days [41], the ISN RDRTF repaired the existing infrastructure of the University Hospital dialysis unit in Port au Prince to support the care of both patients with AKI due to crush injury and 30 of the 100 Haitian chronic dialysis patients [8, 34].

(c) *Present previously and now undamaged*, but insufficient to handle the influx (demand) of patients with AKI (and/or ESRD). This scenario is most likely to be seen in a refugee situation in areas adjacent to, but not affected by, an earthquake or war, after an isolated building collapse, or in the setting of large case numbers of AKI after an infectious outbreak or toxic release. A special case of this is when refugees with ESRD travel from a disaster site to an adjacent area with intact RRT infrastructure, as could be seen after a devastating earthquake, storm, flood, or in the aftermath of a battle or terrorist attack. Excellent examples were the aftermath of Hurricane Katrina in 2005 and after the recent Chilean earthquake [1, 8].

(2) A less commonly discussed event is a disaster that does not produce an increased incidence of AKI or an influx of patients with ESRD, but results in inability of existing local ESRD patients to access dialysis due to disruption of transportation, damage to the dialysis infrastructure, or both. *The demand for RRT is unchanged, but the capacity to provide it is degraded.* The most common cause of such an event would be a weather emergency (such as a hurricane, tornado, flood, or blizzard), but civil unrest, war, and terrorist attacks could also be causes. This was the local scenario after Hurricane Katrina, but occurs to some extent quite commonly after local flooding or blizzards (as seen after the blizzards on the east coast of the US in early 2010) [1, 42].

If one considers the numbers of victims with AKI needing acute RRT after a disaster in the last several decades (Tables 1 and 2), it is striking how proportionately few were identified as having AKI, and then the fewer number who required dialysis. For instance, after the January 2010, Haitian earthquake in which over 200,000 people died, the dialysis response team dialyzed 19 patients with AKI, but also managed 30 patients with ESRD who were dialysis dependent before the earthquake [8]. In Chile, after the earthquake of February 2010, most fatalities were associated with the tsunami, and only 2 patients are reported as requiring RRT due to crush injury-induced AKI. However, there were over 2400 patients with ESRD on chronic dialysis—and their management after the destruction of many chronic dialysis units was the primary challenge facing the local nephrology community [8]. Evacuation to areas unaffected by the earthquake and adjustment of dialysis schedules at units within the earthquake zone that had survived were used to accommodate those patients whose dialysis units were nonfunctional. In the aftermath of Hurricane Katrina, the population of patients requiring chronic dialysis in Baton Rouge, LA increased by approximately 700 patients (the usual population was about 1000) due to the influx of refugees from areas of Louisiana affected by the hurricane [1]. Although there were no immediate deaths reported due to unavailability of dialysis services in this population, CMS data indicated that there was an increase in deaths among ESRD patients in the area within the first 180 days after the hurricane, although later data suggests that there was no significant change in mortality rate in the 6 months following the disaster, when compared to the 6 previous months [1, 43]. Thus, as ESRD services become more commonly available, even in countries which have relatively poor medical infrastructure such as Haiti, the management of patients with ESRD who are unable to access chronic dialysis after disaster may become the primary concern of local nephrologists and renal response teams, rather than RRT for AKI, even in the setting of very severe earthquakes [6].

Table 1: Earthquake-associated crush injury and outcomes after renal replacement therapy.

Author/year	Location	Year	No. deaths	No. requiring RRT*	Mortality after RRT*
Collins and Burzstein 1991 [23]	Mexico City, MX	1985	>3000	Unknown	Unknown
Tattersall et al. 1990 [13]	Northern Armenia	1988	Approximately 25,000	385	2 of 15 reported
Collins and Burzstein 1991 [23]	San Francisco, USA	1989	60	1	Not reported
Atef et al. 1994 [24]	Northwest Iran	1990	>40,000	154	23
Oda et al. 1997 [25]	Kobe, JP	1995	>5,000	8/8 reported	0
Vanholder et al. 2001 [26]	Northwest Turkey	1999	17,479	477	82
Sever et al. 2004 [27]					
Hwang et al. 2001 [28]	Central Taiwan	1999	>2,300	30	Not reported
Huang et al. 2002 [29]					
Viroja et al. 2003 [30]	India	2001	>20,000	33	6
Sever et al. 2006 [7]	Algeria	2003	2,266	15 (?)	unknown
Hatamizadeh et al. 2006 [31]	Iran	2003	25,514	126	19
Vanholder 2006 [32]	Pakistan	2005	74,968	77	11
Vanholder et al. 2010 [33]	Haiti	2010	>200,000	59	3 confirmed of 54 (5 lost to follow up)
Amundson et al. 2010 [34]	Haiti	2010	>200,000	Not reported	Not reported
Vanholder et al. 2011 [8]	Chile	2010	507	2	0

* Data reported is in many cases from single-center analyses; number requiring RRT and deaths therefore do not reflect total morbid burden for each event, rather the experience at a single center or regional area as reported in the referenced article.

Table 2: Reported nonearthquake disasters, requirement for renal replacement therapy, and outcomes.

Author/year	Event and location	Date	No. deaths	No. requiring RRT	Mortality after RRT
Bywaters and Beall 1941 [9]	Crush injury after bombing and building collapse, London	1941	4	NA	NA
Bentley and Jeffreys 1968 [35]	Crush injury after mine collapse, United Kingdom	1968	1	2 of 3	1 of 2
Goldfarb and Chung 2002 [14]	World Trade Center collapse after terrorist attack, New York City	2001	2,752	1	None
Altintepe et al. 2007 [36]	Building collapse, Konya, Turkey	2004	92	2	None
Kutner et al. 2009* [37]	Hurricane, New Orleans, LA	2005	1,836	Unknown	No excess mortality risk identified

* Retrospective cohort study examining mortality rates after Hurricane Katrina among patients with end-stage renal disease receiving dialysis therapy in the New Orleans area.

4. Disaster Planning for the ESRD Population: The Nephrologist's Perspective

How then does an individual nephrologist or chronic dialysis unit prepare for and respond to a disaster that may result in an austere RRT environment? In the United States, the Center for Medicare and Medicaid Services (CMS) requires that dialysis facilities must develop written policies and procedures for emergencies. The Kidney Community Emergency Response Coalition (KCERC), formed in the US after Hurricane Katrina, has published a set of guidelines for emergency planning [1]. Although many of the recommendations apply to federal, state, and local emergency providers, effective strategies are available for patients and providers. The KCERC "Time-Line to Safety" is a helpful, general resource for patients, local dialysis units, and providers in developing a disaster plan, especially for disasters that are predictable (such as weather emergencies). The copy of the CMS publication "Preparing for Emergencies: A guide for people on dialysis" should be available to all patients [5].

The first step is to identify the disasters most likely to occur. Regardless of the type of disaster event, there are several planning recommendations that nephrologists, dialysis directors, nursing staff, and local policy makers should consider in localities with an existing dialysis infrastructure and many dialysis-dependent patients with ESRD.

(1) Assess and implement measures that will keep the dialysis facility functional and safe during and after a disaster event. Simple measures are important, such as knowing where utility shut-off valves are located [1].

(2) Educate patients about modifications to chronic diet and fluid intake in the event of a disaster. Fasting should be avoided, because of the risk of hyperkalemia. Volume overload and hyperkalemia are the most likely complications to “force” RRT treatments [6]. The CMS publication “Preparing for Emergencies: A guide for people on dialysis” contains a detailed 3-day diet plan and food supply list [5].

(3) Provide medications which may delay the need for dialysis to patients before a predictable disaster (such as a hurricane or snowstorm). The most common would be sodium polystyrene sulfonate for control of hyperkalemia. High-dose loop diuretics may increase urine output and kaliuresis in patients with residual renal function. Explicit instructions should be given to the patient on when to begin such medications, and these instructions should be reviewed at regular intervals with all chronic dialysis patients [5, 6].

(4) Ask patients to maintain updated lists of medications, allergies, health problems, and contact information for his/her providers and local dialysis unit, and to carry these records with them in the event of travel out of a disaster area. Medical records, electronic or otherwise, may not be accessible during an emergency. In fact, it should be assumed that communication systems will be nonfunctional for a period of time, and advance planning should focus on optimizing self-sufficiency for each patient as much as possible [1, 5].

(5) Develop emergency evacuation plans—at both the unit and individual ESRD patient levels—that provide for efficient, practical, and safe egress for both patients and staff. It is crucial that this planning incorporate both on-site and from-home scenarios. These plans should be routinely practiced by both staff and patients during scheduled and unscheduled drills. Home dialysis patients, especially PD patients, should not be forgotten, and specific guidelines exist for them with regard to infection control management [5, 43]. These plans require frequent review and training for both patients and staff. At the local and regional levels, policy leaders need to incorporate planning for the orderly and timely evacuation of the chronic dialysis population to areas unaffected by a disaster event.

(6) Anticipate that providers may also be affected by the disaster. Nurses and physicians themselves may be injured, be unable to travel to the facility, and may have personal responsibilities that are equal to their professional ones. Development of a defined and flexible coverage plan for staff during the first days of a disaster should be in place.

5. RRT in the Austere Environment: Practical Considerations

5.1. RRT Equipment. Any successful plan for managing RRT in the event of large-scale resource incapacitation will need to incorporate several key elements, regardless of the type and number of patients being managed. A disaster management plan should be as follows.

(1) Conserve resources (e.g., supplies, transportation, purified water, and staff). A dialyzer reuse plan, plans for limitation of water use (decrease of dialysate flow rate), shortening of dialysis times, and reduction of supply consumption all should be considered. Available supplies (especially dialyzers) may not be the type used before the disaster, or may be in short supply. Dialyzer reuse may not be feasible or safe in many situations, but in scenarios where patient numbers are low, and resupply is totally disrupted, reuse should be considered [34].

(2) Determine thresholds for RRT initiation and frequency. At the height of the disaster, with its attendant difficulties of transportation and resource access, the presence of acute indications for dialysis and the catabolic state may determine which patients receive dialysis treatments, and standard treatment schedules may need to be abandoned. As the situation improves, accepted standards of RRT adequacy should guide treatment decisions regarding both ESRD and AKI patients, although this may be constrained by available resources.

(3) Provide flexibility. Single-pass hemodialysis with dialysate water delivered by a state-of-the-art portable or fixed water treatment plant may not be possible. Alternate RRT modalities must be considered, and each hemodialysis center should plan for the provision of an alternative means of renal replacement therapy should the pre-disaster, existing infrastructure be rendered nonfunctional. None is perfect—and none will be successful with all patients. Many of the same resource constraints are likely to apply to these as to conventional dialysis. Realistically, the modality that can be made to work in the existing environment is the one preferred! Alternatives include the following [44–49].

(a) Peritoneal dialysis [6]: Peritoneal dialysis is an attractive alternative in settings where the electrical supply and the water plant are disrupted. Drawbacks include the need for peritoneal catheter placement, the risk of peritonitis, the need to obtain (or make) large volumes of appropriate sterile dialysate, and difficulty of metabolic control in the severely hypercatabolic patient.

(b) CAVH/D and CVVH/D using replacement fluid/dialysate from readily available commercial IV crystalloid solutions: CAVH/D and CVVH/D have the disadvantage of requiring large volumes of replacement fluid/dialysate and may also be resource intensive from the standpoint of personnel. CAVH requires arterial access, and use of upper extremity AV fistulae/grafts may be difficult with CVVH. Clearance is inefficient over a short period of time. A distinct advantage is the limited electrical power requirements (CAVH requires none), and there is no need for water purification.

(c) Isolated ultrafiltration for volume control, which does not require dialysate or a functioning water treatment plant and may even be achieved with dedicated slow continuous ultrafiltration devices used for management of congestive heart failure (Aquadex ref). Although this approach can control volume, there is no solute clearance [6, 50].

(d) Alternative devices developed for home hemodialysis based on either sorbent or CVVH technology [51, 52]: because these devices have been developed for the home market, they are simple to use and quite robust. Existing chronic dialysis access can be used, and water treatment capacity is not necessary, as they either use a sorbent column or premixed replacement fluid.

(4) Plan for the production of "safe enough" water. Knowledge of water preparation and monitoring for dialysis—not only among nursing and technical staff, but among physicians—is essential. Because chloramines may be increased in potable water after a disaster to prevent water-borne illness, they may need to be monitored with greater frequency. Water may need to have more contact time with activated carbon filters. If possible, product water should be carefully monitored, especially if preparation is by mixed bed deionizer. Product water may need to be stored in tanks, rather than continuously made [8, 34, 48].

(5) Provide for electrical back-up systems/generators, which should be considered and in place before the disaster, with a plan for fueling them.

(6) Include an infection control plan, especially for patients who may be infected with tuberculosis or hepatitis B [1, 34].

5.2. Planning for RRT in Military Situations. The United States military medical services have well-described protocols for the provision of RRT to casualties in theater [46, 48]. The Army has planned to provide RRT to field hospitals via a dialysis "augmentation team" consisting of two dialysis technicians, a nephrologist, and an ICU nurse. The dialysis machine specified for use, until recently, was the REDY 2000, a sorbent-based system, which required 6-7 liters of potable water to manufacture dialysate for a 3-4-hour dialysis treatment. However, because of the success of aeromedical evacuation systems in rapidly removing casualties with AKI from theater, deployment of this augmentation team was never required [48], and the REDY 2000 is no longer manufactured. There have been occasions when alternative, short-term solutions, including peritoneal dialysis, CVVH, and CAVH, have been used in austere conditions to manage individual patients presenting acutely who could not be evacuated in a timely manner [47]. The US Navy maintains a state-of-the art dialysis facility on the USNS Comfort, which uses single pass dialysis machines that one might encounter in a tertiary care medical center. This ship assisted with the dialysis needs of patients in Haiti after the earthquake in 2010 [34].

5.3. RRT Triage and Prescription. The management of RRT for AKI/ESRD under austere conditions can be conveniently divided into management of crush syndrome patients (and, more generally, any patient in a hypercatabolic state) versus those patients with AKI or ESRD who are not hypercatabolic and may require less intense dialysis. For hypercatabolic patients, single-pass hemodialysis is the most efficient method of managing the hyperkalemia and acidosis which are immediately life-threatening, and other modalities (such as CRRT and PD) may not be adequate to prevent life-threatening hyperkalemia. However, such modalities may be tried in settings where single-pass hemodialysis is not feasible, and they may be effective [44–48, 53].

In patients with AKI who are not hypercatabolic and in patients with ESRD, in settings where resources are limited, an effort should be made in the early period after a disaster to triage patients on the basis of their acute need for RRT [1, 48]. This approach to provision of RRT is supported by experience with AKI at the very beginning of the dialysis era. As early as the 1950s, it was well recognized that patients with ATN more-or-less followed a defined course, and that nonoliguric patients had better outcomes than oliguric patients. If an acute event could be avoided (i.e., fatal hyperkalemia, acidosis, volume overload, and life-threatening uremia), patients could be expected to recover, and acute dialysis (which was technically very complex and difficult) was reserved only for these potentially fatal events. Using this approach, mortality in AKI (even trauma-associated AKI) was reduced to approximately 50–60% from the previously near-universal fatality rates which accompanied the most severe AKI [54, 55].

Studies of dialysis withdrawal in well-dialyzed ESRD patients have shown that with aggressive volume restriction and judicious use of kaliuretics and potassium-binding resins, routine dialysis may be delayed for several days before the classic signs and symptoms of uremia develop or a life-threatening electrolyte imbalance occurs [6, 56]. Isolated ultrafiltration, which does not require the use of dialysate, may be helpful to those in whom volume overload is the only indication for RRT and is resource friendly in conditions where supplies are constrained [6].

Screening for the need for acute dialysis can be done simply and requires little in the way of laboratory support [33]. A physical examination and history assessing for symptoms and signs of severe uremia (pericardial friction rub, asterixis, vomiting/severe nausea, neurologic instability) can be done. Solid-state, hand-held blood analyzers may be invaluable in assessing for hyperkalemia and acidosis and may also be used to check the electrolyte content of dialysate [40]. Life-threatening hyperkalemia may also be assessed by ECG [1].

With screening, dialysis treatments may be reserved for patients who are in acute need of them, thus directing scarce resources to those most likely to benefit. Resources may be limited, and "optimal" RRT therapy, as defined in a nondisaster setting, may be impossible to deliver. However, difficult to recognize, it is important for patients and direct providers to remember that in large-scale disaster events, there are likely to be many more victims/refugees who will not require RRT services than those who will, and that there are likely to be other resource-intensive injuries present. Emergency providers must therefore focus on the principals of triage, a systematic patient-prioritization technique whereby decisions regarding care, medical evacuation, or any other resource-intensive intervention of limited supply are made based on a combination of factors to include illness or disease severity, likelihood of survival within the constraints of the resources available, and the number of casualties relative to the resources at hand. The process might be best summarized as an attempt to achieve "the greatest good for the greatest number" [57]. In the mass casualty situation, this can be difficult, as in rare cases decisions to withhold available care to the most severely injured may be necessary in order to save others.

Applying the concepts of triage to decisions regarding maintenance hemodialysis therapies to chronic ESRD patients in a disaster setting may require that the nephrologist set aside his or her standard approaches and adherence to dosing and management guidelines in order to maximize outcomes for the greatest number of individuals. The underlying chronic illness burden and the age of the ESRD patient must be taken into account, as well as adherence to diet and volume restriction, overall dialysis adequacy prior to the disaster, and the likelihood of evacuation. In a situation of fixed and inadequate/barely adequate RRT capacity, it may not be possible to intensify RRT for a particularly fragile or non-dietary-compliant ESRD patient at the expense of dangerously decreasing RRT therapy intensity for others overall. In more extreme situations, especially those involving a mix of ESRD, AKI, and highly catabolic AKI patients, even more difficult RRT triage decisions may be required. Helpful reviews and guidelines are available for those medical personnel involved with disaster planning who may be less familiar with these important concepts [58–60].

The experience of others would support the notion that triage concepts can be applied successfully to the management of ESRD patients after natural disasters: Sever et al. have reported on the successful management of ESRD patients using a reduced dialysis schedule at seven dialysis centers in Turkey after the Marmara earthquake. In their report, an approximate 50% reduction in functional capacity contributed to a 3-fold increase in the number of once-weekly dialysis treatments. Despite this, interdialytic weight gain and blood pressures remained relatively stable, likely due to successful self-management of fluid intake and dietary restriction [61].

Disclaimer

The views expressed in this paper are those of the authors and do not reflect the official policy of the Department of Army, the Department of Defense, or the US government.

References

[1] J. B. Kopp, L. K. Ball, A. Cohen et al., "Kidney patient care in disasters: emergency planning for patients and dialysis facilities," *Clinical Journal of the American Society of Nephrology*, vol. 2, no. 4, pp. 825–838, 2007.

[2] K. Solez, D. Bihari, A. J. Collins et al., "International dialysis aid in earthquakes and other disasters," *Kidney International*, vol. 44, no. 3, pp. 479–483, 1993.

[3] C. H. Schultz, K. L. Koenig, and E. K. Noji, "A medical disaster response to reduce immediate mortality after an earthquake," *The New England Journal of Medicine*, vol. 334, no. 7, pp. 438–444, 1996.

[4] R. Vanholder, W. Van Biesen, N. Lameire, and M. S. Sever, "The role of the international society of nephrology/renal disaster relief task force in the rescue of renal disaster victims," *Contributions to Nephrology*, vol. 156, pp. 325–332, 2007.

[5] Centers for Medicare and Medicaid Services, *Preparing for Emergencies: A Guide for People on Dialysis*, Centers for Medicare and Medicaid Services, Baltimore, Md, USA, October 2007, http://www.medicare.gov/publications/pubs/pdf/10150.pdf.

[6] R. Zoraster, R. Vanholder, and M. S. Sever, "Disaster management of chronic dialysis patients," *American Journal of Disaster Medicine*, vol. 2, no. 2, pp. 96–106, 2007.

[7] M. S. Sever, R. Vanholder, and N. Lameire, "Management of crush-related injuries after disasters," *The New England Journal of Medicine*, vol. 354, no. 10, pp. 1052–1063, 2006.

[8] R. Vanholder, D. Borniche, S. Claus et al., "When the earth trembles in the Americas: the experience of Haiti and Chile 2010," *Nephron Clinical Practice*, vol. 117, no. 3, pp. c184–c196, 2011.

[9] E. G. L. Bywaters and D. Beall, "Crush injuries with impairment of renal function," *British Medical Journal*, vol. 1, no. 4185, pp. 427–432, 1941.

[10] A. Atef-Zafarmand and S. Fadem, "Disaster nephrology: medical perspective," *Advances in Renal Replacement Therapy*, vol. 10, no. 2, pp. 104–116, 2003.

[11] O. S. Better and J. H. Stein, "Early management of shock and prophylaxis of acute renal failure in traumatic rhabdomyolysis," *The New England Journal of Medicine*, vol. 322, no. 12, pp. 825–829, 1990.

[12] M. Durkin, S. Aroni, and A. Coulson, "Injuries in the coalinga earthquake," in *The Coalinga Earthquake of May 1983*, pp. 271–283, Earthquake Engineering Research Institute, Berkeley, Calif, USA, 1983.

[13] J. E. Tattersall, N. T. Richards, M. McCann, T. Mathias, A. Samson, and A. Johnson, "Acute haemodialysis during the Armenian earthquake disaster," *Injury*, vol. 21, no. 1, pp. 25–28, 1990.

[14] D. S. Goldfarb and S. Chung, "The absence of rhabdomyolysis-induced renal failure following the world trade center collapse," *American Journal of Medicine*, vol. 113, no. 3, p. 260, 2002.

[15] E. K. Noji, "Prophylaxis of acute renal failure in traumatic rhabdomyolysis," *The New England Journal of Medicine*, vol. 323, no. 8, p. 550, 1990.

[16] C. Y. Sheng, "Medical support in the Tangshan earthquake: a review of the management of mass casualties and certain major injuries," *Journal of Trauma*, vol. 27, no. 10, pp. 1130–1135, 1987.

[17] R. A. Zager, K. M. Burkhart, D. S. Conrad, and D. J. Gmur, "Iron, heme oxygenase, and glutathione: effects on myohemoglobinuric proximal tubular injury," *Kidney International*, vol. 48, no. 5, pp. 1624–1634, 1995.

[18] R. Vanholder, M. S. Sever, E. Erek, and N. Lameire, "Rhabdomyolysis," *Journal of the American Society of Nephrology*, vol. 11, no. 8, pp. 1553–1561, 2000.

[19] M. Odeh, "Mechanisms of disease: the role of reperfusion-induced injury in the pathogenesis of the crush syndrome," *The New England Journal of Medicine*, vol. 324, no. 20, pp. 1417–1422, 1991.

[20] A. I. Gunal, H. Celiker, A. Dogukan et al., "Early and vigorous fluid resuscitation prevents acute renal failure in the crush victims of catastrophic earthquakes," *Journal of the American Society of Nephrology*, vol. 15, no. 7, pp. 1862–1867, 2004.

[21] D. Ron, U. Taitelman, M. Michaelson, S. Bursztein, and O. S. Better, "Prevention of acute renal failure in traumatic rhabdomyolysis," *Archives of Internal Medicine*, vol. 144, no. 2, pp. 277–280, 1984.

[22] A. van der Tol, A. Hussain, M. S. Sever et al., "Impact of local circumstances on outcome of renal casualties in major disasters," *Nephrology Dialysis Transplantation*, vol. 24, no. 3, pp. 907–912, 2009.

[23] A. J. Collins and S. Burzstein, "Renal failure in diasters," *Critical Care Clinics*, vol. 7, no. 2, pp. 421–435, 1991.

[24] M. R. Atef, I. Nadjatfi, B. Boroumand, and A. Rastegar, "Acute renal failure in earthquake victims in Iran: epidemiology and management," *Quarterly Journal of Medicine*, vol. 87, no. 1, pp. 35–40, 1994.

[25] Y. Oda, M. Shindoh, H. Yukioka, S. Nishi, M. Fujimori, and A. Asada, "Crush syndrome sustained in the 1995 Kobe, Japan, earthquake; Treatment and outcome," *Annals of Emergency Medicine*, vol. 30, no. 4, pp. 507–512, 1997.

[26] R. Vanholder, M. S. Sever, M. De Smet, E. Erek, and N. Lameire, "Intervention of the renal disaster relief task force in the 1999 Marmara, Turkey earthquake," *Kidney International*, vol. 59, no. 2, pp. 783–791, 2001.

[27] M. S. Sever, E. Erek, R. Vanholder et al., "Lessons learned from the catastrophic Marmara earthquake: factors influencing the final outcome of renal victims," *Clinical Nephrology*, vol. 61, no. 6, pp. 413–421, 2004.

[28] S. J. Hwang, K. H. Shu, J. D. Lain, and W. C. Yang, "Renal replacement therapy at the time of the Taiwan Chi-Chi earthquake," *Nephrology Dialysis Transplantation*, vol. 16, no. 5, pp. 78–82, 2001.

[29] K. C. Huang, T. S. Lee, Y. M. Lin, and K. H. Shu, "Clinical features and outcome of crush syndrome caused by the Chi-Chi earthquake," *Journal of the Formosan Medical Association*, vol. 101, no. 4, pp. 249–256, 2002.

[30] D. Viroja, P. Shah, H. L. Trivedi, V. Shah, and A. Vaniker, "Management of crush syndrome following Gujarat earthquake—January 2001," *Nephrol Dial Transplant*, vol. 18, supplement 4, pp. 659–660, 2003.

[31] P. Hatamizadeh, I. Najafi, R. Vanholder et al., "Epidemiologic aspects of the Bam earthquake in Iran: the nephrologic perspective," *American Journal of Kidney Diseases*, vol. 47, no. 3, pp. 428–438, 2006.

[32] R. Vanholder, "Intervention of the renal disaster relief task force (RDRTF) in the Kashmir earthquake," *Nephrology Dialysis Transplantation*, vol. 21, no. 1, p. 40, 2006.

[33] R. Vanholder, N. Gibney, V. A. Luyckx, and M. S. Sever, "Renal disaster relief task force in Haiti earthquake," *The Lancet*, vol. 375, no. 9721, pp. 1162–1163, 2010.

[34] D. Amundson, G. Dadekian, M. Etienne et al., "Practicing internal medicine onboard the USNS COMFORT in the aftermath of the Haitian earthquake," *Annals of Internal Medicine*, vol. 152, no. 11, pp. 733–737, 2010.

[35] G. Bentley and T. E. Jeffreys, "The crush syndrome in coal miners," *Journal of Bone and Joint Surgery. British*, vol. 50, no. 3, pp. 588–594, 1968.

[36] L. Altintepe, I. Guney, Z. Tonbul et al., "Early and intensive fluid replacement prevents acute renal failure in the crush cases associated with spontaneous collapse of an apartment in Konya," *Renal Failure*, vol. 29, no. 6, pp. 737–741, 2007.

[37] N. G. Kutner, P. Muntner, Y. Huang et al., "Effect of Hurricane Katrina on the mortality of dialysis patients," *Kidney International*, vol. 76, no. 7, pp. 760–766, 2009.

[38] J. S. Cameron, "The history of viral haemorrhagic fever with renal disease (hantavirus)," *Nephrology Dialysis Transplantation*, vol. 16, no. 6, pp. 1289–1290, 2001.

[39] M. J. Kim, "Nephrology and renal replacement therapy in South Korea: a brief report on the Korean Society of Nephrology and Korean Society of Transplantation," *Nephrology Dialysis Transplantation*, vol. 11, no. 6, pp. 979–981, 1996.

[40] N. Sun, Y. Shen, Q. Sun et al., "Diagnosis and treatment of melamine-associated urinary calculus complicated with acute renal failure in infants and young children," *Chinese Medical Journal*, vol. 122, no. 3, pp. 245–251, 2009.

[41] M. Hogan, "In Haiti, nephrologists on the ground report challenges and successes in treating earthquake victims," *Nephrology Times*, vol. 3, supplement 2, p. 1, 12, 13, 14, 2010.

[42] N. Popovich, *Big Snow Brings Big Problems for Dialysis Patients. [Internet]*, National Public Radio, Washington, DC, USA, February 2010, http://www.npr.org/blogs/health/2010/02/big_snow_brings_big_problems_f.html.

[43] Centers for Disease Control and Prevention, *Infection Control for Peritoneal Dialysis (PD) Patients after a Disaster*, Centers for Disease Control and Prevention, Atlanta, Ga, USA, September 2005, http://www.bt.cdc.gov/disasters/icfordialysis.asp.

[44] M. K. Mani, "Continuous arteriovenous haemofiltration and haemodialysis," *The Journal of the Association of Physicians of India*, vol. 41, no. 6, pp. 327–328, 1993.

[45] L. Omert, H. N. Reynolds, and C. E. Wiles, "Continuous arteriovenous hemofiltration with dialysis (CAVH-D): an alternative to hemodialysis in the mass casualty situation," *Journal of Emergency Medicine*, vol. 9, no. 1, pp. 51–56, 1991.

[46] R. Perkins, J. Simon, A. Jayakumar et al., "Renal replacement therapy in support of operation Iraqi freedom: a tri-service perspective," *Military Medicine*, vol. 173, no. 11, pp. 1115–1121, 2008.

[47] R. M. Perkins, R. George, C. R. Fox, and C. M. Yuan, "Successful CAVH in an austere environment using readily available disposable hospital supplies," *Nephrology Dialysis Transplantation*, vol. 22, no. 4, pp. 1241–1246, 2007.

[48] P. G. Welch, "Deployment dialysis in U.S. Army: history and future challenges," *Military Medicine*, vol. 165, no. 10, pp. 737–741, 2000.

[49] K. K. Chung, R. M. Perkins, and J. D. Oliver, "Renal replacement therapy in support of combat operations," *Critical Care Medicine*, vol. 36, no. 7, pp. S365–S369, 2008.

[50] M. R. Costanzo, M. E. Guglin, M. T. Saltzberg et al., "Ultrafiltration versus intravenous diuretics for patients hospitalized for acute decompensated heart failure," *Journal of the American College of Cardiology*, vol. 49, no. 6, pp. 675–683, 2007.

[51] S. R. Ash, "Approaches to quotidian dialysis: the Allient Dialysis System," *Seminars in Dialysis*, vol. 17, no. 2, pp. 164–166, 2004.

[52] W. R. Clark and J. E. Turk, "Approaches to quotidian dialysis: the NxStage System One," *Seminars in Dialysis*, vol. 17, no. 2, pp. 167–170, 2004.

[53] M. S. Sever, E. Erek, R. Vanholder et al., "Renal replacement therapies in the aftermath of the catastrophic Marmara earthquake," *Kidney International*, vol. 62, no. 6, pp. 2264–2271, 2002.

[54] P. E. Teschan and C. R. Baxter, "The future of hemodialysis in military medicine," *Journal of the American Medical Association*, vol. 166, no. 1, pp. 11–14, 1958.

[55] P. E. Teschan, C. R. Baxter, T. F. O'Brien, J. N. Freyhoff, and W. H. Hall, "Prophylactic hemodialysis in the treatment of acute renal failure," *Annals of Internal Medicine*, vol. 53, pp. 992–1016, 1960.

[56] B. Birmelé, M. François, J. Pengloan et al., "Death after withdrawal from dialysis: the most common cause of death in a French dialysis population," *Nephrology Dialysis Transplantation*, vol. 19, no. 3, pp. 686–691, 2004.

[57] E. R. Frykberg, "Triage: principles and practice," *Scandinavian Journal of Surgery*, vol. 94, no. 4, pp. 272–278, 2005.

[58] J. L. Hick and D. T. O'Laughlin, "Concept of operations for triage of mechanical ventilation in an epidemic," *Academic Emergency Medicine*, vol. 13, no. 2, pp. 223–229, 2006.

[59] L. Rubinson, J. B. Nuzzo, D. S. Talmor, T. O'Toole, B. R. Kramer, and T. V. Inglesby, "Augmentation of hospital critical care capacity after bioterrorist attacks or epidemics: recommendations of the working group on emergency mass critical care," *Critical Care Medicine*, vol. 33, no. 10, pp. 2393–2403, 2005.

[60] S. G. Venticinque and K. W. Grathwohl, "Critical care in the austere environment: providing exceptional care in unusual places," *Critical Care Medicine*, vol. 36, no. 7, pp. S284–S292, 2008.

[61] M. S. Sever, E. Erek, R. Vanholder et al., "Features of chronic hemodialysis practice after the Marmara earthquake," *Journal of the American Society of Nephrology*, vol. 15, no. 4, pp. 1071–1076, 2004.