Pediatr Nephrol (1994) 8: 357–366
© IPNA 1994

Pediatric Nephrology

Practical pediatric nephrology

Fluid resuscitation of pediatric burn victims: a critical appraisal

Hugo F. Carvajal

Department of Pediatrics, University of Texas Health Science Center at San Antonio and Women's and Children's Hospital, 7922 Ewing Halsell Suite 380, San Antonio Texas 78229, USA

Received January 12, 1994; accepted January 20, 1994

Abstract. The objectives of fluid therapy in the burned child can be simply stated and defined, and they should represent the basis for the resuscitation process. During the first 24 h after the burn, the ultimate goal is restoration of the patient's volume and electrolyte homeostasis. All efforts should be directed at monitoring or restoring organ function while simultaneously minimizing edema formation. Only the minimum amount of fluids and other nutrients needed to restore cell function should be provided. Electrolyte deficits and lactic acidosis must be promptly corrected and every attempt should be made to prevent further derangement in body homeostasis by replacing concurrent losses and anticipating maintenance fluid and electrolyte requirements. Restoration and maintenance of perfusion pressures should lead to maximal oxygenation of injured and noninjured tissues, which promotes spontaneous healing, minimizes wound conversion, decreases bacterial colonization and prepares the injured areas for early excision and grafting. It must be emphasized, however, that restoration of fluid and electrolyte balance and organ function does not necessarily imply a return to normal of all physiological variables. The cardiac output, for example, may not return to preburn levels for 24–48 h post injury, even when the intravascular volume has been completely replenished. Likewise, oliguria may persist for 48–72 h, or even longer, after the burn, as a result of excessive secretion of antidiuretic hormone stimulated by the stress of the injury rather than its effect on fluid balance. Thus, while the objectives can be easily enumerated and defined, they are difficult to meet.

Key words: Pediatric burn victims – Fluid resuscitation

Introduction

Despite nearly 50 years of experience and intense study by hundreds of investigators, the controversy regarding fluid resuscitation of burned patients lingers on. Lack of agreement exists not only in regard to the quantity and composition of the fluids to administer, but also in regard to the choice and significance of the guidelines used to assess the effectiveness and end-point of therapy.

Estimating the total amount of fluids to administer: the burn formula

The various formulae that have been proposed for resuscitation of burned patients are depicted in Table 1. Early formulae based their estimates on the weight of the patient, the total serum protein level or the hematocrit [1–5]. The size of the burn was not consistently taken into consideration until 1947, when Cope and Moore [6] proposed the surface area formula. Their method allowed 75 ml of plasma and 75 ml of crystalloid for every 1% of body surface burned, plus *maintenance fluids*. Half of the fluids were given during the first 8 h and the other half during the subsequent 16 h. A maximum fluid allowance, equivalent to 10%–12% of the body weight in liters for the first 24 h, was later added to minimize fluid overload [7].

The Evans formula, developed in 1952, allowed 2 ml/kg percentage burn per 24 h, plus 2,000 ml for replacement of normal fluid losses. The use of equal amounts of plasma and crystalloids, as well as a maximum ceiling for burn size equivalent to 50%, was introduced [8]. The Brooke formula developed by Reiss et al. [9] agreed with the estimates of the Evans formula, but used only half of the colloid allowance. Volume and rate of fluid administration and ceilings for burn size remained unchanged.

The formulae of Cope and Moore [6], Evans et al. [8] and Reiss et al. [9] are the original prototypes of what we have termed "two-figure formulae". This term refers to the estimation of burn-related losses separately from maintenance fluid requirements (two independent formulae). Such an approach offers safeguards for the very young, the very large or the child with burns at the extremes of the spectrum, which are not afforded by "single-figure formulae" [10–12].

Table 1. Formulae for estimating fluid requirements in burned patients

Authors/ reference	Formula for estimating fluid needs	Hydrating solution	Rate of fluid administration and special instructions
Cope and Moore (1947) [6]	150 ml/% BSA burned per 24 h + (maintenance fluids)	½ plasma and ½ crystalloid, 5% dextrose in water	Half during first 8 h and half during subsequent 16 h; ceiling: 10%–12% of body weight in liters
Evans et al. (1952) [8]	2 ml/kg/% BSA burned per 24 h + 2,000 ml/24 h (maintenance fluids)	½plasma and ½ crystalloid, 5% dextrose in water	Half during first 8 h and half during subsequent 16 h; ceiling: 50% burn
Gelin (1952) [10]	<30% burn = 2 ml/kg/% BSA burned per 48 h[a] 30%–60% burn = 2.5 ml/kg/% BSA burned per 48 h[a] >60% burn = 3 ml/kg/% BSA burned per 48 h[a]	Dextran (low molecular weight)	
Reiss et al. (1953) [9]	2 ml/kg/% BSA burned per 24 h + 2,000 ml/24 h (maintenance fluids)	¼ plasma and ¾ crystalloid, 5% dextrose in water	Half during first 8 h and half during subsequent 16 h; ceiling: 50% burn
Eagle (1956) [13]	30 ml/% BSA burned per 48 h + 10% of body weight in kg/48 h + 4,000 ml/m² BSA per 48 h	Dextrose 5%, 0.66 N saline containing 20 g of human serum albumin/l	Ceiling: 50% burn; burns <15% do not administer the fluid equivalent to 10% of the body weight
Batchelor et al. (1961) [15]	Mean (children) 3 ml/kg/% BSA burned per 24 h[a] Range (children) 1–5 ml/kg/% BSA burned per 24 h[a]	Plasma and blood only	In children there is too wide a variation to rely on a single-figure formula
Welch (1962) [17]	A. 1.5 ml/kg/% BSA burned per 24 h + B. 1 ml/kg/% BSA burned per 24 h + C. 1,500 ml/m² BSA	a. Plasma b. Normal saline c. Dextrose 5% in water	Rate: ⅓ first 8 h, ⅓ second 16 h, ⅓ 2nd day
Baxter and Shires (1968) [11]	4 ml/kg/% BSA burned per 24 h[a]	Crystalloids only (isotonic salt solutions)	Half during first 8 h and half during subsequent 16 h; no ceiling
Carvajal (1975) [21]	5,000 ml/m² BSA burned per 24 h + 2,000 ml/m² total body surface per 24 h	Dextrose 5% lactated Ringer's solution containing 12.5 g of human-serum albumin/l	Half during first 8 h and half during subsequent 16 h; no ceiling
Pruitt (1978) [12]	3 ml/kg/% BSA burned per 24 h[a]	Crystalloids only (isotonic salt solutions)	Half during first 8 h and half during subsequent 16 h; no ceiling
Bowser and Caldwell (1983) [51]	2 ml/kg/% BSA burned per 24 h	Hypertonic lactated saline	Ceiling: 50% burn

BSA, Body surface area

[a] Total fluid intake – no separate allowance for maintenance fluids

Single-figure formulae were first proposed by Gelin in 1952 [10]. Using low molecular weight dextran as the hydrating solution, he suggested that patients with burns of less than 30% be given 2 ml/kg percentage burn per 24 h, those with moderate-sized burns (30%–60%) 2.5 ml/kg percentage burn per 24 h and those with severe burns (>60%) 3 ml/kg percentage burn per 24 h as the total fluid allowance.

Up to this point, resuscitation programs had been designed for the adult burn victim with *"proportionately smaller quantities"* recommended for children. In 1956 Eagle [13], for the first time, proposed a different formula for hydration of burned children. This initial effort used a combination of body surface area in square meters, weight and percentage of burn to arrive at fluid estimates for burn-related losses and maintenance fluids [14].

In 1961, Batchelor et al. [15] again emphasized the need to consider the size of the patient and the extent of the burn for rehydration of burned children. Although Batchelor's group used only plasma and blood for resuscitation, they

Table 2. Comparison of first 24-h fluid estimates (Parkland formula) and maintenance fluid requirements in burned patients

Age, weight and total body surface	BSA burned (%)	Parkland formula fluid estimate per (4 ml/kg/% burn per 24 h)	Average maintenance fluid requirements (ml)[a]	Allowance for burn-related losses	
				Quantity	% of maintenance
1 year, 10 kg, 0.46 m^2	15	600		–200[b]	
	30	1,200		400	50
	45	1,800	800	1,000	125
	60	2,400		1,600	200
	75	3,000		2,200	275
	90	3,600		2,800	350
4 years, 16.5 kg, 0.68 m^2	15	990		–210[b]	
	30	1,980		780	65
	45	2,970	1,200	1,770	148
	60	3,900		2,760	223
	75	4,950		3,750	312
	90	5,940		4,940	412
12 years, 40 kg, 1.3 m^2	15	2,400		150	6
	30	4,800		2,550	113
	45	7,200	2,250	4,950	215
	60	9,600		7,350	326
	75	12,000		9,750	433
	90	14,400		11,750	522
16 years, 70 kg, 1.86 m^2	15	4,200		950	29
	30	8,400		5,150	158
	45	12,600	3,250	9,350	288
	60	16,800		13,550	417
	75	21,000		17,750	546
	90	25,200		21,950	675

[a] Calculated on the basis of 1,750 ml/m^2 of body surface per day
[b] Strict adherence to the Parkland formula would result in a fluid deficit

reported that the amount of plasma required by burned children varied between 1 and 5 ml/kg percentage burn per 24 h. Although the average was 3 ml/kg percentage burn, Batchelor warned that such a figure could not be relied upon to consistently hydrate all patients.

In 1961, Metcoff et al. [16] reported that, despite "adequate resuscitation," burned children remained oliguric for several hours after the burn. Metcoff postulated that this phenomenon was due to an excess of antidiuretic hormone (ADH) and attributed edema to a relative excess of water and sodium. While Metcoff's group cautioned against overhydration and proposed the use of body surface area rather than weight for all calculations, Welch [17] continued to support a combination of both body surface area and weight.

The large surface area-to-weight ratio of children in comparison to adults was also stressed by Haynes [18] in 1965, who, recognizing the fallacies of the Evans formula, advocated continuous bedside monitoring and frequent hematocrit determinations to guide the hydration process.

While single-figure formulae such as the Parkland formula [19] or the modified Brooke formula [12] have enjoyed worldwide popularity, many inaccuracies and major modifications of the initial resuscitation plan have been reported with their use. The main problem with these formulae is that they do not differentiate between maintenance fluid requirements and burn-related fluid losses. In children, *maintenance fluid requirements* are not directly proportional to body weight; *thus, no single formula based on weight alone can be used for patients of different ages and sizes*. Estimation of *burn-related fluid losses* on the basis of body weight may also lead to inaccuracies because these losses bear a closer relationship to the extent of the burn rather than to the weight of the patient [20–23].

Maintenance fluid requirements and total fluid estimates for children with varying burn sizes are depicted in Tables 2 + 4. Notice that in the 1-year-old or in the 4-year-old child with a 15% burn, the Parkland formula grossly underestimates fluid intake (a deficit is created as the predicted amount is less than maintenance). In contrast, the 12-year-old and the 16-year-old child with burns over 50% of their body surface would be predicted to receive excessive quantities of fluids (Table 2).

Thus, unless single-figure formulae are corrected for age and burn size, they tend to underhydrate the small child or the child with small burns and overhydrate older children, particularly those with extensive injuries [20–22]. Since the proponents of these formulae advocate that no ceiling for burn size be used, and since a leaky vascular bed can lead to accumulation of large quantities of fluid in the interstitium, significant hydration errors can go unrecognized.

The surface area formula, also known as the Galveston formula [22], is the only formula that uses body surface area for all calculations, i.e., 5,000 ml/m^2 of body surface burned per 24 h (allowance for burn-related fluid losses) plus 2,000 ml/m^2 of total body surface per 24 h (maintenance fluids). The rationale behind this approach is that burn-related fluid losses are proportional to burn edema and evaporative fluid losses, and that both of these are also proportional to the surface are burned [23, 24].

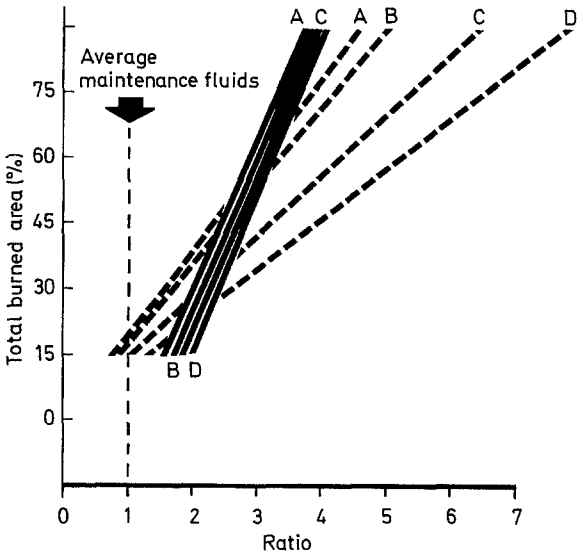

Fig. 1. Relationship between total fluid allowance for burned patients, as predicted by the Parkland (19) and surface area (22) formulae, and maintenance fluid requirements. Notice that while the ratio of total fluid estimates to maintenance fluids increases in proportion to the size of the burn, the relationship between these two variables remains constant for all ages with the surface area formula, but varies widely with the Parkland formula; *A*, 1-year-old; *B*, 4-year-old; *C*, 12-year-old; *D* 16-year-old. Adapted from: Carvajal HF, Parks DH (eds) Burns in children. Year Book Publishers, Chicago, 1988

The use of two separate figures to estimate burn-related fluid losses and maintenance fluids makes the *surface area formula* suitable for burns of all sizes and assures that all patients, regardless of age, receive fluids in proportion to the size of their injury. Figure 1 shows that while the ratio of total fluid estimates to maintenance fluids increases in proportion to the size of the injury, with the surface area formula the increments remain constant for all age groups, but vary widely with the Parkland formula. With the surface area formula, children with 60% surface area burn would be estimated to require fluid volumes equivalent to 3 times their daily maintenance requirements (300% of maintenance) independent of age (Table 2); with the Parkland formula, fluid estimates become progressively larger as the child gets older (200% for a 1-year-old child, 326% for a 12-year-old and up to 417% for a 16-year-old).

Choosing the proper hydrating solution

The basic issues regarding the composition of hydrating fluids are whether isotonic or hypertonic salt solutions should be used for burn resuscitation and whether or not colloids need to be added to the various mixtures. Although multiple investigations have shown that isotonic crystalloid solutions can be used successfully for burn resuscitation, several studies have also suggested that when hypertonic salt mixtures are used the total quantity of fluid can be curtailed and edema can be minimized [25–29]. While such an approach seems plausible, the occurrence of several undesirable side effects continue to be a source of concern [30–35].

Colloid resuscitation

The addition of plasma or albumin to resuscitation fluids has been criticized on the assumption that the burn-induced increase in vascular permeability and the consequent extravasation of proteins persist for up to 36 h post injury [7, 31, 36, 37]. The main concern is that protein administration during the first 24 h increases protein accumulation in the interstitium and thus traps water [38].

Using ^{131}iodine-labeled albumin and autoradiographic techniques to demonstrate albumin extravasation in experimental burn models, Brouhard et al. [23, 39] and Carvajal et al. [40] have shown that effective transcapillary sieving of albumin molecules into burned skin essentially stops at approximately 8 h post injury and that edema of injured tissues, maximal at 3 h post burn, persists beyond 24 h post injury. In contrast to injured tissues, neither albumin extravasation nor water accumulation occurred in unburned tissues [40]. Further investigations revealed that the depth of the burn had only minimal effect upon microvascular sieving of albumin molecules and that burn edema occurred rapidly and was of similar magnitude for superficial as well as deep burns [41]. Carvajal [22] also noted that when albumin was added to resuscitation fluids, the serum albumin levels were maintained within the normal range, edema was curtailed and the general condition of the patient was improved. Even though these studies did not quantitate albumin in the extravascular space, they suggested that most of the exogenously administered albumin remained intravascular. Thus, if the phenomenon of increased vascular permeability is indeed transient, withholding albumin or plasma beyond the first 6–8 h post burn would not only lack experimental support, but could be detrimental to the patient. Holleman et al. [42] have shown that when crystalloids are solely used for resuscitation, the colloidosmotic pressure of plasma decreases, fluid escapes the intravascular space and hypovolemia, as well as pulmonary and peripheral edema, develops.

Alterations in microvascular integrity may not be the only mechanism responsible for volume shifts. Capillary endothelial cell gaps and other electron microscopy findings can be demonstrated within minutes of the injury, but their role in the formation of edema is unclear. Hypoproteinemia leads to a reduction in colloidosmotic pressure and indirectly (through depletion of interstitial protein stores) it may also result in increased fluid conductivity [43, 44]. The use of crystalloids alone further reduces the colloidosmotic pressure of plasma and reduces the gradient between the colloidosmotic pressure of plasma and the interstitium. The increase in fluid conductivity, as well as other changes mediated by histamine, serotonin, leukotrienes, prostaglandins or oxygen radicals lead to efflux of fluid from the intravascular compartment and the development of edema, which may or may not be related to extravasation of proteins. It is conceivable then that while coexisting during the first few hours after the injury, protein extravasation and interstitial edema may be independent of one another.

If, as reported by Baxter in 1974 [45], the disturbance in the cell membrane manifested by decreased transmembrane potentials and decreased adenosinetriphosphatase is secondary to hypovolemia and tissue ischemia, cellular sodium

Table 3. Burn resuscitation using hypertonic lactated saline[a]

Variable		Adults 29 (36)	Children 22 (88)	Total 51 (48)
	n (%)			
Survivors	Body surface burned (%)	40	33	37
	Na intake – 1st day (mEq/kg/% burn)	0.49	0.74	0.59
	Na intake – 2nd day (mEq/kg/% burn)	0.19	0.41	0.28
	Na intake – 1st 48 h (mEq/kg/% burn)	0.68	1.15	0.88
	Water intake – 1st day (ml/kg/% burn)	1.96	3.94	2.81
	Water intake – 2nd day (ml/kg/% burn)	1.5	3.04	2.16
	Water intake – 1st 48 h (ml/kg/% burn)	3.46	6.98	4.97
Nonsurvivors	*n* (%)	52 (64)	3 (12)	55 (52)
	Body surface burned (%)	64	64	64
	Death during 1st 72 h *n* (%)	?	?	21 (20)
Total	*n* (%)	81 (76)	25 (24)	106 (100)

Na, Sodium

[a] Adapted from ref [28]

influx and intracellular edema could be another yet unrelated or loosely associated phenomenon.

Hypertonic lactated saline

The use of hypertonic salt solutions in burn resuscitation was first proposed by Moyer et al. [46] in 1944. Using a severely scalded dog burn model, these investigators observed that survival could be prolonged by administration of solutions containing 129 mEq/l of sodium bicarbonate. Subsequent animal studies by Fox and Baer [25] and Moyer et al. [47] revealed that heat-injured cells avidly trapped sodium. These observations provided the basis for the first clinical trials of hypertonic lactated saline (HLS) in burn resuscitation [29, 47–49]. Using solutions containing 300 and 250 mEq/l of sodium and 200 and 100 mEq/l of racemic lactate, Monafo et al. [27, 28, 32] reported that *"successful resuscitation"* could be achieved in either adults or children with extensive burns (Table 3). Assuming a normal weight-for-height ratio, we have estimated that the children in Monafo's studies received fluids with an average sodium concentration of 187 mEq/l for the first 48 h post injury; this is considerably less than what is generally associated with the HLS resuscitation program. A reduced sodium concentration results from the simultaneous administration of oral or intravenous hypotonic salt solutions, not initially described as part of the HLS program.

Another aspect of the HLS program, the significance of which has not been fully appreciated, is that its proponents accept lower hourly urine volumes as indicative of adequate hydration [32]. This is particularly important because the volume of fluid "required" to reach the "expected goal" would be considerably less than in the patient whose therapy is expected to result in higher urine volumes.

Over the years, the HLS program has been extensively modified. First, the development of hypernatremia and metabolic alkalosis necessitated a reduction in the concentration of sodium and racemic lactate as well as an increase in the chloride concentration [28]. Later, the simultaneous administration of hypotonic solutions, intravenously or per os [32], was allowed. While the original HLS program offered no formula to estimate fluid needs, both single-figure and two-figure formulae for the first and second 24 h, respectively, are curently recommended [50–52]. Thus, while the modified HLS hydration program is now better tolerated, it still lacks obvious advantages over conventional therapy. Fluid intake and overall weight gain are reportedly minimized, but burn edema remains unaltered [53] and edema in nonburned areas may actually increase [53, 54]. Furthermore, since HLS increases the osmolality of all fluid compartments and since sodium is an extracellular ion, the net result is expansion of the extracellular space at the expense of intracellular fluids. Thus, the protection derived from the excess sodium is only transient and limited by the ability of the kidneys to excrete the sodium load. It is possible then that some of the benefits that have been attributed to resuscitation with HLS may be related to the acceptance by their proponents of a state of relative dehydration and uneven distribution of water among body fluid compartments, rather than to any specific properties or effects of the sodium ion upon cellular or vascular receptors.

Bowser and Caldwell [51, 52] published the only human studies where HLS has been compared with isotonic and colloid-containing fluids. However, their three study groups were not comparable (median age was 3 years for the colloid, 5 years for the hypotonic and 12 years for the HLS group) and the guidelines they used to estimate fluid requirements and evaluate treatment objectives were different for each group. In addition, most of their data (weight gain, fluid intake, urine production and sodium intake and output) were reported only as group means. Since the patients in the HLS group were older and had a decreased surface area-to-weight ratio, it could have been predicted a priori that they were going to require less fluid per kilogram of body weight, the main observations reported.

In a separate study, crystalloid solutions with sodium concentrations of less than 150 mEq/l, 150–199 mEq/l and greater than 199 mEq/l were compared. Even though mortality was high (42%) for all groups (31/74 patients died) and 7 of the 31 patients who died did so within 48 h of injury, a correlation between sodium intake and improved survival was reported. Because urine output ranged between 0.5 and 1.0 ml/kg per hour for all patients, and no differences between groups were demonstrated, we have deduced that either the urine output did not reflect the level of hydration, and death resulted from overhydration, or that an overall excess of water and sodium was responsible for the increased mortality.

According to Bowser and Caldwell [51, 52], the major therapeutic effect of HLS is secondary to the sustained hypernatremia and hyperosmolality that is attained with its use. These investigators theorize that the increased osmolality of the extracellular fluid results in a fluid shift from the intracellular to the extracellular compartment, inhibits edema formation and improves kidney function by an "osmotic diuresis" effect. The latter counteract the antidiuresis that is so characteristic of burn trauma. However, neither Sokawa et al. [53] nor Carvajal and Parks [54] were able to demonstrate a reduction in edema formation or an improved diuresis with the use of hypertonic saline resuscitation.

By virtue of being an extracellular ion, the quantity of sodium, rather than the resulting change in osmolality, is what determines the volume of the respective fluid compartments [55]. As the sodium content of the intravascular and interstitial fluid compartments increases, so does their volume. Thus, from a physiological standpoint edema in the interstitium should be directly proportional to its sodium content, and HLS resuscitation should enhance rather than diminish interstitial edema – whether the tissues are injured or not [54]. Since the water content of the intracellular compartment is decreased by the consequent increase in extracellular fluid osmolality and outward fluid shift, "cellular edema" is decreased, but only in those cells that maintain a normally functioning sodium/potassium pump. Since burned sheep resuscitated with HLS remain oliguric and maintain a high urine osmolality, an osmotic diuretic effect does not seem plausible either [54]. Thus, from a theoretical standpoint it is difficult to conceive that HLS resuscitation, which results in hypernatremia, hyperosmolality, increased interstitial edema, delayed restoration of cardiac output, natriuresis, kaliuresis and no improvement in urine output, is advantageous to the burn victim. Furthermore, the persistent increase in serum osmolality should be viewed with concern, as it is poorly tolerated by children; cerebral hemorrhage, idiogenic osmol formation and rebound cerebral edema, circulatory congestion and inhibition of lipolysis are potential complications of this therapy that deserve further investigation in pediatric populations [56–63].

HLS with albumin

The addition of 12.5 g of albumin to each liter of HLS containing 240 mEq sodium and 120 mEq each of chloride and lactate (HLSA) for burn resuscitation was first proposed by Jelenko et al. in 1979 [64]. These investigators compared the effects of three different solutions [located Ringer's (LR), HLS and HLSA] on burn resuscitation of adult burn victims. Fluids were administered according to a demand program, the objectives of which were to maintain mean arterial pressure between 60 and 100 mmHg and a urine flow rate of 30–50 ml/h. Jelenko et al. [65] reported that patients in the HLSA group "required" less fluids, were resuscitated over a shorter period of time, were able to tolerate oral fluids earlier and required shorter periods of ventilatory support than those in the other two groups. Since the resuscitation guides used in this study have not received widespread acceptance, and since the treatment objectives varied between groups, interpretation of these results is still awaiting further confirmatory studies. For example, urine production, used to guide resuscitation, was different for the various groups; it should have been equal. The authors reported differences in central venous pressures among the groups; since this was one of the variables used to judge therapy, no significant differences should have occurred. In addition, the mean arterial pressure that the authors chose to guide fluid administration (60–100 mmHg) was too wide to presume equal hemodynamic balance for all patients studied. Studies in burned sheep have recently questioned the validity of mean arterial pressure and hourly urine volume measurements as guides to fluid resuscitation and have failed to demonstrate significant advantages from the use of HLSA over more conventional treatments [66].

Ascertaining the adequacy of resuscitation

Lack of agreement also exists in regard to the choice of resuscitation guides. While most investigators use hourly urine volume exclusively [1, 11, 15, 67–76], Welch [17] and Haynes [18] have proposed frequent measurements of hematocrit. Monitoring of central venous pressure has been recommended by Moncrief [37] and Hall and Sorensen [77]; Jelenko et al. [65] utilize mean arterial pressure. The use of invasive monitoring, including measurement of the cardiac index and ventricular stroke work index, has also been reported at some institutions [78–81].

The basic problem is that the objectives of the various programs have not been adequately defined. Hence, the guidelines used to evaluate success or failure have become

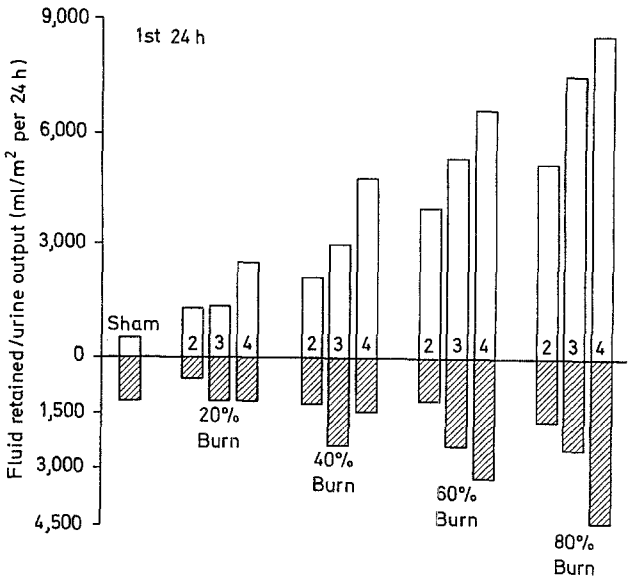

Fig. 2. Relationship between fluid retained (□, intake minus output) and urine output (▨) in burned sheep (20%, 40%, 60% and 80% burns) resuscitated with 2, 3 or 4 ml/kg per % burn per 24 h of an isotonic colloid-containing solution (D_5LR plus 12.5 g of albumin/l). Adapted from:Carvajal HF, Parks DH (eds) Burns in children. Year Book Publishers, Chicago, 1988

the subject of criticism. For example, if the goal of therapy is to prevent the development of renal insufficiency, this should not be equated with urine production equal to or greater than 50 ml/h; the same may be accomplished with lesser quantities of fluids and a less pronounced diuresis. Likewise, if the objective of resuscitation is to restore cardiac output to normal, the time factor during which this should be accomplished must be defined; rapid fluid infusion and other therapeutic interventions could accomplish this goal within 4 h, but unacceptable complications such as pulmonary edema or excessive peripheral edema may not justify it, particularly if a slower return of the cardiac output to normal is associated with a lower morbidity [37, 82].

Some of the difficulties associated with interpretation of many of the published studies were illustrated by Carvajal and Parks [54, 66] in two studies in burned sheep. In one of the studies [66], animals with burns of 20%, 40%, 60%, 80% and 90% of their body surface were resuscitated with a total 24-h fluid intake equivalent to either 2, 3 or 4 ml/kg percentage area of burn. In this study, the rate of fluid administration was fixed (one-half during the first 8 h post burn and the other half during the subsequent 16 h) and only one solution (LR containing 12.5 g of human serum albumin/l) was used. Several clinical and hemodynamic variables were measured at frequent intervals and the animals were sacrificed at 24 h post injury. A sham group of animals (nonburned) was subjected to the same experimental manipulations but received only maintenance fluids during the same time interval. Figure 2 depicts the total fluid intake and average urine production for all animals in the study. When compared with the sham animals, all burned animals, with the exception of the 20% burn – 2 ml/kg per % burn – group, had adequate urine outputs and, presumably, were adequately resuscitated. Although the increase in fluid administration was associated with an increase in urine output, as more fluids were given more fluids were retained and the weight of the animals progressively increased.

Even though the animals with burns of 60% and 80% increased their urine output by two- to threefold compared with the sham controls, water clearance measurements revealed that an antidiuretic effect still prevailed and that water was being reabsorbed even at high rates of urine production. This observation supports the contention that inappropriate secretion of ADH is at least partly responsible for the state of antidiuresis that characterizes the burn injury. It also suggests that high urine volumes must be viewed with concern as they don't always reflect optimal hemodynamics – thus, recognition of the state of antidiuresis may be more important than selection of any given fluid formula or fluid composition in preventing edema formation.

Quantity of fluids

While no consensus exists concerning the quantity of fluids needed for resuscitation of burned children, there is now general agreement that excessive fluid administration can be deleterious and curtailment of edema formation is currently regarded as a resonable therapeutic objective by all.

When compared with adults, children have a larger surface area-to-weight ratio, a higher rate of water turnover, a proportionally higher water load presented to the kidneys for excretion and a lower urine concentrating capacity. These physiological differences place the child at a disadvantage and must be taken into consideration when designing rehydration regimens. In burns as well as in other severe fluid and electrolyte disorders, maintenance fluids should be calculated separately from other losses. "Single-figure formulae" are usually fraught with inaccuracies and should not be used to estimate fluid requirements in burned children. While fluid formulae are usually regarded as approximations or starting points, the quantity of fluid they predict must be appropriate for children of all ages and burns of various sizes.

The surface area formula relates maintenance fluids to body surface and takes into consideration the extent of the burn in square meters to calculate burn-related fluid losses. This has proven to be simple, accurate and reliable [22, 83] and represents the method of choice for hydrating burned children.

Composition of the hydration solution

The electrolyte and protein composition of the various solutions currently advocated for fluid resuscitation of the burned patient varies widely. These differences are of such magnitude that dramatically different effects upon body homeostasis would be anticipated. Many human and animal studies have been undertaken to evaluate the benefits of one therapy over another, but several confounding factors have impeded proper interpretation of the results. Despite much

Table 4. First day fluid allowance for burned children as calculated with the Parkland and surface area formulae[a]

Age (years)	Burn size (%)					
	15	30	45	60	75	90
1 year (10 kg, 0.46 m^2)						
Parkland	600	1,200	1,800	2,400	3,000	3,600
Surface area	1,285	1,610	1,955	2,300	2,645	2,990
	(–685)	(–410)	(–155)	(+100)	(+355)	(+610)
4 years (16.5 kg, 0.68 m^2)						
Parkland	990	1,980	2,970	3,900	4,950	5,940
Surface area	1,870	2,380	2,890	3,400	3,910	4,420
	(–820)	(–400)	(+80)	(+500)	(+960)	(+1,520)
12 years (40 kg, 1.3 m^2)						
Parkland	2,400	4,800	7,200	9,600	12,000	14,400
Surface area	3,525	4,450	5,375	6,300	7,225	8,150
	(–1,125)	(+350)	(+1,825)	(+3,300)	(+4,775)	(+6,250)
16 years (70 kg, 1.86 m^2)						
Parkland	4,200	8,400	12,600	16,800	21,000	25,200
Surface area	5,115	6,500	7,905	9,300	10,695	12,090
	(–915)	(+1,900)	(+4,695)	(–7,500)	(+10,405)	(+13,110)

[a] Figures in parentheses represent absolute differences between the two estimates (ml/24 h)

of the controversy, the following statements are probably valid: (1) colloid-containing solutions exert a more rapid and complete resuscitation than do crystalloids alone, even during the first 24 h post injury; colloid-containing fluids restore hemodynamics with lesser infusate volumes, maintain the colloidosmotic pressure of plasma, minimize edema formation and support cardiac, pulmonary, renal and gastrointestinal function; (2) the optimal colloid composition of resuscitation solutions remains to be determined, but it probably lies between 1% and 2%; (3) administration of crystalloids worsens hypoproteinemia and results in a further drop in the colloidosmotic pressure of plasma; (4) hypertonic salt solutions offer no practical advantage to the pediatric burn victim and may be deleterious.

Hydration guides

Restoration of body homeostasis, the optional goal of fluid resuscitation, implies the provision of sufficient amounts of oxygen and other nutrients to satisfy the requirements of tissue beds. This should be accomplished at the least physiological cost; trends rather than actual values should be evaluated [67, 75, 83].

Since the methods that are currently available to measure oxygen delivery are cumbersome, and of themselves can be associated with significant morbidity [84], indirect evidence of the same should be sought. Restoration of cardiac, pulmonary, renal and central nervous system function are reasonable resuscitation goals. Clinically, these translate into restoration of the blood pressure, heart rate, capillary refill, respiratory rate and arterial blood pH and blood gases. Urine production and ability to concentrate the urine maximally should be demonstrated [76] and the patient should be lucid with a normal neurological examination [22].

It must be recognized that restoration of these variables to normal may not be possible or desirable and that trends in the right direction are reasonable therapeutic end-points. A heart rate that is declining toward normal, a borderline blood pressure and a slightly prolonged capillary refill may be quite acceptable if the variables are improving in the right direction. A patient that is lethargic, but is recovering from stupor or coma, or a child that is oliguric with a concentrated urine does not necessarily require a major change in therapy – particularly if other variables suggest a reasonable state of hydration. A well-hydrated unburned child receiving maintenance fluids should be expected to produce 650–750 ml of urine/m^2 body surface per day (30–35 ml/m^2 per hour). In the burned child, lesser quantities of urine should be anticipated. This state of antidiuresis is secondary to the secretion of ADH and other hormones in response to trauma, pain, fear, apprehension, abnormal postures and the effects of various drugs [85–87]. During the acute phase, exaggerated sympathetic responses also contribute to a reduction in urine production. Thus, in the burned child it is impossible to determine how much urine should be produced or how much would be appropriate. The expectation would be for a value around 30 ml/m^2 per hour, but the exact figure is likely to vary.

Attempts to force diuresis by progressively increasing fluid administration invariably lead to a positive water balance and excessive edema formation. Since a relative oliguria is likely to persist despite fluid overload, urine production is best evaluated at 4-h rather than 1-h intervals and interpreted along with other clinical and laboratory guides, before a decision to increase or decrease the rate of fluid administration is made. In general, the lower the ex-

pectation for urine production, the lower the quantity of fluid that the patient ends up "requiring for resuscitation." Finally, invasive monitoring should be reserved for massive burns, patients with smoke inhalation injury or those with associated injuries [87].

References

1. Black DA (1940) Treatment of burn shock with plasma and serum. BMJ 2: 693–697
2. Elkinton JR, Wolffe WA, Lee WE (1940) Plasma transfusions in the treatment of the fluid shift in severe burns. Ann Surg 112: 150–157
3. Elman R (1941) The therapeutic significance of plasma protein replacement in severe burns. JAMA 116: 213–216
4. Lam CR (1941) Plasma therapy of burns. Ann Surg 113: 1089
5. Harkins HN, Cope O, Evans EW, Phillips RA, Richards DW Jr (1945) The fluid and nutritional therapy of burns. JAMA 128: 475–479
6. Cope O, Moore FD (1947) The redistribution of body water and the fluid therapy of the burned patient. Ann Surg 126: 1010–1045
7. Cope O, Graham JB, Moore FD, Ball MR (1948) The nature of the shift of plasma protein to the extravascular space following thermal trauma. Ann Surg 128: 1041–1055
8. Evans EI, Purnell OH, Robinett PW, Batchelor A, Martin M (1952) Fluid and electrolyte requirements in severe burns. Ann Surg 135: 804–816
9. Reiss E, Stirman JA, Artz CP, Davis JH, Amspacher WH (1953) Fluid and electrolyte balance in burns. JAMA 152: 1309–1313
10. Gelin LE (1952) Macrodex and oxygen in the primary treatment of extensive burns. Acta Chir Scand 103: 351–352
11. Baxter CR, Shires GT (1968) Physiological response to crystalloid resuscitation of severe burns. Ann NY Acad Sci 150: 874–893
12. Pruitt BA Jr (1978) Fluid and electrolyte replacement in the burned patient. Surg Clin North Am 58: 1291–1312
13. Eagle JF (1956) Parental fluid therapy of burns during the first 48 hours. NY J Med 56: 1613–1618
14. Eagle JF, Schenk WG, Shim W (1960) Parental fluid therapy of burns (use of a single solution during the first 48 hours). JAMA 174: 1589–1592
15. Batchelor ADR, Kirk J, Sutherland AB (1961) Treatment of shock in the burned child. Lancet I: 123–127
16. Metcoff J, Buchman H, Jacobson M, Richter H Jr, Bloomenthal ED, Zacharias M (1961) Losses and physiologic requirements for water and electrolytes after extensive burns in children. N Engl J Med 265: 101–111
17. Welch KJ (1962) Thermal burns. In: Benson CD, Mustard WT, Ravitch MM (eds) Pediatric surgery, vol 1. Year Book Medical, Chicago, pp 53–70
18. Haynes BW (1965) The management of burns in children. J Trauma 5: 267–277
19. Baxter CR (1982) Controversies in the resuscitation of burn shock. Curr Concepts Therm Care 5: 5–14
20. Hutcher N, Haynes BW Jr (1972) The Evans formula revisited. J Trauma 12: 453–458
21. Carvajal HF (1975) Acute management of burns in children. South Med J 68: 129–131
22. Carvajal HF (1980) A physiologic approach to fluid therapy in severely burned children. Surg Gynecol Obstet 150: 379–384
23. Brouhard BH, Carvajal HF, Linares HA (1978) Burn edema and protein leakage in the rat. I. Relationship to time of injury. Microvasc Res 15: 221–228
24. Lamke LO, Nilsson GE, Reithner HL (1977) The evaporation water loss from burns and the water vapor permeability of grafts and artificial membranes used in the treatment of burns. Burns 3: 159–165
25. Fox CL Jr, Baer H (1947) Redistribution of potassium, sodium, and water in burns and trauma and its relation to the phenomena of shock. Am J Physiol 151: 155–167
26. Fox CL Jr, Stanford JW (1974) Comparative efficacy of hypo-, iso-, and hypertonic sodium solutions in experimental burn shock. Surgery 75: 71–79
27. Monafo WW (1970) The treatment of burn shock by the intravenous and oral administration of hypertonic lactated saline solution. J Trauma 10: 575–586
28. Monafo WW, Chuntrasakul C, Ayvasian V (1973) Hypertonic sodium solution in the treatment of burn shock. Am J Surg 126: 778–783
29. Moyland JA, Rechler JM, Mason AS (1973) Resuscitation with hypertonic lactate saline in thermal injury. Am J Surg 125: 580–584
30. Kravath RE, Aharon AS, Abal G, Finberg L (1970) Clinically significant physiologic changes from rapidly administered hypertonic solutions: acute osmol poisoning. Pediatrics 46: 267–275
31. Markley K, Smallman E, Milliken C (1964) The efficacy and toxicity of iso-, hypo-, and hypertonic sodium solutions in the treatment of burn shock in mice. Surgery 57: 698–703
32. Monafo WW, Halverson JD, Schechtman K (1984) The role of concentrated sodium solutions in the resuscitation of patients with severe burns. Surgery 95: 129–134
33. O'Neill JA (1982) Fluid resuscitation in the burned child – a reappraisal. J Pediatr Surg 17: 604–607
34. Schwartz S (1979) Consensus summary on fluid resuscitation. J Trauma 19: 876–877
35. Shimazaki S, Yoshioka T, Tanaka N, Sugimoto T, Onji Y (1977) Body fluid changes during hypertonic lactated solution therapy for burn shock. J Trauma 17: 38–43
36. Markley K, Bocanegra M, Bazan A, Temple R, Chiappori M, Morales G, Carrion A (1956) Clinical evaluation of saline solution therapy in burn shock. JAMA 161: 1465–1473
37. Moncrief JA (1973) Burns. N Engl J Med 288: 444–454
38. Demling RH (1987) Fluid replacement in burned patients. Surg Clin North Am 67: 15–30
39. Brouhard BH, Carvajal HF (1979) Effect of inhibiting prostaglandin synthesis of edema formation and albumin leakage during thermal trauma in the rat. Prostaglandins 17: 939–946
40. Carvajal HF, Brouhard BH, Linares HA (1975) Effects of antihistamine antiserotonin and ganglionic blocking agents upon increased capillary permeability following burn trauma. J Trauma 15: 969–975
41. Carvajal HF, Linares HA (1980) Effect of burn depth upon edema formation and albumin extravasation in rats. Burns 7: 79–83
42. Holleman JH, Gabel JC, Hardy JD (1978) Pulmonary effects intravenous fluid therapy in burn resuscitation. Surg Gynecol Obstet 147: 161–166
43. Demling RH (1982) Burn edema. 1. Pathogenesis. J Burn Care Rehabil 3: 138–148
44. Granger ND, Gabel JC, Drake RE (1978) Physiologic basis for the clinical use of albumin solutions. Surg Gynecol Obstet 146: 97–104
45. Baxter CR (1974) Fluid volume and electrolyte changes of the early post-burn period. Clin Plast Surg 1: 693–703
46. Moyer CA, Coller FA, Iob V, Vaughan HH, Marty D (1944) A study of the interrelationship of salt solutions, serum and defibrinated blood in the treatment of severely scalded, anesthetized dogs. Ann Surg 120: 367–376
47. Moyer CA, Margraft HW, Monafo WW (1965) Burn shock and extravascular sodium deficiency-treatment with Ringer's solution with lactate. Arch Surg 90: 799–811
48. Moylan JA, Mason AD Jr, Rogers PW, Walker HL (1973) Post-burn shock: a critical evaluation of resuscitation. J Trauma 13: 354–358
49. Crum R, Bobrow B, Shochford S, et al. (1988) The neurohumoral response to burn surgery in patients resuscitated with hypertonic saline. J Trauma 28: 1181–1187

50. Caldwell FT Jr, Bowser BH (1979) Critical evaluation of hypertonic and hypotonic solutions to resuscitate severely burned children: a prospective study. Ann Surg 189: 546–552
51. Bowser BH, Caldwell FT Jr (1983) The effect of resuscitation with hypertonic vs. hypotonic vs. colloid on the wound and urine fluid and electrolyte losses in severely burned children. J Trauma 23: 916–923
52. Bowser BH, Caldwell FT (1986) Fluid requirements of severely burned children up to 3 years old: hypertonic saline vs. Ringer's lactate-colloid. Burns 12: 549–555
53. Sokawa M, Monafo E, Dietz F (1981) The relationship between experimental fluid therapy and wound edema in scald wounds. Ann Surg 193: 237–244
54. Carvajal HF, Parks DH (1988) The optimal composition of burn resuscitation fluids. Crit Care Med 16: 695–699
55. Pitts RF (1968) Volume and composition of the body fluids. In: Pitts RF (ed) Physiology of the kidney and body fluids. Year Book Medical, Chicago, pp 22–43
56. Sotos JF, Dodge PR, Meara P, Talbot N (1960) Studies in experimental hypertonicity. I. Pathogenesis of the clinical syndrome, biochemical abnormalities and cause of death. Pediatrics 26: 925–938
57. Gennari FH, Kassirer JP (1974) Osmotic diuresis. N Engl J Med 291: 714–720
58. Gennari FH (1984) Serum osmolality uses and limitations. N Engl J Med 310: 102–105
59. Fimberg L (1959) Pathogenesis of lesions in the nervous system in hypernatremic states.
60. Finberg L, Kravath RE, Fleishman AR (1982) Hypernatremic dehydration. In: Finberg L, Kravath RE, Fleishman AR (eds) Water and electrolytes in pediatrics. Saunders, Philadelphia, pp 78–89
61. Eklund J, Hallberg D (1970) Hypersomolality and lypolysis: an experimental study with reference to hypernatremia in burned patients. Acta Chir Scand 136: 91–93
62. Crum R, Bobrow B, Shackford S, Hansbrough J, Brown M (1988) The neurohumoral response to burn injury in patients resuscitated with hypertonic saline. J Trauma 28: 1181–1187
63. Arieff AI, Guisado R, Lazarowitz VC (1977) The pathophysiology of hyperosmolar states. In: Andreoli TE, Grantham JJ, Rector FC Jr (eds) Disturbances in body fluid osmolality. Williams and Wilkins, Baltimore, pp 277–250
64. Jelenko C III, Williams JB, Wheeler ML, Callaway BD, Fackler VK, Albers CA, Barger AA (1979) Studies in shock and resuscitation. I. Use of a hypertonic, albumin-containing, fluid demand regimen (HALFD) in resuscitation. Crit Care Med 7: 157–167
65. Jelenko C III, Solengerger RI, Wheeler ML, Callaway BD (1979) Shock and resuscitation. III. Accurate refractometric COP determinations in hypovolemia treated with HALFD.JACEP 8: 7–11
66. Carvajal HF (1988) Controversies in fluid therapy and their impact upon pediatric populations. In: Carvajal HF, Parks DH (eds) Burns in children. Year Book Publishers, Chicago, pp 51–57
67. Agarwal N, Petro J, Salisbury RE (1983) Physiologic profile monitoring in burned patients. J Trauma 23: 577–583
68. Arturson G, Hedlund A (1984) Primary treatment of 50 patients with high tension electrical injuries. Scand J Plast Reconstr Surg Hand Surg 18: 111–118
69. Artz CP (1971) The Brooke formula. In: Polk HC Jr, Stone HH (eds) Contemporary burn management. Little Brown, Boston, pp 43–51
70. Demling RH (1983) Fluid resuscitation after major burns. JAMA 250: 1438–1440
71. Demling RH (1987) Fluid replacement in burned patients. Surg Clin North Am 67: 15–30
72. Griffith RW (1981) A low volume burn resuscitation regimen: assessment of performance of probit analysis. Br J Surg 68: 225–228
73. Griffiths RW, Laing JE (1981) A burn formula in clinical practice. Ann R Coll Surg Engl 63: 50–53
74. Jenkinson LR (1982) Fluid replacement in burns. Ann R Coll Surg Engl 64: 336–338
75. Pruitt BA Jr (1981) Fluid resuscitation for extensively burned patients. J Trauma 21: 690–692
76. Settle JA (1974) Urine output following severe burns. Burns 1: 23–42
77. Hall KVN, Sorensen B (1978) The treatment of burn shock – results of a five-year randomized controlled clinical trial of dextran 70 vx. Ringer's lactate solution. Burns 5: 107–112
78. Aikawa N, Martyn JAJ, Burke JF (1978) Pulmonary artery catheterization and thermodilution cardiac output determination in the management of critically ill burned patients. Am J Surg 135: 811–817
79. Aikawa N, Ishibiki K, Naito C, Abe O, Yamamoto, Motegi M, Sudo M (1982) Individualized fluid resuscitation based on hemodynamic monitoring in the management of extensive burns. Burns Incl Therm Inj 8: 249–255
80. Carvajal HF, Reinhard JA, Traber DL (1976) Renal and cardiovascular functional response to thermal injury in dogs subjected to sympathetic blockade. Circ Shock 3: 287–298
81. Martyn AJ, Snider MT, Farago LF, Burke JF (1981) Thermodilution right ventricular volume: a novel and better predictor of volume replacement in acute thermal injury. J Trauma 21: 619–626
82. Turner R, Carvajal HF, Traber DL (1977) Effects of ganglionic blockade upon renal and cardiovascular dysfunction induced by thermal injury. Circ Shock 4: 103–113
83. Carvajal HF (1985) Management of severely burned patients: sorting out the controversies. Emerg Med Rep 6: 89–96
84. Shoemaker WC, Czer LC (1979) Evaluation of the biologic importance of various hemodynamic and oxygen transport variables. Crit Care Med 7: 424–431
85. Stark H, Weinberger AH, Ben-Bassat M (1979) Persistent hyponatremia and inappropriate antidiuretic hormone secretion in children with extensive burns. J Pediatr Surg 14: 149–153
86. Barter FC, Schwartz WB (1967) The syndrome of inappropriate secretion of antidiuretic hormone. Am J Med 42: 790–806
87. Martyn JA, Snider MT, Szyfelbein S, Burke JF, Laver MB (1980) Right ventricular dysfunction in acute thermal injury. Ann Surg 191: 330–335