TURKISH JOURNAL OF EMERGENCY MEDICINE

Invited Review Article

Access this article online

Quick Response Code:

Website:
https://turkjemergmed.com/

DOI:
10.4103/tjem.tjem_11_24

Surgical and critical care management of earthquake musculoskeletal injuries and crush syndrome: A collective review

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Submitted: 19-01-2024
Accepted: 24-01-2024
Published: 04-04-2024

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Abstract:

Earthquakes are unpredictable natural disasters causing massive injuries. We aim to review the surgical management of earthquake musculoskeletal injuries and the critical care of crush syndrome. We searched the English literature in PubMed without time restriction to select relevant papers. Retrieved articles were critically appraised and summarized. Open wounds should be cleaned, debrided, receive antibiotics, receive tetanus toxoid unless vaccinated in the last 5 years, and re-debrided as needed. The lower limb affected 48.5% (21.9%–81.4%) of body regions/patients. Fractures occurred in 31.1% (11.3%–78%) of body regions/patients. The most common surgery was open reduction and internal fixation done in 21% (0%–76.6%), followed by plaster of Paris in 18.2% (2.3%–48.8%), and external fixation in 6.6% (1%–13%) of operations/patients. Open fractures should be treated with external fixation. Internal fixation should not be done until the wound becomes clean and the fractured bones are properly covered with skin, skin graft, or flap. Fasciotomies were done in 15% (2.8%–27.2%), while amputations were done in 3.7% (0.4%–11.5%) of body regions/patients. Principles of treating crush syndrome include: (1) administering proper intravenous fluids to maintain adequate urine output, (2) monitoring and managing hyperkalemia, and (3) considering renal replacement therapy in case of volume overload, severe hyperkalemia, severe acidemia, or severe uremia. Low-quality studies addressed indications for fasciotomy, amputation, and hyperbaric oxygen therapy. Prospective data collection on future medical management of earthquake injuries should be part of future disaster preparedness. We hope that this review will carry the essential knowledge needed for properly managing earthquake musculoskeletal injuries and crush syndrome in hospitalized patients.

Keywords:

Acute compartment syndrome, acute kidney injury, critical care, crush syndrome, disaster, earthquake, injury, orthopedics, surgery, trauma

Introduction

Earthquakes are unpredictable, sudden natural disasters that come without notice, causing massive destruction of cities and major injuries and death.[1,2] The twin Kahramanmaraş earthquakes in 2023, one of the most recent devastating earthquakes in Turkey, caused the death of at least 56,000 inhabitants.[3] About 7.7% of patients who were treated during this earthquake had crush injuries.[4] Continuous prolonged

How to cite this article: Abu-Zidan FM, Jawas A, Idris K, Cevik AA. Surgical and critical care management of earthquake musculoskeletal injuries and crush syndrome: A collective review. Turk J Emerg Med 2024;24:67-79.

EMAT EMERGENCY MEDICINE ASSOCIATION OF TURKEY

mechanical pressure of the falling parts of the buildings on the muscles of victims may cause crush syndrome.[5] Following extrication of the patients after extended time will relieve muscle compression but will cause an ischemia-reperfusion injury. This will be associated with a sudden release of metabolites and toxic material, which may lead to serious metabolic changes.[6] Sodium and water will move from the extracellular space into the cells. This causes hypovolemia, cell swelling, possibly shock, and metabolic acidosis. The muscle cell walls are prone to be lysed (rhabdomyolysis), releasing potassium and myoglobin into the circulation. Hyperkalemia may cause sudden cardiac arrest, muscle cell swelling may cause acute extremity compartment syndrome, while myoglobin may deposit in the renal tubules, causing acute kidney injury (AKI)[7] [Figure 1]. Earthquake crush syndrome has high mortality,[8] being the second cause of death after direct trauma.[9]

We have previously reviewed the prehospital medical management of earthquake crush injuries targeting health-care providers in the earthquake field.[10] That review covered the pathophysiology of crush syndrome, acute compartment syndrome (ACS), and AKI, and addressed the principles of first aid, triage, field management, and transportation of earthquake victims to the hospitals. The majority of those who will arrive alive at hospitals have crush injuries to the extremities.[11] Hereby, we aim to review the hospital-based surgical management of earthquake musculoskeletal injuries and the critical care of AKI of crush syndrome after patients arrive to hospitals.

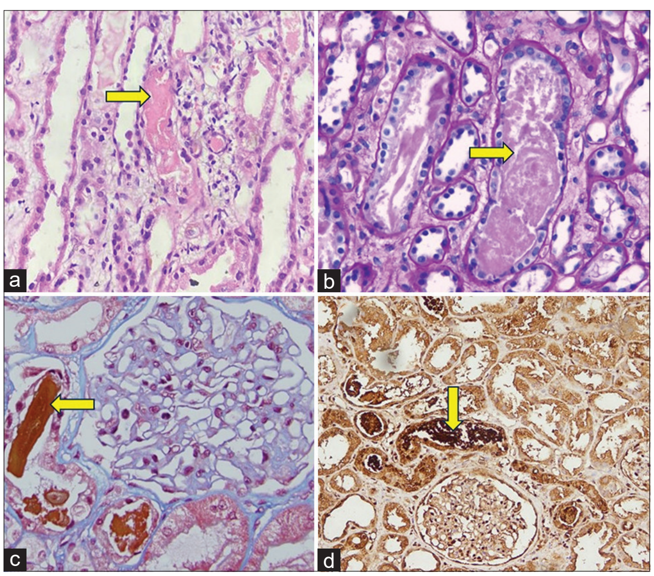

Figure 1: Histopathological findings of myoglobin casts (yellow arrows) of the renal tubules. These casts are granular eosinophilic pigment casts on hematoxylin and eosin staining (a), which are weakly positive on Periodic acid–Schiff staining (b) and bright red on Masson trichrome staining (c). Immunohistochemistry for myoglobin (d) confirmed the diagnosis. Note the normal glomeruli and the diffuse flattening of tubular epithelial cells. Reproduced after modification from Islam *et al*.,[7] which is distributed under the terms of the Creative Commons Attribution 4.0 International License

Methods

PubMed was searched on March 1, 2023, using general terms, including earthquake, crush injury, and rhabdomyolysis that were published in English without time restriction. The titles were initially browsed, and abstracts of the articles of interest were then read. Related articles on the topic were selected and downloaded using access to the National Medical Library of the United Arab Emirates University.[12] If the articles were not available through this access, then they were requested through other international resources. The search was repeated on November 19, 2023, using the more general terms of Turkey, and earthquakes starting from February 1, 2023, to cover recent publications on Kahramanmaraş 2023, Turkey twin earthquakes. Further relevant articles were retrieved from the references of the studied articles. The retrieved articles were divided and allocated to four experts in: (1) emergency medicine (AAC), (2) vascular surgery (AJ), (3) critical care medicine (KI), and (4) acute care surgery and disaster medicine (FAZ), to cover areas relevant to their expertise. The allocated selected literature was critically read and summarized using tables when applicable. The senior author (FAZ) has finally restructured the review, critically read, and repeatedly edited it. When needed, illustrations were retrieved from open-access sources or were drawn by the authors. Due to the extent of the topic and differences in the management resources of the prehospital and hospital settings, the review was split into two sections; the first one addressing the prehospital management of crush injuries has already been published,[10] and the current one which addresses the hospital-based surgical and critical care management of earthquake musculoskeletal injuries, crush syndrome, and AKI.

At Arrival to the Hospital

It is important to perform hospital-based triage whenever the patients arrive at the hospital, and actively manage and resuscitate them accordingly. It is preferred to perform the triage in a wide area outside the hospital to better organize the flow of the patients.[13] Triage classifies patients based on the medically required resources relevant to the available ones. It is based on Airway, Bleeding, and Circulation priorities.[14] The patients are then moved to color zones according to their severity. These include (1) red zone for life-threatening conditions that can be saved; (2) yellow zone for urgent less severe injuries; (3) green zone for minor injuries; (4) gray zone for nonsalvageable patients who arrive alive (Expectant); and (5) black zone for dead patients.[14,15]

Patients are then managed according to the hospital-based advanced trauma life support guidelines, even if this has been done before in another location. This should include both the primary physiological survey (Airway, Breathing, Circulation, Disability, Exposure, and Environmental control) and the anatomical secondary survey (head to toe, front and back, including rectal examination).[14] Focused Assessment Sonography of Trauma is a useful adjunct to this survey.[14,16,17] Whole-body trauma computed tomography (CT) scan is then done, if available and affordable. It was useful for the diagnosis of injuries of the victims of Kahramanmaraş earthquakes in 2023.[18] A tertiary survey should be repeated in the ward or the intensive care unit (ICU) after admission to check occult missed injuries in hospitalized patients.[19] The injuries that are missed at initial management in the Emergency Department and were detected by tertiary survey has an average (range) of 4.3% (1.3%–65%) of the admitted trauma patients.[20]

Management of Musculoskeletal Injuries

Table 1 shows 12 papers[4,21-31] that addressed the management of musculoskeletal injuries during the period of 2001–2023, one of them[24] compared two different earthquakes (Wenchuan 2008, and Yushu 2010). The papers stemmed from five countries, including Turkey (6 studies), China (4 studies), Nepal, India, and Haiti (1 study each). They reported data from 7 earthquakes, including Kahramanmaras 2023 (5 studies), Wenchuan 2008 (3 studies), Gujarat 2001, Yushu 2010, Haiti 2010, Van 2011, and Nepal 2015 earthquakes, (1 study each). Majority had a Severity Richter Scale of ≥7 and were retrospective, except the one by Giri *et al*.[27] which was prospective. The papers studied a median (range) of 533 (124–3292) patients. The data of the studies were used to analyze the distribution, complications [Table 2], and surgical management [Table 3] of earthquake musculoskeletal injuries.

Wound management

Soft tissue injuries are the most common type of crush injuries, with the lower limb being mostly affected.[8,30,32,33] Ulusoy studied the wound types in 94 patients. The most common types were abrasions (50%), crush dry necrosis (46.8%), stump infection (26.6%), and crush infected necrosis (22.3%). Necrotizing fasciitis occurred in 4.2%.[33] Table 4 summarizes the basic principles of wound management of earthquake injuries. The wound should be cleaned, debrided, and irrigated with saline. The wound then should be repeatedly dressed and checked every 2 days by a wound care nurse if available. Surgical re-debridement should be done as needed.

Topical negative pressure wound therapy (NWPT) applies sub-atmospheric pressure to the surface of a wound to improve wound healing by draining the exudate and encouraging granulation tissue.[34,35] This was the most common wound care method used by Ulusoy *et al*. in 94 earthquake victims[33] Kılıçarslan *et al*.[36] retrospectively compared a less expensive method of subcuticular polydioxanone (PDS) traction (n = 30) with a more expensive method of Vacuum Assisted Closure (VAC) (n = 22). The PDS group had significantly more primary closure without a need for skin grafts compared with VAC (14 (46.7%) compared with 4 (18.2%), P = 0.04, Fisher's exact test) favoring the cheap subcuticular PDS traction. The times needed for closure and infection rates were similar between the two groups.[36] Plastic surgeons should be involved early to plan the management of complex earthquake wounds. Ergani *et al*.[37] have treated 120 Kahramanmaraş earthquake injured patients in the Plastic Surgery Department, 41% were in the ICU. Seven (5.8%) patients had NPWT, skin grafts were performed in 59 (49.17%) patients, while free flaps were done in 14 (11.67%) patients. Three patients died (2.5%).[37]

Crush injuries are susceptible to wound infection. Those having open comminuted fractures are more prone to have

Table 1: Selected articles that reported the management of musculoskeletal earthquake injuries

Authors	Reference	Earthquake	Country	Year	Severity Richter scale	Number of patients	Type of the study
Phalkey *et al*.	[21]	Gujarat	India	2001	7.9	575	Retrospective
Dai *et al*.	[22]	Wenchuan	China	2008	8	205	Retrospective
Yang *et al*.	[23]	Wenchuan	China	2008	8	533	Retrospective
Min *et al*.	[24]	Wenchuan	China	2008	8	2283	Retrospective
Min *et al*.	[24]	Yushu	China	2010	7.1	170	Retrospective
Bar-On *et al*.	[25]	Haiti	Haiti	2010	7	684	Retrospective
Guner *et al*.	[26]	Van	Turkey	2011	7.2 and 5.7 (twin)	3292	Retrospective
Giri *et al*.	[27]	Nepal	Nepal	2015	7.8 and 7.3 (twin)	815	Prospective
Kulakoğlu *et al*.	[4]	Kahramanmaras	Turkey	2023	7.8 and 7.6 (twin)	957	Retrospective
Akkaya *et al*.	[28]	Kahramanmaras	Turkey	2023	7.8 and 7.6 (twin)	338	Retrospective
Özdemir *et al*.	[29]	Kahramanmaras	Turkey	2023	7.8 and 7.6 (twin)	439	Retrospective
Gürü *et al*.	[30]	Kahramanmaras	Turkey	2023	7.8 and 7.6 (twin)	124	Retrospective
Gökmen and Uluöz	[31]	Kahramanmaras	Turkey	2023	7.8 and 7.6 (twin)	1092	Retrospective

Table 2: Distribution and complications of musculoskeletal earthquake injuries

Authors	LL, *n* (%)	UL, *n* (%)	Fractures, *n* (%)	Crush syndrome, *n* (%)	ACS, *n* (%)	Amputation, *n* (%)	Wound infection, *n* (%)
Phalkey *et al.*	204/534 (38.2)	52/534 (9.7)	293/534 (54.87)	31/534 (5.8)	NA	38/564 (6.7)	78/503 (15.5)
Dai *et al.*	176/349 (50.4)*	63/349 (18.1)*	160/205 (78)	19 (9.3)	18 (8.8)	10 (4.9)	71 (34.6)
Yang *et al.*	NA	NA	NA	21 (3.9)	7 (1.3)	32 (6)	59 (11.1)
Min *et al.*	693/1148 (60.4)*	249/1148 (21.7)*	891/2283 (39)	66/2283 (2.9)	NA	85/2283 (3.7)	NA
Min *et al.*	57/70 (81.4)*	13/70 (18.6)*	53/170 (31.1)	4/170 (2.4)	NA	1/170 (0.6)	NA
Bar-On *et al.*	227/360 (63.1)*	84/360 (23.3)*	320 (47)	8 (1.2)	NA	22 (3)	NA
Guner *et al.*	205/442 (46.4)*	138/442 (31.2)*	442/3292 (13.4)	41/3292 (1.2)	40 (1.2)	12/501 (2.4)	NA
Giri *et al.*	520 (48)*	219 (20.2)*	624 (58)*	36 (3)*	18 (2)*	5 (0.4)*	NA
Kulakoğlu *et al.*	104/212 (49)*	62/212 (29.2)*	202/957 (21.1)	NA	20 (2.1)	4/957 (0.4)	NA
Akkaya *et al.*	NA	NA	338/2981 (11.3)	NA	NA	39/338 (11.5)	NA
Özdemir *et al.*	21.9*	59.1*	LL 33.6, UL 20.7*	72 (16.4)	NA	50 (10.6)	NA
Gürü *et al.*	41.9	22.6	27.4	NA	NA	NA	NA
Median (range)	48.5 (21.9–81.4)	22.2 (9.7–59.1)	31.1 (11.3–78)	3 (1.2–16.4)	2 (1.2–8.8)	3.7 (0.4–11.5)	15.5 (11.1–34.6)

*Percentage out of fractures or body region injuries. ACS: Acute compartment syndrome, NA: Not available, LL: Lower limb, UL: Upper limb

Table 3: Surgical management of musculoskeletal earthquake injuries

Authors	Plaster of paris/ spica splint, *n* (%)	External fixation, *n* (%)	Open reduction internal fixation, *n* (%)	Fasciotomy, *n* (%)	Vacuum drainage, *n* (%)
Phalkey *et al.*	100/564 (17.7)	5/564 (1)	94/564 (16.7)	NA	NA
Dai *et al.*	NA	32/246 (13)*	51/246 (20.7)*	NA	NA
Min *et al.*	NA	119/1018 (11.7)*	283/1018 (27.8)*	NA	117/1018 (11.5)
Min *et al.*	NA	1/64 (1.6)*	49/64 (76.6)*	NA	2/64 (3.1)*
Bar-On *et al.*	16/684 (2.3)	73/684 (10.6)	0	NA	NA
Guner *et al.*	91/501 (18.2)	37/501 (7.4)	117/501 (23.4)	31/501 (6.2)	NA
Kulakoğlu *et al.*	NA	14/212 (6.6)*	28/212 (13.2)*	27/957 (2.8)	23 (2.4)
Akkaya *et al.*	165/338 (48.8)	11/173 (6.4)*	63/173 (36.4)*	47/173 (27.2)*	NA
Özdemir *et al.*	183 (41.7)	21 (4.5)	99 (21)	118 (23.8)	Routine use
Median (range)	18.2 (2.3–48.8)	6.6 (1–13)	21 (0–76.6)	15 (2.8–27.2)	3.1 (2.4–11.5)

*Percentages are out of operations performed, none reported the use of hyperbaric oxygen therapy. NA: Not available

osteomyelitis. Wound infection in earthquake victims occurred in a median (range) of 15.5% (11.1%–34.6%) of patients in different studies [Table 2]. Aerobic bacteria, including Gram-positive and Gram-negative bacteria, are common. Some patients may develop anaerobic infection.[15,23] The bacteriological culture will differ in those hospitalized for a long time. Wound infection occurred in 62/92 (66%) hospitalized patients having complex wounds. The most common bacteria in these patients were Pseudomonas aeruginosa and Acinetobacter baumanii.[33] Patients who have deep open irregular wounds of more than 6 h duration, necrosis, ischemia, infection, or foreign bodies are more prone to have tetanus infection.[15] Risk factors for increased infection in crush syndrome include the time of muscle compression before extrication from the rubble, performing a fasciotomy, and the period of renal impairment.[38] This may progress to severe sepsis, adult respiratory distress syndrome, disseminated intravascular coagulation, and even death.[8,39]

Contaminated wounds and open fractures should receive prophylactic antibiotics. The Worldwide Antimicrobial Resistance National/International Network Group Collaborators has published its golden rules for optimal antibiotic use. These include: (1) to give the appropriate antibiotic(s) to the right patient, at the right time, with the right dose, right route, and right duration; (2) to initiate, as soon as possible, targeted treatment based on the results of bacterial culture and susceptibility testing. This will narrow the initial empirical treatment which was required; and (3) to control the source of infection, which is of utmost importance, like repeated debridement of necrotic tissues as much as needed.[35,40] The recommendations for the management of crush victims in mass disasters state that: "Assume all open wounds are contaminated. Consider surgical debridement, in addition to antibiotics, in the presence of necrosis or significant infection. Obtain cultures before initiation of antibiotics. Administer tetanus toxoid to all patients with open wounds, unless in those who have definitely been vaccinated within the last 5 years."[15] Tetanus human immunoglobulin should be administered to patients who have wounds of more than 12 h, being heavily contaminated, especially in obese patients.[15]

Fracture management

Table 2 shows the distribution and complications of musculoskeletal earthquake injuries. The lower limb

Table 4: Basics of wound management in earthquake injuries

Take a proper history of time and mechanism of injury, extrication time, environmental conditions, and prehospital management
Address the tetanus risk and the need for tetanus vaccine and immunoglobulin
Decide the need for antibiotic therapy
Follow the principles of antibiotic administration and tailor it based on the wound nature, presence of fracture, region of injury, presence of infection, local bacteriological setting, and bacteriological culture results
Properly debride lacerated wounds when needed
Change dressing every 2–3 days, depending on resources
Aim at delayed primary closure using VAC dressing if available
Review the wound and re-debride as needed
Do not ignore the need for analgesics
Consider the need for sedation or general anesthesia, and asses their risks before debridement
Once the wound becomes clean, consider delayed closure/skin graft and fracture management
Involve the wound care nursing and experts if available
Consult the plastic surgeons early when needed

VAC: Vacuum-assisted closure

was the most common injured region which affected a median (range) of 48.5% (21.9%–81.4%) regions/patients. The upper limb affected a median (range) of 22.2% (9.7%–59.1%) regions/patients. Fractures occurred in a median (range) of 31.1% (11.3%–78%) regions/patients. A systematic review, that covered the period of 2000–2014, analyzed 35 papers. It showed that fractures were more in lower (42.12%) compared with upper limbs (19.57%). Closed fractures were three times more common than open fractures (64.96% compared with 21.36%).[41]

Table 3 summarizes the surgical management of musculoskeletal earthquake injuries of the studied papers in the current review. The most common method was open reduction and internal fixation (ORIF), which was done in a median (range) of 21% (0%–76.6%) of the patients, followed by nonoperative methods (Plaster of Paris), which was done in a median (range) of 18.2% (2.3%–48.8%) of the patients; and finally, external fixation which was done in 6.6% (1%–13%) of the patients. The previously mentioned systematic review showed that ORIF was performed in 10.23%, external fixation in 5.38% and amputation in 1.23% of the patients. Each patient had an average of 0.99 operations.[41]

Open fractures should be treated initially with external fixation after cleaning and debridement of the wounds. Patients should receive antibiotics. Internal fixation should not be done until the wound becomes clean and fractures are properly covered with skin, skin graft, or flap. Severely injured limbs can be complicated with nonunion or osteomyelitis. These may need special expertise and techniques, like the Ilizarov method.[42] The surgical principles of this technique are debridement, soft tissue coverage, and stable fixation of the fracture to allow weight-bearing. Tilkeridis *et al*. used this method in eleven patients; fractures united in ten patients, while only one ended with an amputation.[42]

Early on, crushed limbs are mildly painful secondary to neuropraxia, which may mask compartment syndrome. Pain then increases and can be extremely severe. Analgesia should be given as needed. Ketamine and narcotics can be given, but nonsteroidal anti-inflammatory drugs should be avoided because of their possible effects on the kidneys.[11,15]

Diagnosis of acute compartment syndrome

Early diagnosis of ACS, although challenging, is essential for favorable clinical outcome. ACS occurred in a median (range) of 2% (1.2%–8.8%) of regions/patients [Table 2]. Despite progress in methods of measurement of intra-compartmental pressure (ICP), clinical assessment remains the cornerstone for the diagnosis. This is even more important in major disasters when clinicians depend on their clinical examination because it takes a shorter time, can be repeated, and has less risk of limb infection.[10] Accurate diagnosis of ACS will avoid the side effects of unnecessary fasciotomies. Delayed diagnosis may lead to limb loss or even death. The clinical symptoms and signs of ACS and its diagnosis, including the measurement of the ICP had been described in detail in our first review on the management of earthquake crush injuries.[10] Clinical findings include pain out of proportion of the clinical findings, pallor, paraesthesia, paralysis, and pulselessness. Pain exacerbated by passive stretching of the muscles is the most accurate sign of ACS.[10] High clinical suspicion is very important for diagnosing ACS. Taking attention to pain severity, which can be scored overtime on a numerical scale by a conscious patient, can be helpful (a scale of 0–10, where 0 = no pain while 10 = the most severe pain) [Figure 2]. Initially, the extremity pain can be mild due to neuropraxia or distraction pain, but then it becomes agonizing during the occlusion of the microcirculation. Pedal pulses can be felt at this stage because the major vessels are not yet occluded. When the leg becomes dead, the pain subsides, and the foot pulses may disappear or become weaker. Severe pain not responding to intravenous narcotics should raise the suspicion of ischemia because drugs cannot reach the nerve endings in the ischemic limb. This approach of active observation can be restricted in the prehospital setting when treating doctors are occupied in the management of mass causalities but is useful in hospitals where there is enough manpower.

Nevertheless, clinical manifestations are not reliable in unconscious patients, ventilated patients, and

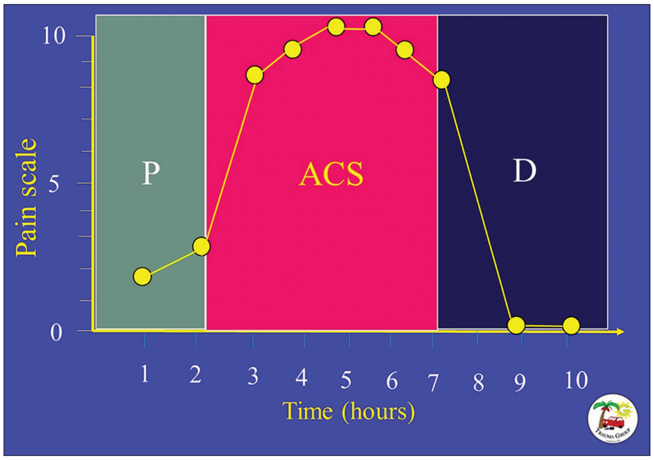

Figure 2: A theoretical example of the progress of leg pain over time in a severe case of acute compartment syndrome (ACS). This can be scored on a numerical pain scale of 0–10 (0 = no pain, 10 = the most severe pain). At early stage (P) the extremity pain can be mild due to neuropraxia or distraction pain but then it becomes agonizing during the occlusion of the microcirculation of the leg (ACS). If the leg becomes dead (D), the pain may subside. (Illustrated by Professor Fikri Abu-Zidan, Professor of Disaster Medicine, The Research Office, College of Medicine and Health Sciences, United Arab Emirates University)

children. Beware that the severity of pain can be deceiving in diabetic patients having neuropathy. Measurement of the ICP can be done either directly, by inserting a needle that is connected to a pressure monitor, or indirectly, by measuring an increase in limb circumference.[10] Normal ICP should be <10 mmHg. Fasciotomy is recommended if the ICP is >30 mmHg or if the delta pressure (diastolic blood pressure minus the direct compartment pressure, also termed perfusion pressure) is <20–30 mmHg.[43] The needle technique of ICP measurement is invasive and painful, with concerns regarding its accuracy and reliability, which impeded its widespread use. This increases the need for non-invasive, reliable, low cost and safe methods like ultrasound for measuring ICP.

Ultrasound

Ultrasound is a useful diagnostic tool in disasters, such as earthquakes. It is simple, rapid, feasible, light, portable, can be done bedside, and uses rechargeable batteries for up to 8 h.[44] Furthermore, it is useful in the diagnosis of musculoskeletal injuries and monitoring fluid resuscitation by measuring the size of the inferior vena cava when there is concern over fluid overload.[45,46] A study of 50 patients of the Wenchuan earthquake 2008 with rhabdomyolysis and 18 patients with both rhabdomyolysis and compartment syndrome showed that ultrasound findings included: (1) edema of the subcutaneous tissue, (2) thickened striated muscle, (3) good continuity, (4) vague muscle texture, and (5) enhanced echo.[47] Sonographic findings when compartment syndrome was present included: (1) increased volume of the striated muscles, (2) arched protrusion and displacement of the fascia of the affected muscles, and (3) poor blood flow filling of the distal arteries with monophasic waveform and low-speed spectrum.[47] Furthermore, ultrasound can guide needle insertion into the muscular compartments to correctly measure ICP instead of a blind technique.[48]

Two-dimensional ultrasound shear-wave elastography uses shear waves to quantitatively measure tissue stiffness. It is a safe, real-time, non-invasive, painless imaging technique that can assess different compartments, and can be used for dynamic monitoring and evaluation. It can be effective in diagnosing ACS. Zhang *et al*. studied nine patients with clinical suspicion of ACS. A statistically significant difference was observed in the elasticity of the muscles between the affected and unaffected sides in the fasciotomy groups.[49] Nevertheless, it has a high cost and limited availability. Sellei *et al*.[50] measured muscle compartment relative elasticity (RE) by ultrasound in lower limbs to diagnose ACS. These values were compared with the invasive needle measurement. The RE in the healthy compartments revealed a mean level of 17.95%, whereas the RE of the affected limbs significantly decreased to a mean of 5.14% ($P < 0.0001$). RE <10.5% of the anterior tibial compartment had a sensitivity of 95.8% and a specificity of 87.5% for diagnosing ACS.[50]

An experimental model of ACS was generated in 40 legs (20 human cadavers) by infusion of saline into the anterior compartment of the leg to incrementally increase ICP from 10 to 100 mmHg. The angle between the anterolateral cortex of the tibia and the fascia of the anterior compartment was measured at each 10-mmHg pressure increase using ultrasound. ICP of the anterior compartment of the calf could be estimated in this model.[51] A dual-sensor (ultrasound and pressure) technology to detect elevated muscle ICP was also tested on a cadaver model of elevated ICP in 6 cadaver legs. The width of the anterior compartment and the pressure needed to flatten the bulging superficial compartment fascia were measured. These measurements had a high correlation with the ICP.[52] Marmor *et al*.[53] examined the use of these findings in the clinical setting in 52 patients. Patients with tibia fractures were prospectively enrolled. Observers used a dual-sensor probe to measure the amount of pressure required to flatten the anterior compartment fascia. Direct ICP measurements and fasciotomy were done for suspected ACS. Nine patients underwent fasciotomy for a clinical diagnosis of ACS. The pressures were significantly higher in the fasciotomy group compared with the nonfasciotomy group. This suggests that ultrasound may replace direct ICP measurements in the future. Nevertheless, clinical trials with a large number of subjects are needed to validate these findings.[53]

Computed tomography and magnetic resonance imaging

CT is not formally used to determine the need for fasciotomy; however, CT findings of rhabdomyolysis, including focal areas of muscle hypoattenuation and enlarged edematous musculature, may raise the suspicion of ACS. Peripherally enhancing intramuscular collections indicate progression to myonecrosis.[54,55] In many patients with suspected rhabdomyolysis, iodinated contrast is often not administered to avoid further insult to the kidneys.[55]

Magnetic resonance imaging (MRI) is useful in evaluating a painful, swollen leg and can be helpful in identifying the cause of compartment syndrome. Chawla *et al*.[56] described the MRI features of various conditions causing painful swollen legs in T1 weighted (T1W), Fat-sat T2W, and postcontrast phase.[56] The T1W findings include: (1) swollen muscle, (2) thickening of skin, subcutaneous tissue, and fascial planes, (3) hyperintense acute hematoma, and (4) fractures. The Fat-sat T2W findings include hyperintense signals in the skin, subcutaneous tissue with swollen fat, and hyperintense signals in the muscles, while the post-contrast images show diffuse enhancement of muscles with or without areas of necrosis.[56] The MRI has certain limitations: (1) It is usually not available in emergency settings, (2) it needs more time, (3) it is more expensive, (4) its findings are not specific, and (5) relevant clinical information are vital for making the correct diagnosis. This will limit its role during an earthquake disaster but may be used for follow-up in main hospitals away from the earthquake center.

Fasciotomy

The role of fasciotomy in the management of crush injuries is debatable.[11,57] Those who support it think that it will dramatically reduce the compartment pressure, improving the blood perfusion of a limb.[58] If done, this should be within 6 h of injury, depending on the acuteness of the onset; otherwise, tissues become necrotic, having a high risk of ischemia reperfusion injury. Understandably, fasciotomy should not be done for dead limbs. This has no benefit, and it just increases the deleterious effects of the ischemia-reperfusion injury. Others think that this procedure should not be done because it increases the risks of bleeding and infection, leading to sepsis.[8,59] Reis and Better,[11] after critically reviewing the literature, concluded that "fasciotomy is contraindicated in patients with closed acute muscle crush compartment syndrome" because it does not improve the clinical outcome. Earthquake crush injuries differ from acute arterial ischemia because they cause direct muscle injury besides the ACS.[11]

If a decision to perform a fasciotomy was made, it should be done properly. Although it is a simple surgical procedure, care should be taken about its details. The length of the incision should be adequate otherwise it can make constrictive rings of the skin, which may acutely jeopardize the circulation. Fasciotomy was performed in a median (range) of 15% (2.8%–27.2%) of body regions/patients in our analyzed studies [Table 2]. Figures 3 and 4 show the two recommended incisions to relieve the four leg compartments. These compartments are the anterior, lateral, deep posterior, and superficial posterior. Excision of necrotic tissues is essential. It is usually incomplete due to severe bleeding. Principles of damage control surgery should be applied by packing and correcting the coagulopathy before repeating the debridement. Debridement usually needs to be repeated under intraosseous ketamine or general anesthesia.[11,60]

The long-term effects of fasciotomy following crush syndrome need to be more clarified. Matsuoka *et al*.[61] studied the function of 52 crushed limbs of 42 patients injured during the 1995 Hanshin-Awaji earthquake, Japan. Severe disabilities related to the fasciotomy were higher with those having fasciotomy compared with those who did not (8/17 (47%) compared with 4/25, (16%) although not significant ($P = 0.09$, Fishers' exact test) possibly due to the small sample size. Subgroup analysis showed that the damage was significantly more severe in the anterior compartment, toe flexors, and toe extensors. The authors concluded that fasciotomy did not improve the clinical outcome and suggested more studies to be done.[61] Similarly, Safari *et al*.[62] evaluated the outcome of fasciotomy in patients who had AKI in the 2003 Bam earthquake, Iran. They compared 70 patients who had fasciotomy with 130 patients who did not have fasciotomy. There was no statistical difference between the two groups in sepsis, amputation, the need for dialysis, hospital stay,

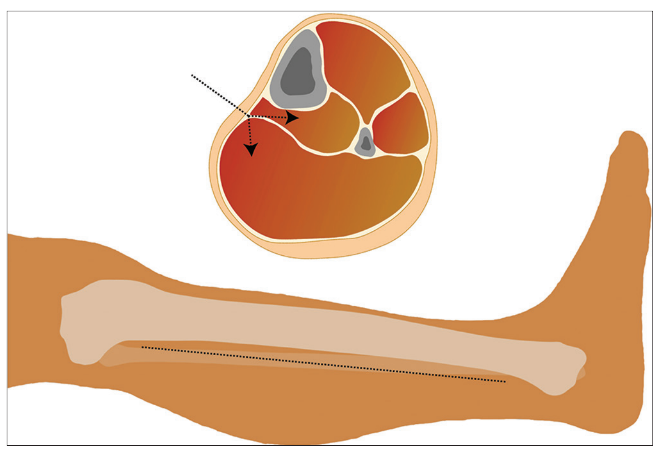

Figure 3: The posteromedial surgical incision in which both the deep and superficial posterior muscle compartments are opened through the same incision. Black doted arrows indicate the direction of the incision in the deep tissues to open the compartments (Illustrated by Professor Arif Alper Cevik, Section of Emergency Medicine, Department of Internal Medicine, College of Medicine and Health Sciences, United Arab Emirates University)

and mortality (8.1% compared with 11.9%). The authors concluded that fasciotomy did not worsen the clinical outcome in the patients who had crush-induced AKI.[62] Out of 323 AKI patients who had fasciotomies, 25% had sepsis, and 16.4% died. In comparison, 316 patients, who did not have fasciotomies, had significantly less sepsis (13%, $P < 0.001$) but statistically similar mortality (13.9%, $P = 0.38$).[63] The recommendations for the management of crush victims in mass disasters state that "Unless clearly indicated by physical findings or ICP measurements, do not perform fasciotomies routinely to prevent compartment syndrome."[15] This area needs more future studies simply because surgeons treating patients at normal conditions would transfer their daily practice and experience to disaster situations. For example, out of 84 extremity injuries in 237 crush syndrome patients, 70 (83%) had fasciotomies, 32 (38.1%) had amputations.[64] Similarly, Gökmen and Uluöz studied 1092 patients with musculoskeletal injuries treated by orthopedic surgeons of whom 327 (30%) patients had fasciotomies.[31] Out of 120 patients treated by plastic surgeons, 75 (62.5%) had fasciotomies.[37] This may reflect either selection bias by treating more severe patients or concern of having a liberal approach toward fasciotomies and amputations. We think that fasciotomy should not be done routinely for earthquake-crushed limbs. It should be individualized depending on the time of injury, the risk of distal gangrene, and the definite diagnosis of ACS.

Amputations

Limb amputations were performed in a median (range) of 3.7% (0.4%–11.5%) of body regions/patients in our analyzed studies [Table 2]. Although some victims may require on-filed limb amputation, this is only recommended as a life-saving measure to rescue the victim, and not to prevent crush syndrome. It should be the last resort to extricate a trapped, crushed patient.[15] Prophylactic amputation to prevent the crush syndrome has no evidence and should not be practiced[8] If amputation is required, intravenous/intraosseous ketamine at a dose of 1–4.5 mg/kg for 1–2 min is the drug of choice as it provides proper sedation, analgesia, and amnesia while maintaining spontaneous breathing and gag reflexes of the patient.[60]

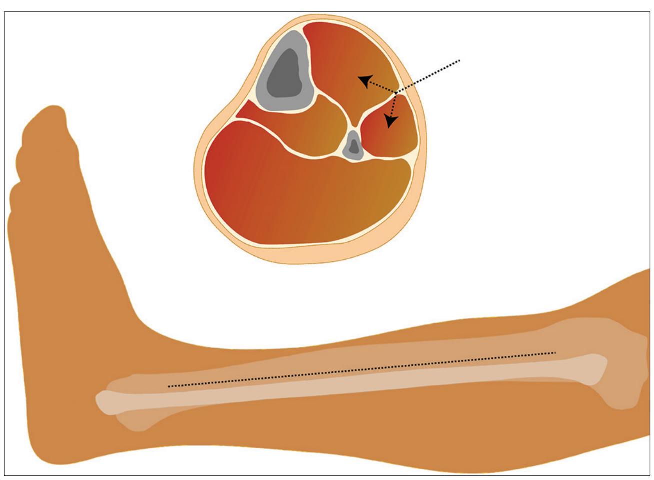

Figure 4: The anterolateral surgical incision in which both the anterior and lateral muscle compartments are opened through the same incision. Black dotted arrows indicate the direction of the incision in the deep tissues to open the compartments. (Illustrated by Professor Arif Alper Cevik, Section of Emergency Medicine, Department of Internal Medicine, College of Medicine and Health Sciences, United Arab Emirates University)

Deciding which crushed injured limb is viable and should receive further treatment and which one needs amputation is an important decision to be made in the field. This decision also affects the triage to appropriate units and transport methods. The mangled extremity severity score (MESS) is useful for this decision.[65] A patient with a score of 7 or above should be considered for amputation. The recommendations for the management of crush victims in mass disasters state that "(1) Amputate a compromised limb if it jeopardizes the patient's life; (2) Perform amputations only based on strict indications; (3) When clearly indicated, have amputations performed as early as possible."[15]

Hyperbaric oxygen therapy

Hyperbaric oxygen therapy (HBOT) delivers 100% oxygen at a pressure of 2–3 absolute atmospheres [Figure 5]. It helps in one of the following ways: (1) increasing the oxygen delivery to tissues aiming at keeping partially injured tissues viable, (2) reducing tissue edema, (3) reducing the reperfusion injury, (4) improving the leukocytes function, (5) inhibiting anaerobic bacterial growth, and (6) enhancing antibiotic activity.[34,66] Nevertheless, it needs proper logistics, facilities, preparation, and experience if it is going to be practiced. It has been recommended in Turkey because of available resources and proper training.[57] A recent study has shown that it was used in 33 out of 84 (39.2%) of extremity-injured patients having a crush syndrome.[64] Aktas stated that the aim of an HBOT Unit should be to

Figure 5: An earthquake-injured patient, who stayed under the rubble for 144 h in cold weather, had frostbite (a). Appearance after 18 sessions of hyperbaric oxygen therapy (b). Reproduced from Ulusoy *et al*.[33] which is an open-access article under the terms of the Creative Commons Attribution-NonCommercial License (http://creativecommons.org/licenses/by-nc/4.0/)

save the tissues and functions of an injured crushed limbs, to treat its complications, including nonhealing wounds and osteomyelitis, to save the limb from amputation, and to save the life of the patient.[57] It is not commonly used by many centers. None of the 12 analyzed papers in Table 1 used it except Gökmen and Uluöz[31] who used it when fasciotomies were infected, following the advice of an infectious disease specialist. Nevertheless, they did not report their results. Ergani *et al*.[37] utilized HBOT for 21 (28%) out of 75 patients who had fasciotomy. Amputation was performed only in 4 patients out of these 75 patients (5.3% of fasciotomies, and 19% of those having HBOT). Nevertheless, upper limbs, which usually have good blood supply, constituted 78.7% of those who had fasciotomies, explaining these good results and indicating a selection bias of these reported data.[37] A recent study by Kilic *et al*. studied 23 patients having severe earthquake crush injury with a MESS ≥7 who initially refused amputation. The clinical level of amputation was decided before giving daily HBOT for an average of 26.5 h. 22 (96%) had an amputation at the same level decided before the HBOT. The authors concluded that HBOT results were not satisfactory in those having postfasciotomy severe muscle necrosis and severely mangled limbs.[67] This study highlights the importance of selecting the proper therapeutic window when using HBOT as an adjunct to surgery. Furthermore, it is important to stress that HBOT, when used, should not interfere, or delay the standard care of patients.[34]

Management of Crush Syndrome

A systematic review covering the period of 2000–2014 showed that crush injuries occurred in 0.91% of the patients having soft-tissue injuries.[41] Crushed syndrome occurred in a median (range) of 3% (1.2%–16.4%) of regions/patients in our analyzed studies [Table 2]. Diagnosis of crush injury rhabdomyolysis depends on three findings: (1) a crushed limb, (2) dark urine, and (3) elevated concentration of serum creatinine phosphokinase (CPK) of more than five times the upper normal limit which is around 1000 U/L.[8,68] Kundakci *et al*.[69] have shown that those who have bilateral thigh and leg injuries had significantly more CPK (more than double) and death rates compared with those having unilateral leg and thigh injuries (mortality of 13.2% compared with 7.5% for bilateral and unilateral thigh injuries consecutively; mortality of 16.4% compared with 3.2% for bilateral and unilateral leg injuries consecutively).[69]

Table 5 shows a checklist for the management of acute crush syndrome. This management needs to be started as soon as possible to prevent AKI or reduce its severity. Muscle toxin release and hypovolemia are the main reasons behind the crush syndrome. Accordingly, crush syndrome clinical assessment should include a careful search for shock findings, including hypotension, altered mental status, dry mucosa, delayed capillary refill time, decreased skin turgor and tonus, skin color, and temperature changes. Regardless of these findings, intravenous/intraosseous line should be established, and fluid resuscitation should be started with infusion at a rate of 1–1.5 L/h in adults (10–20 ml/kg/h for children) for the first 2 h, and then decreasing infusion to 500 ml/h in adults (10 ml/kg/h for children)[15,70] aiming to maintain a urine output of around 200–300 ml/h.[9] Patients should be monitored at regular intervals during the first 6 h to check their response and whether fluids have to be reduced. Fluid volume should be individualized depending on age, hemodynamic status, clinical findings, urine output, environmental conditions, and logistical considerations.[15] Measuring the diameter of inferior vena cava by point-of-care ultrasound (POCUS) can be helpful in guiding fluid resuscitation.[46]

Table 5: Checklist for the management of acute crush syndrome

Investigations
Blood tests: CBC, ABG, CPK, CMP
Coagulation profile: PT, aPTT, INR, fibrinogen
Urine tests: Dipstick and urine sediments
12-lead ECG to assess findings for hyperkalemia or hypocalcemia
Management
Start aggressive intravenous fluids to maintain a urine output of around 200–300 mL/h
Monitor potassium every 4 h and manage hyperkalemia aggressively
Correct hypocalcemia only when symptomatic (tetany or seizures)
Consult a nephrologist when dialysis is indicated including volume overload, hyperkalemia, severe acidemia, and uremia

CBC: Complete blood count, ABG: Arterial blood gas, CPK: Creatine phosphokinase, CMP: Comprehensive metabolic panel, ECG: Electrocardiogram, PT: Prothrombin time, aPTT: Activated partial thromboplastin time, INR: International normalized ratio

Alkalinization with sodium bicarbonate, keeping the urine pH >6.5, is recommended to prevent myoglobin and uric acid deposition in the renal tubules.[8,71] Mannitol with a maximum 2 g/kg/day (max 200 g/day) helps to prevent acute renal failure caused by myoglobinuria.[70] Mannitol should be used cautiously because it may itself induce renal failure.[72]

Victims may suffer from electrolyte and acid-base abnormalities such as hyperkalemia, hypocalcemia, and acidosis, which may cause cardiac arrhythmias and arrest. Early investigations for serum electrolytes, blood pH, and ECG may help to early detect cardiac arrhythmias and treat them. Patients with hyperkalemia should be treated empirically with potassium-binding resins.[8] Inhaled antiasthmatic beta-2 adrenoceptor agonists can be used to treat hyperkalemia in the early phase of rescue.[70]

Urine output should be continuously monitored; conscious patients should be asked to urinate in a container; condom catheters should be used in male patients if controlled urination is not achievable. After ensuring that the patient does not have urethral bleeding or perineal laceration, an indwelling bladder catheter should be inserted if there is no urine flow after administering the necessary amount of fluid for resuscitation.[15] Spinal cord injuries may cause urinary retention despite having normal renal function. POCUS evaluating the urinary bladder volume can be useful in this situation.

Following the Great Marmara earthquake of 1999, Demirkiran *et al*.[73] recommended transferring crushed injured patients as soon as possible to well-prepared critical care units at hospitals, to receive proper therapy.[73] In comparison, Li *et al*.[74] advocated the use of an on-field critical care unit which was close to the epicenter of the 2008 Wenchuan earthquake in China, so as to monitor and treat earthquake severe multiple trauma patients.[74] Although the installation of temporary dialysis equipment close to a disaster zone can be advantageous, it requires adequate water sources and can only accommodate a small number of patients.[71] However, it is usually impossible to install improvised dialysis units in the affected area since nearby hospitals are frequently destroyed or at risk of being damaged by aftershocks.[75] Mass crush injuries may produce excess demand for dialysis facilities and critical care units, with a need for more dialysis machines and operators as well as ventilators and critical care health providers. The need for acute hemodialysis may overwhelm local resources and threaten access for chronic hemodialysis patients. There should be an emergency plan to transfer patients who need renal dialysis to other hospitals in the country, as occurred in the Christchurch 2011 earthquake, New Zealand.[76] This may require the activation of surge plans, equipment caches, or secondary transport of casualties to areas with still intact infrastructure able to manage these casualties.[2,76]

Renal Replacement Therapy

AKI, as a component of crush syndrome is frequently fatal if left untreated. It is defined as "*a 1.5-fold increase in serum creatinine or by 0.5* mg/dl *or a decrease in glomerular filtration rate by 50%,* and/or *a reduction in urine output below 0.5* ml/kg/*h for more than 6 h*.[75] However, it is avoidable or reversible with appropriate medical therapy, fluid resuscitation, and/or dialysis.[75] The longer the fluid resuscitation is delayed, or inadequate fluid volume provided, the victims' chance to have AKI increases.[11] Furthermore, sepsis, disseminated intravascular coagulation, adult respiratory distress syndrome, fasciotomy, and amputation are more common among those victims with AKI compared with those without it.[77] Prevention and treatment of secondary insults and complications such as sepsis and shock, especially in the oliguric phase, is very important to improve renal function.[15]

The percentage of patients of crush syndrome that develop AKI varies between different studies depending on fluid resuscitation before arriving to the hospital, the distance between the hospital and the earthquake area, the severity of the crush syndrome, and the studied population. Out of 3184 patients treated at Kayseri State Hospital, Kayseri, Turkey, 639 were hospitalized. 237 (7.4% of those treated and 37% of those hospitalized) patients had crush syndrome. Seventy-one patients (30%) of those who had crush injury needed dialysis, 41 (58%) of them died.[64] Aslan and Bigli[78] studied 18 patients admitted with crush syndrome, 15 (83%) developed AKI of whom 6 (40%) needed kidney replacement therapy. One patient died (5.5%). The preferred mode was hemofiltration.[78] Kundakci *et al*.[69] studied 233 patients with crush syndrome, 132 (56.7%) needed renal dialysis, 72 (30.9%) had amputations, and 41 (17.6%) had fasciotomies.[69] Atmis *et al*. studied 310 pediatric patients admitted with earthquake injuries, 97 (31%) had crush syndrome, and only 22 (23%) needed kidney replacement therapy. This was by hemodialysis in 16 (73%) patients, and by hemodiafiltration in 6 (27%) patients.[79]

Table 6 shows the indications for renal replacement therapy. The method of renal replacement therapy will depend on available resources. The recommendations for the management of crush victims in mass disasters state that: "Although continuous renal replacement therapy or peritoneal dialysis can be used depending on availability and patient needs, prefer intermittent hemodialysis as the first choice of renal replacement therapy."[15] Peritoneal dialysis is technically straightforward, does not require electricity or running water, and may be initiated quickly. But still, it has its challenges, such as the risk of infection, and the need for high amounts of sterile dialysate.[71] While there are limited data on the optimal technique for continuous renal replacement in rhabdomyolysis, a randomized controlled trial on 70 patients reported that myoglobin clearance was

Table 6: Indications for renal replacement therapy

Serum potassium concentration >6.5 mmol/L or its rapid rise
pH ≤7.1 (severe acidosis)
BUN concentration >30 mmol/L
Serum creatinine concentration >700 µmol/L
Uremic symptoms (hypervolemia, encephalopathy, and pericarditis)
Continued oliguria (200 mL/12 h) or anuria (50 mL/12 h) despite adequate fluid resuscitation

BUN: Blood urea nitrogen

improved using continuous veno-venous hemodialysis with high cutoff dialyzer and regional citrate anticoagulation (n = 35) compared with continuous veno-venous hemodiafiltration having high-flux dialyzer with regional citrate anticoagulation (n = 35).[80] Once AKI is established, aggressive intravenous fluid resuscitation is no longer appropriate. Hemodialysis is initiated for the usual indications of volume overload, hyperkalemia, severe acidemia, and uremia [Table 6]. Crush injury can be associated with very rapid and severe onset of hyperkalemia, and occasionally hemodialysis may be required two or more times a day to control further worsening of hyperkalemia**.** Nevertheless, this should be considered depending on the availability of resources.

Other supportive medications can be useful. Sodium polystyrene sulfonate (Kayexalate) should be given orally or rectally to prevent hyperkalemia during reperfusion. It can prevent the intestinal absorption of dietary potassium. It is given either as a preventive measure or in combination with dialysis to treat hyperkalemia. Its side effects include hypokalemia, nausea, vomiting, and rarely bowel necrosis.[15] Acetazolamide can be given intravenously when arterial blood pH is >7.45 (secondary to bicarbonate administration).[15] Allopurinol is a xanthine oxidase inhibitor which reduces the production of oxygen free-radicals and uric acid production. It may be protective against AKI in crush syndrome. Although there is experimental evidence and weak clinical evidence suggesting that allopurinol may be useful in protecting rhabdomyolysis and AKI.[81-83] it cannot be recommended to be given routinely. Guidelines for the management of earthquake crush injuries do not include this drug in their recommendations.[9,15] More evidence is needed to define its role in crush injuries.

Conclusions

Earthquakes may cause severe musculoskeletal injuries, crush syndrome, and acute renal injury in mass multiple injured patients. We have reviewed the hospital-based surgical and critical care management of these conditions aiming to early recognize, and properly manage them. We hope that our review carries the essential knowledge to reach that objective. Due to the low quality of studies on important areas, like indications for fasciotomy, limb amputation, and the use of HBOT, prospective data collection on future medical management of earthquake injuries should be part of disaster preparedness.

Author contribution statement

All authors have contributed to the idea. Fikri M. Abu-Zidan supervised the project, did the literature search, retrieved the literature, critically read and wrote sections on surgical management, organized the structure of the manuscript, and repeatedly edited the manuscript. Ali Jawas critically read and wrote the section on the diagnosis of ACS. Kamal Idris critically read and wrote the section on the management of AKI. Arif Cevik Alper critically read and wrote the section on the management of Crush Syndrome in the Emergency Department and drew Figures 3 and 4. All authors approved the last version of the manuscript.

Conflicts of interest

None Declared.

Ethics approval

Data of the review are publicly published data. The study does not require ethical approval.

Funding

None.

Acknowledgement

The authors thank Dr Nawaf Jurdi, Pathologist, Department of pathology and laboratory medicine, American University of Beirut, Lebanon, for reviewing the modifications of Figure 1.

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