Cutaneous and Ocular Toxicology, 25: 67–83, 2006

ISSN: 1556-9527 print/1556-9535 online
DOI: 10.1080/15569520600695520

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WATER DECONTAMINATION OF CHEMICAL SKIN/EYE SPLASHES: A CRITICAL REVIEW

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Skin/eye chemical splashes are a significant workplace problem. Initial water decontamination is usually recommended, but there are few well-conducted experimental animal and human studies of efficacy. An extensive review of the literature and other available information sources was performed to define the scope of the problem and critically review the evidence for water decontamination efficacy. Although water decontamination can decrease the severity of chemical skin/eye burns, it cannot completely prevent them. An ideal replacement decontamination solution would be sterile, nontoxic, chelating, polyvalent, amphoteric, and slightly hypertonic to retard skin or corneal penetration of the chemical.

Keywords: Chemical burns; Chemical splash; Eye burns; Eye decontamination; Skin decontamination

INTRODUCTION

Burns of all types result in significant morbidity and mortality. Skin/eye chemical burns are a significant problem. More than 25,000 chemical products, including oxidizing agents, reducing agents, and corrosives, have been identified as having the potential to cause burns (1). In 2001, the Bureau of Labor Statistics, U.S. Department of Labor recorded 5900 occupational deaths; 8.5% (502 deaths) of these were due to "Exposure to Harmful Substances or Environments," 68,269 nonfatal injuries due to "Exposure to Harmful Substances or Environments," 25,125 nonfatal injuries from exposure to "Harmful Chemicals or Environments," and 9541 chemical burns (2).

Josset et al. (1986) (3) reported that there were approximately 7000 serious occupational injuries from chemical burns in France, and about half of these involved the eyes. These burns resulted in 120,000 lost workdays and 250 cases of permanent disability.

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In the United States, national data on exposures reported to poison centers are published by the American Association of Poison Control Centers in the Toxic Exposure Surveillance System. In 2002, there were 2,380,028 total human poison exposure cases reported, with 1153 deaths. There were 193,822 dermal exposures and 130,857 eye exposures (4).

Following removal of contaminated clothing, which decreases chemical skin decontamination by up to 80% (5), standard references recommend water or normal saline for immediate decontamination of skin/eye chemical splashes with the addition of soap if the chemical substance is lipid soluble (5–8). Soap should not be used in the eyes. Older literature suggests that immediate flushing of the eyes for about 30 minutes from the nearest shower or faucet should be done after sodium or ammonium hydroxide ocular exposure (9). In the United States, the Occupational Safety and Health Administration (OSHA) regulations mandate emergency eyewash stations and quick-drench showers in all facilities where potentially dangerous chemical agents are present (1). Most of these emergency facilities use water for skin/eye decontamination.

Lewis (10) recommended initial copious water decontamination, followed by neutralization (1/2 ounce of sodium bicarbonate dissolved in 1 pint of water for acids; 1% sodium citrate for alkalis), followed by a second decontamination with copious amounts of water for skin splashes (10).

The purpose of this review is to research and describe the available literature on water decontamination of eye/skin chemical splashes. The ideal decontamination solution would be sterile (to avoid infections), hypertonic (to avoid tissue damage in the eyes or on the skin), amphoteric (to neutralize chemicals that are chemically opposed such as acids or bases), water-soluble (to avoid loss of the advantages of water), and nontoxic (as water is not always).

MATERIALS AND METHODS

In-depth electronic and paper literature searches were performed to retrieve pertinent articles involving water decontamination of skin/eye chemical splashes and chemical burns. Searches were done in the National Library of Medicine MEDLINE and TOXLINE databases by using combinations of search terms such as "chemical burns," "skin burns," "dermal burns," "eye burns," "ocular burns," "occupational burns," "workplace burns," "chemical decontamination," "skin decontamination," "eye decontamination," and "ocular decontamination." For older literature, hard-copy versions of Index Medicus were reviewed back to 1929. The references/bibliography section of each retrieved article was also reviewed for any pertinent references.

Organization Web pages, such as that of the American Burn Association, were reviewed for data on the occurrence and etiology of chemical burns and for references/links to other sources of chemical burn data such as State Health or Health and Environment Departments. These Web pages were also reviewed. Chemical burn occurrence and outcome data from the U.S. Department of Labor Bureau of Labor Statistics Web site were also reviewed. Internet Google searches were also conducted by using all combinations of the above search terms.

A brief literature search for evidence of efficacy of water decontamination of hydrofluoric acid (HF) splashes was also performed.

RESULTS

Retrieved and reviewed information was distributed into the following categories: 1) occupational burn information collected by governmental agencies or assembled from government or regional sources; 2) burn center/unit data; 3) experimental animal studies; 4) older human case reports; 5) more recent human case reports; 6) case series/epidemiological studies.

Occupational Burn Information Collected by Governmental Agencies or Assembled from Government Sources

West Anglia and Oxford region, UK. In four UK counties in the West of Anglia and Oxford region, Wilkinson (11) reviewed the epidemiology of burn patients treated in Accident and Emergency Departments or admitted to the hospital for burn care during 1994 and 1995. About half of the burn patients admitted to the hospital were treated in burn units, one fourth were treated on plastic surgery wards, and the remainder were admitted to specialty units including trauma, orthopedics, pediatrics, and ophthalmology. The largest numbers of admitted patients were in the working age group, which was also the largest group in the general population. Burn patients accounted for approximately 1% of cases seen in Accident and Emergency Departments, and about 10% of these patients were admitted to the hospital, with a mean length of stay of 7.5 days (11).

South Wales, UK. Munnoch et al. (12) studied work-related burns in South Wales during a 2-year period between 1995 and 1996. There were 324 cases of work-related burns and records were available for 319 of these. Twenty percent of all burns referred to the Burn Center in Swansea occurred in the workplace. Chemical burns were the most frequent cause (23%) with caustic soda exposure in 21 cases, cement in 15 cases, and a mixture of acids and alkalis accounting for the remaining 37 cases. Of these 319 patients, 175 were admitted to the Burn Center and 79 required surgery. The mean length of hospital admission was 8.5 days (range: 1–110 days), representing overall 1485 hospital days. Males aged 16–40 years comprised 70% of the patients with work-related burns. Fifty-five percent of patients with work-related burns were admitted to hospital, and approximately 25% required surgery (12).

Switzerland. de Roche et al. (13) studied the epidemiology and costs of work-related burn injuries in Switzerland. They noted that about 4.6% of all accidents in Switzerland are burns and that 3.0% of all accidents are work-related burn injuries. Estimates based on population suggest that there are 36,000 burns annually in Switzerland with 5% requiring hospital admission and one third of these being treated in a burn center. There is a compulsory insurance program for workers in Switzerland that covers accidents both on and off the job. In 1984, 6814 burn accidents were covered by this insurance program, 58% work-related and 42% non-work-related. The total cost for the burns was 17.7 million Swiss francs, with 19%

for medical care, 34% for salaries while off work, and 46% for annuities (13). The proportion of chemical burns was not reported.

Taiwan. Chien et al. (14) studied the epidemiology of hospitalized patients with burns in Taiwan during a 2-year period between 1997 and 1999: a total of 4741 patients were hospitalized for burn treatment. Work-related burns occurred in 1459 patients (30.8%). Among adult patients, chemical burns due to exposure to corrosive agents such as strong acids or alkalis accounted for 9% of the injuries. Burns due to explosions and chemical contact occurred more frequently in the workplace (32.9%), were more serious (average 25% a total body surface area (TBSA), and resulted in longer average hospital admission times (23 days) (14).

U.S. NIOSH/CPSC. Over 3 months in 1981, the U.S. National Institute for Occupational Safety and Health (NIOSH) and the Consumer Product Safety Commission (CPSC) conducted a surveillance program of occupational injuries treated at a sample of 66 U.S. hospital emergency departments (15). There were a total of 2747 burn injuries (cause not specified), which represented 4.5% of the total 61,585 occupational injuries treated in these facilities. The most common sites of burns were face, arm, and trunk. On the basis of the surveillance system, it was estimated that there were 3.3 million occupational injuries treated in U.S. emergency departments in 1981 (15). If the percentage of burns were constant, this would represent 148,500 occupational burn injuries yearly. Chemical burns were not listed separately from all occupational burns in this report.

New England, USA. Rossignol et al. (16) collected data on burned patients aged 20 years or older admitted to any of 240 of New England's 256 acute-care hospitals for treatment of a new burn injury. Chemical burns were among the type of injuries included in the study. Overall, 1614 new burn injuries were identified during the 1-year study period between 1978 and 1979. Of these, 485 burns (30%) were work-related. Overall, 40% of the 1133 burns in males were work-related, whereas only 7% of the 481 burns in women were work-related. There were 91 chemical burns in males, of which 67 (74%) were work-related.

State of North Carolina, USA. Hunt et al. (17) in a survey of occupation-related burn injuries during 1994 using data from the U.S. National Census of Fatal Occupational Injuries (fatal cases) and the North Carolina Department of Labor (nonfatal cases) found that there were 34 burn deaths (15.3%) and 1720 nonfatal burns. Burn injury was the fourth most common cause of workplace deaths, but the proportion of these that were chemical burns was not specified. Of the nonfatal burns, 709 (41.2%) were caused by chemical exposure. Involved chemicals were alkalis (20%), cleaners and solvents (16.9%), propane (12.2%), halogens (7.0%), inorganic and other acids (3.6%), hydrocarbons (2.0%), and other chemicals (38.3%). Chemicals and chemical products were the most common agents causing workplace burn injuries (17).

State of Washington, USA. In a study of occupational burns in Washington State during a 5-year period of 1989–1993, there were 27,323 Workers' Compensation claims for work-related burns; 26.8% (7,323) of these were chemical burns (18). These authors note that in 1994, the U.S. Bureau of Labor Statistics reported that there were 53,800 occupation-related burns resulting in lost work time and that work-related burn patients admitted to burn centers ranged from 21% to 30% of all admissions and accounted for 20–30% of all serious burns (18). Of exposures, 2173 (8.0%) were to unspecified chemicals, 906 (3.3%) were to soaps and detergents, 604 (2.2%) were to solvents/degreasers, 462 (1.7%) were to calcium hydroxide, 451 (1.6%) were to sulfuric acid, 488 (1.6%) were to chlorine compounds, and 371 (1.4%) were to sodium hydroxide. Industries at the highest risk for chemical burns were hazardous waste landfill cleanup; portable cleaning and washing; pulp and paper manufacturing; and chemical blending, mixing, and manufacturing (18).

State of Washington, USA. Baggs et al. (19) investigated work-related burns in Washington State during 1994–1998. There were a total of 20,213 work-related burn claims accepted by the Workers' Compensation system during this period, but only 1.5% of burned workers were admitted to the hospital. However, this 1.5% of burned workers represented 5% of the cost incurred. The cost for all work-related burns were in excess of $U.S. 5 million annually. Patients hospitalized for work-related burns lost an average of 132 workdays, whereas burned workers not requiring hospitalization lost an average of 3 workdays. They noted that the Workers' Compensation data underestimated the frequency and cost of work-related burns (19). Burns were evaluated in two categories: thermal and chemical. Among previously identified high-risk industries were hazardous waste cleanup and the chemical industry. In this study, chemical mixing and manufacturing, concrete work, and construction ranked high as industries having hospitalized work-related burn cases; janitorial services was also an industry having chemical burn cases reported which had not been identified in previous studies (19).

State of Utah, USA. The Utah Department of Health, Bureau of Epidemiology collected data on work-related burns during 1997 (20). In 1997, there were 699 hospital admissions for burn treatment, of which 133 were work-related. Males accounted for 82% of these cases. Workers aged 25–44 had 60% of all work-related burns (20).

State of Colorado, USA. The Colorado Department of Health and Environment noted that over a period of 1980–1998, an average of 24 state residents died each year from burn injuries (21). Approximately 330 Colorado citizens are hospitalized yearly for burn injuries, and approximately half of these are due to scalds, hot objects, or exposure to caustic substances (21).

State of Massachusetts, USA. Rossignol et al. (22) studied the epidemiology of work-related burn injuries in Massachusetts that necessitated hospital admission during a 1-year period in 1978–1979. Of 825 total burn admissions, 240 (29%) were work-related. Of the work-related burns, 95% were in males. There were 29 chemical burns that accounted for a total of 248 hospital admission days.

State of Ohio, USA. Chatterjee et al. (23) studied 199 burn injuries in Northeastern Ohio evaluated in an emergency department during 1977, representing 2.4% of all patients evaluated for any type of trauma. The cause of the burn was known in 187 cases (94%). Of these, 124 (66%) were due to hot substances, corrosive liquids, or steam (not further delineated). Of these patients, 55 had a work-related burn and 52 claimed eligibility for Workers' Compensation (23).

Burn Center/Unit Data

Toronto, Ontario, Canada. In a review of chemical burn patients admitted to a regional Burn Center in Toronto, Ontario, over an 8-year period, the 24 chemical burn patients comprised 2.6% of all admissions (24). Work-related accidents accounted for 75% of these burns, with the involved chemicals being hydrofluoric acid, sulfuric acid, black liquor (a heated mixture of sodium carbonate, sodium hydroxide, sodium sulfide, sodium thiosulfate, and sodium sulfate), various lyes, potassium permanaganate, and phenol. Of these 24 patients, 14 required extensive excision and skin grafts. Complications were frequent (58% of patients), including eye contact with the chemical, wound infections, tendon exposures, toe amputation, and systemic toxicity from chemical absorption. One patient with a chemical scald burn involving 98% of the total body surface area died. In 14 of 24 patients (58%), removal of contaminated clothing followed by immediate water shower decontamination was done; 5 other exposed patients did not have these interventions. Five of the eight eye splash cases had immediate decontamination at the site (presumably with water). Although the three eye splash patients who did not have immediate decontamination developed prolonged conjunctivitis, three of the five who were decontaminated immediately developed corneal erosions and one who had eye exposure to black liquor had a very deep corneal erosion, which resulted in blindness (24). Despite immediate decontamination of the skin or eyes with water, some of these patients developed burns and significant complications.

Chandigarh, India. In a study of 27 cases of acid and alkali burns evaluated over a 5-year period, Sawheny and Kaushish (25) noted that chemical injuries differed from thermal injuries. Of 562 patients admitted to a burn center over a 5-year period, 16 were acid exposures (sulfuric or nitric acid) and 11 were caustic soda (sodium hydroxide) exposures. The 11 patients exposed to caustic soda were involved in the collision of a tank truck with a passenger bus. The majority of chemical burns (20 of 27 [74%]) involved less than 15% of the TBSA and 81.5% were full-thickness burns, mainly on the face, upper truck, arms, and hands (25). Eye involvement was present in 74% of patients, and both eyes were involved in 15% (25). Severe conjunctivitis was present in all patients with eye exposure, with keratitis and corneal ulcerations progressing to opacities occurring in 63% of patients. Corneal perforation progressing to panophthalmitis and vision loss occurred in two cases. Severe eyelid ectropion developed in 12 patients (44%). By the end of the 3rd week, wound infections developed in two thirds of patients, and all wounds were infected by 4 weeks after surgery. Invasive sepsis occurred in only one patient (25). In those patients, "... thorough and continuous irrigation of the area of damaged tissues with copious volumes of water..." was done as early as possible, although this may have been after a delay of hours following exposure but was noted to be of limited effectiveness when the patients did not arrive until after a delay of days (25).

Boston, Massachusetts, USA. In a study of 857 inpatients treated at a Burn Center in Boston during a 4-year period from 1976 to 1980, 35 (4%) had chemical burns (26). The chemicals involved were acids (sulfuric, hydrochloric, hydrofluoric, carbolic, chlorosulfonic, and trichloracetic) (15 cases), alkalis (lye, cement) (9 cases), and other/unknown substances (10 cases). The mean TBSA burn was 8.7%, the mortality was 6% (two patients), and the length of hospital admission was 15 days. The injury occurred in the workplace in 18 cases (51%), in the home in 10 cases (29%), and was due to a deliberate chemical assault in 7 cases (20%). Sixteen patients had immediate water decontamination (within 10 minutes of exposure and lasting at least 15 minutes) and 19 had delayed water decontamination. The delayed contamination group had a fivefold greater incidence of full-thickness burns and a significantly longer duration of hospital admission, despite the fact that the mean TBSA burn in the delayed decontamination group was one-half that of the immediate decontamination group (26). Although immediate water decontamination appeared to decrease burn severity, it was unable to completely prevent them, and the 16 patients in this category still required hospital admission for a mean of 7.7 days, and 12.5% of them had full-thickness burns.

Iowa City, Iowa, USA. In a review of patients with chemical burns admitted to a burn center, 94 (3.3%) of a total of 2762 had chemical burns (27). Of the chemical burn patients, 31 (34%) were due to anhydrous ammonia. Chemicals involved included acids (14 cases), bases (68 cases), inorganic agents (2 cases), organic agents (6 cases), and unknown agents (5 cases). The majority had work-related burn injuries. Patients either had immediate water decontamination at the incident site and/or underwent water flushing in the burn center until the skin pH returned to normal. Further water irrigation was done if discomfort recurred, and daily hydrotherapy was performed. There was one fatality in this group, and 36/94 (38%) required skin grafting with five patients having multiple procedures. Complications including wound infections, pneumonia, cardiac failure, cardiac arrhythmias, and myocardial infarction occurred in 24 of 94 cases (25.5%), and sequelae were noted in 27 of 94 cases (28.7%) (27). Early and prolonged water decontamination did not prevent serious burns from developing.

Experimental Animal Studies

Older experimental animal literature supports immediate and even prolonged (up to 8 hours) continuous irrigation with water for acid or alkali chemical burns, noting that the sooner it is begun, the more likely it is to be effective (28–30). Delays to initiation of water decontamination of as little as 5–30 seconds sometimes make significant differences in its ability to prevent or decrease the severity of burns (29, 30). Of note, statistical comparison of various treatment modalities are generally lacking in these older studies.

One of the earliest series of experimental animals studies was by Davidson (28) who investigated acid (50 and 70–71% nitric acid; 10, 25, 50, and 96% sulfuric acid; 37% hydrochloric acid; 99% acetic acid; saturated and half-saturated trichloroacetic acid) and alkali; (50% sodium hydroxide; and 50% potassium hydroxide) burns in rats by immersing a hind leg in the solutions for periods from 15 seconds to 1 minute. At a higher concentration of acids and bases, many animals receiving no decontamination died and/or developed severe burns. Neutralization with 5% sodium bicarbonate (acid burns) or 1% acetic acid (alkali burns) was compared with water decontamination either by holding the exposed limb under running tap water or by placing the rat in a large tank of water. In all cases, animals treated with neutralization developed less severe burns than untreated controls, whereas animals decontaminated with water developed less severe burns than those treated with neutralization (28). However, all animals except those exposed to 10% (no burns even in untreated controls) and 25% (no burns in animals receiving either neutralization or water decontamination) sulfuric acid developed burns, regardless of treatment modality.

Rats with skin exposure to 2 N sodium hydroxide were washed with 500 mL of distilled water at a rate of 33 mL/minute beginning at 1, 10, and 30 minutes after exposure (31). Subcutaneous tissue pH was measured at 1-minute intervals for up to 90 minutes following exposure. The peak tissue pH measurements were 7.97 for the 1-minute group, 10.57 for the 10-minute group, and 12.17 for the 30-minute group. The pH measurements for the groups with water washing begun at 10 and 30 minutes postexposure were not different from those seen in exposed controls that received no decontamination (31). Using the same rat model, a comparison was made of subcutaneous tissue pH between rats washed with 500 mL of distilled water and 500 mL of a 0.35 M sodium citrate solution as a neutralizing agent (32). Compared with the water decontamination group, subcutaneous tissue pH measurements were significantly higher in the 1-minute group and significantly lower in the 10- and 30-minute washing groups. Regardless of which decontamination measure was used, the upper layers of the skin became necrotic, and deeper burns were observed in the groups with delayed (10 or 30 minutes) beginning of decontamination (32).

Brown et al. (33), while studying the efficacy of polyethylene glycol (PEG) for decontamination of phenol and related compounds exposure in rats, also compared PEG with water for decontamination of 45% sodium hydroxide and concentrated sulfuric acid exposures. Water decontamination was more efficacious than PEG, although burns of varying severity developed in all animals exposed to sulfuric acid and decontaminated with water, whereas burns of varying severity developed in 12 of 90 animals exposed to 45% sodium hydroxide and decontaminated with water (33).

Andrews et al. (34) challenged the dogma that skin burns caused by alkaline substances should be decontaminated with water and that neutralization should not be attempted. In an experimental animal study of rats exposed to 2 N sodium hydroxide, decontamination with 5% acetic acid was superior to water decontamination at attaining a physiological pH, resulted in less severe tissue damage, and was associated with improved wound healing, thus supporting the idea that perhaps water decontamination is not the best initial intervention in alkaline chemical burns (34).

Older Human Case Reports

Older literature also describes attempts at chemical neutralization following skin/eye chemical splash exposures. Terry (35) described that the use of a 5% ammonium chloride solution for neutralization with sodium bicarbonate followed by plain water washing did not prevent significant burns. Although no actual patient data were presented, this author stated that immediate 5% ammonium chloride solution irrigation "... in the great majority of cases prevented a burn"; however, skin burns did occur when there was more than a 30- to 40-second delay before ammonium chloride irrigation was begun (35). For caustic soda eye splashes, this author recommended a 5-minute irrigation with 5% ammonium chloride solution followed by a 55-minute irrigation with boric acid/saline solution, which "... has reduced the time of recovery of caustic soda burns of the eye from weeks to days" (35).

Carson (36) described three cases of extensive industrial burns. The first patient fell into a vat of a cresylic acid derivative and developed burns over 15% of the TBSA. Despite immediate removal of contaminated clothing and thorough water shower decontamination, he developed anuria, hypokalemia, and cardiac failure and died on the 10th day after the accident (36). A second patient slipped and inadvertently immersed his arm in a vat of chromic acid, developing an extensive burn of the entire limb despite immediate water washing. About 45 minutes later, the arm was again decontaminated with a phosphate buffer solution. Extensive excision and delayed skin grafting was required, requiring 44 days in hospital (36). A third patient fell into a vat of hot (81°C) nickel-plating solution (nickel chloride, nickel sulfate, boric acid, and cumarin). Sodium bicarbonate was applied at the company infirmary, and 40 minutes later a "buffer solution" compress was applied. Burns involved 40% of the total body surface area. Hypotension, oliguria, and hyponatremia developed, and the patient expired on the 5th day following the accident (36).

More Recent Human Case Reports

With exposure to relatively dilute sodium hydroxide (4%) oven cleaner aerosol, full-thickness burns of the face requiring skin grafting may occur despite the lack of early pain (37). A patient with such an exposure did not present to the emergency department until 2 hours after aerosol exposure. The patient had wiped her face with a water-moistened cloth immediately after exposure but did not irrigate her face with water. Continuous water irrigation in the emergency department did not significantly modify the pH of the patient's facial skin or prevent the development of full-thickness burns requiring skin grafting (37).

A 20-year-old man fell into a caustic lime pit and developed an 85% TBSA burn (38). Treatment was delayed by more than 20 hours because of initial misdiagnosis and confusion over what the exposure actually involved, and he arrived at the burn center still covered with a thick, adherent layer of the lime. Decontamination in a water-filled Hubbard tank was only partially successful. Skin grafting was completed by 30 days after the injury, although some areas had to be secondarily debrided and regrafted with permanent wound closure obtained only after 2 months. Functional restoration was achieved at 3 months after injury (38).

O'Donoghue et al. (39) described three cases of caustic soda burns of the hands or feet. In two cases, the patients had immediate copious water decontamination; in the third case, decontamination was not described. All three patients developed significant, deep neurotic burns requiring debridement and skin grafting. In two cases, recurrent necrosis occurred over 6 and 13 months (39).

A 36-year-old male was exposed to sodium hydroxide (pH 12–14) from a spilled barrel in a leather-processing factory (40). Contaminated clothing was immediately removed, and the worker was washed with water continuously in a shower for approximately 20 minutes. On admission to the burn center, there were 53% TBSA burns present. Irrigation with water was done for a further 2 hours and repeated six times with 4-hour rest periods in between. Debridement and skin grafting were required over a 43-day hospitalization, after which pressure garments were worn for 18 months. No functional deficits were noted at the conclusion of treatment (40).

Paulsen et al. (41) described two workers sprayed with liquid titanium tetrachloride while dismantling piping in a chemical plant. Titanium tetrachloride reacts with water releasing heat and hydrochloride acid and should initially be dry-wiped from exposed areas before other decontamination is attempted (41). These two workers were perspiring heavily, and the titanium tetrachloride reacted with the perspiration, releasing hydrochloric acid. They were immediately dry-wiped with towels and then decontaminated with water in safety showers. On hospital admission, they had 18% and 20% TBSA partial thickness burns. One also had bilateral corneal burns. Both required debridement and skin grafting and remained in the hospital for 2 weeks. Return to light duty was allowed after 8 weeks (41).

Seven Saudi Arabian children had skin exposure to sulfuric acid when they tipped over a drum stored on the rooftop of their residential block (42). These children developed chemical burns of 3–60% TBSA. Contaminated clothing was not removed, and water decontamination was not done until one-half hour after exposure. Following water irrigation, four children were treated and released, and three children with 10, 15, and 60% TBSA burns were hospitalized. The child with 60% TBSA burns had 166 days of initial hospital admission, eight autografting and one homografting procedures, and two further hospital admissions and surgical procedures for burn sequelae (42). Among these seven children, one-half hour of water irrigation begun one-half hour after sulfuric acid skin exposure did not prevent burns and significant sequelae in one child.

Two workers had similar skin and inhalation exposures to liquid anhydrous ammonia and its vapor when a hose became disconnected during transfer from a river barge to a dock tank (43). One worker immediately left the area, showered with water, and removed contaminated clothing. He developed bilateral corneal burns, edematous and peeling lips, and hyperemia of the face and neck. After a 1-day hospital admission, rapid healing occurred. The second worker did not change contaminated clothing or shower immediately. On hospital arrival 90 minutes later, the face and lips were swollen, breathing was difficult, the pharynx and vocal cords were swollen, and endotracheal intubation was required to maintain a patent airway. There were 14% TBSA partial thickness burns on the face, neck, chest, arms, hands, and thigh. Skin grafting was required, and wound infection developed in the thigh burn. Hospital admission was for 13 days (43). Although immediate water decontamination was associated with less severe burns in one of these two workers, it did not prevent burns from developing.

Case Series/Epidemiological Studies

In a study of 51 patients, to evaluate whether immediate water decontamination was adequate, patients were divided into groups, and adequate treatment was defined as immediate dilution or neutralization therapy (44). The *mortality* in this study was 13%, most of the chemical burn patients were young men, and the injuries were most often work-related. The largest group of chemicals involved were alkalis (sodium and potassium hydroxides) followed by sulfuric acid, gasoline, anhydrous ammonia, white phosphorus, and hydrofluoric acid; four of the five *deaths* were work-related. Five of 38 deaths were caused by chemical burns, and 4 of 23 (17%) were work-related. Although the group with immediate water decontamination had a generally shorter length of burn center admission and decreased mortality, this intervention did not prevent the development of burns or a 9.5% mortality (44).

Bromberg et al. (45) reviewed 273 chemical burns treated at two hospitals in New York during 1957–1963. Accidental exposures and deliberate assaults with caustic substances were approximately equally represented. Alkalis were involved in 208 of 273 cases (76%) and resulted in more severe burns than did acids. The head and neck were most often involved, and a high percentage of patients had concomitant corneal burns. A subset of 85 patients was further described, either receiving continuous water irrigation in a shower, brief water irrigation (30–60 minutes), continuous water soaks, or open treatment. Continuous water irrigation in a shower decreased the waiting period until skin grafting could be done to 22 days compared with 26–34 days with the other treatment modalities. It also decreased the average length of hospital treatment to 19 days as opposed to 23–39 days with the other modalities. The requirement for skin grafting was 20% less in the group receiving continuous water irrigation (45). Hydrotherapy, especially by immersion, has been associated with sepsis and alternative local wound care with sterile solution, and patient isolation maintenance has been shown to decrease lethal infectious complications (46).

Wolfort et al. (47) reported a series of 416 patients with lye injuries treated at two hospitals in Baltimore between 1952 and 1968. Of these, 42 had cutaneous lye burns involving 5–60% of the TBSA. Only nine injuries resulted from workplace accidents; the majority were deliberate assaults. The mean hospital admission time was 32 days, and one fatality occurred but was attributed to an anesthetic accident rather than the burn itself. Complications included tympanic membrane perforations (from lye running into the external auditory canal), parotid fisulas, a greater potential for keloid formation than seen with thermal burns, and the early appearance of Marjolin's malignant ulcers in the burn scars (seen at 3–9 years following lye burns and an average of 34 years following thermal burns). Treatment protocols at these two hospitals included early water decontamination followed by 12–24 hours of continuous water irrigation in a shower (47). Despite these interventions, all 42 patients developed burns requiring debridement and skin grafting.

Curreri et al. (48) described 111 patients with chemical burns treated in the U.S. Army Institute of Surgical research over a 19-year period from 1950 through 1968. Of these, 96 patients had white phosphorus burns, 5 were burned with concentrated sulfuric acid, 3 were burned with lye, 3 with mustard gas, and 4 with other chemicals. There was a longer healing period for patients with chemical burns than for those with burns from other etiologies, although the mortality was less: 5.4% for patients with chemical burns compared to an overall burn patient mortality of 10.5%. There was a high incidence of periorbital and ocular complications in the chemically burned patients.

Mozingo et al. (49) described 87 patients with chemical burns treated at the U.S. Army Institute of Surgical Research during a 17-year period between 1969 and 1985. The most common chemical involved was white phosphorus (49 cases). Other causative chemicals were acids (13 patients), alkalis (10 patients), organic solvents (5 patients), and a variety of other chemicals (15 patients). Patients with chemical burns from other than white phorphorus had shorter hospital admission times. In the 38 patients with other than white phosphorus chemical burns, the average TBSA was 29.8%, the average third-degree TBSA burn was 17.8%, and there was a 26.3% mortality. Three of these patients had associated eye injuries. Complications were noted in the nonwhite phosphorus chemical burn patients, including joint contractures (three cases), cellulitis (six cases), septicemia (three cases), upper GI bleeding (one case), pneumonia (two cases), burn wound infection (two cases), blindness (two cases), myocardial infarction (two cases), phenol toxicity (two cases), pulmonary embolus (two cases), brain death (one case), formate toxicity (one case), nitrate toxicity (one case), pancreatitis (one case), and other (seven cases).

In patients with burn injuries treated at the United States Army Institute of Surgical Research from 1963 to 1968, 104 cases with ocular burn injury were identified (50). Although flame injury was the most common etiology, chemical exposure was the cause in 27 patients (50).

Hydrofluoric Acid Burns

Hydrofluoric acid (HF) is a relatively weak acid that penetrates deeply into the tissues resulting in severe burns and in high concentrations can also cause life-threatening systemic poisoning and fatalities (51–59). Penetration of H^+ and F^- ions into the tissues causes the corrosive lesions; chelation of calcium leads to systemic hypocalcemia (60, 61), and other serious electrolyte imbalances (hypomagnesemia, hyperkalemia) may occur (62, 63), leading to severe metabolic acidosis, cardiovascular shock, cardiac conduction abnormalities, and cardiac arrhythmias including nonperfusing Torsades de Pointes ventricular tachycardia. Hydrofluoric acid has widespread usage in industry (57).

There are various methods for decontaminating and treating HF dermal burns (62, 64–69). Concentrated HF (40–70%, anhydrous) rapidly produces painful lesions (70), requiring that decontamination and treatment be undertaken immediately. Despite early water decontamination followed by repeated topical calcium gluconate inunction or subcutaneous injection, development of burns often cannot be prevented. The risk of systemic and sometimes fatal HF toxicity is greatest with concentrated HF splashes (55).

Dilute HF has sometimes been successfully decontaminated with water followed by topical application of calcium gluconate gel. The difficulty in such cases is perception of the need to immediately undertake these measures in the absence of pain, which may be delayed in onset (70–72). The duration of the HF contact with the tissues may be prolonged in such situations. With dermal exposure to either dilute or concentrated HF, surgical debridement, excision, or even amputation of necrotic areas may be required in certain cases (73–76).

DISCUSSION

Water decontamination has the following proposed mechanisms of action (45): 1) dilution of the chemical agent; 2) rinsing off the chemical agent; 3) decreasing the rate of the chemical reaction; 4) decreasing tissue metabolism and, therefore, the inflammatory reaction; 5) minimizing the hygroscopic effects of chemicals that produce them; and 6) restoring normal skin pH in acid and alkali burns.

The ANSI Z358.1-1998 standard is a consensus standard for emergency water decontamination equipment for the skin and eyes (77). It specifies that emergency showers should deliver a pattern of flushing solution 20 inches (50.8 cm) across with a flow rate of 20 gallons (75.7 liters) per minute and a velocity sufficiently low to not cause injury to the user (77). For eyewash stations, a 15-minute uninterrupted water supply must be available, and plumbed units should deliver between 2.0 and 3.5 gallons (7.5–13.25 liters) per minute (77). These emergency decontamination stations should be clearly marked and should take a chemical-exposed worker no more than 10 seconds to reach (77).

For eye decontamination, it has been said that "the ideal flushing solution is a sterile, isotonic, preserved, physiologically balanced solution" (78). However, "at a minimum, flushing fluid should be clean and non-toxic," which would include potable water (78). There remains the problem of disposal of water used for skin/eye decontamination of chemical splashes, particularly whether a chemical can be discharged in the sanitary system even in a very dilute concentration (77). In some cases, it may be necessary to install a special holding tank for runoff water from emergency eyewashes and showers and to dispose of the decontamination water as hazardous waste (77).

In a frequently cited review, Jelenko (79) noted that chemical agents do not "burn" in the classic sense of tissue destruction by heat. Rather, they act by coagulating protein through oxidation, reduction, salt formation, corrosion, protoplasmic poisoning, metabolic competition or inhibition, desiccation, or vesicant activity and its resultant ischemia (79). Although neutralization has been said not to be as efficacious as water decontamination for acid and alkali exposures (45), Lewis (10) recommended initial copious water decontamination followed by neutralization and then a second decontamination with copious amounts of water.

Psychosocial consequences are consequences often overlooked in patients with chemical burns, especially those involving the head, face, eyes, and neck. Rumsey et al. (80) found that a considerable portion of patients with disfiguring conditions, including burns, had psychosocial difficulties including increased anxiety levels, depression, social anxiety, social avoidance, and reduced life quality.

CONCLUSION

From this review, it is clear that although chemical burn injuries represent a small portion of total burn injuries, their human and economic impact is significant. Although immediate water decontamination has generally been shown to decrease the severity of chemical skin/eye burns, it is also obvious that it does not prevent such burns from developing, nor does it always prevent the need for lost work time, hospitalization, burn center/unit admission, the requirement for surgical treatment, and sequelae. Significant sequelae and death can occur following chemical splashes, even when water decontamination is done on a timely basis. If water is all you have, then water is what you use. If water decontamination were done in a timely manner and with low concentrations of toxicants, then maybe no burns will result, but this cannot be determined from the available data. So when temperature is considered, alternative solutions can be heated. When environmental conditions are such that a person might have to stand under a water deluge shower at very low temperatures, this might not be a good alternative. Hypothermia is a serious medical condition and must not be ignored.

Given a renewed interest in neutralization measures, decontamination solutions that are sterile, chelating, polyvalent (bind a wide variety of chemicals/chemical groups), amphoteric (bind opposed chemical groups such as acids/bases, oxidizers/reducing agents, etc.) nontoxic, hypertonic (to help prevent skin/cornea penetration), and water-soluble (so that beneficial diluting and rinsing effects of water are not lost) should be critically evaluated by those concerned with initial decontamination of skin/eye chemical splashes. Comparative, blinded, controlled studies of various eye/skin decontamination solutions, including water, are needed.

ACKNOWLEDGMENT

Funding to prepare this review was provided by Laboratoire PREVOR, Valmondois, France.

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