REVIEW

Fluid and electrolyte overload in critically ill patients: An overview

Bruno Adler Maccagnan Pinheiro Besen, André Luiz Nunes Gobatto, Lívia Maria Garcia Melro,
Alexandre Toledo Maciel, Marcelo Park

Bruno Adler Maccagnan Pinheiro Besen, André Luiz Nunes Gobatto, Lívia Maria Garcia Melro, Alexandre Toledo Maciel, Marcelo Park, Intensive Care Unit, Department of Medical Emergencies, Hospital das Clínicas, University of Sao Paulo Medical School, Sao Paulo 05403000, Brazil
André Luiz Nunes Gobatto, Alexandre Toledo Maciel, Imed Research Group, Intensive Care Unit, Hospital Sao Camilo Pompéia, Sao Paulo 05022-001 Brazil

Correspondence to: Bruno Adler Maccagnan Pinheiro Besen, MD, Intensive Care Unit, Department of Medical Emergencies, Hospital das Clínicas, University of Sao Paulo Medical School, Carvalho Aguiar street, 255, 6th Floor, Room 6040, Sao Paulo 05403000, Brazil. brunobesen@yahoo.com.br
Telephone: +55-11-26616457

Abstract

Fluids are considered the cornerstone of therapy for many shock states, particularly states that are associated with relative or absolute hypovolemia. Fluids are also commonly used for many other purposes, such as renal protection from endogenous and exogenous substances, for the safe dilution of medications and as "maintenance" fluids. However, a large amount of evidence from the last decade has shown that fluids can have deleterious effects on several organ functions, both from excessive amounts of fluids and from their non-physiological electrolyte composition. Additionally, fluid prescription is more common in patients with systemic inflammatory response syndrome whose kidneys may have impaired mechanisms of electrolyte and free water excretion. These processes have been studied as separate entities (hypernatremia, hyperchloremic acidosis and progressive fluid accumulation) leading to worse outcomes in many clinical scenarios, including but not limited to acute kidney injury, worsening respiratory function, higher mortality and higher hospital and intensive care unit length-of-stays. In this review, we synthesize this evidence and describe this phenomenon as fluid and electrolyte overload with potentially deleterious effects. Finally, we propose a strategy to safely use fluids and thereafter wean patients from fluids, along with other caveats to be considered when dealing with fluids in the intensive care unit.

Key words: Fluid therapy; Critically Ill; Oliguria; Water-electrolyte balance; Central venous pressure; Resuscitation; Acute kidney injury; Diuretics; Multiple organ dysfunction syndrome; Systemic inflammatory response syndrome

Core tip: Fluids are a cornerstone of the management of critically ill patients with systemic inflammatory response syndrome who are at risk of multiple organ dysfunction syndrome. However, as with any therapy, fluids can be associated with harm, such as added or worsening organ dysfunctions. Therefore, patients should be weaned from fluids when possible, sometimes through an active de-resuscitation strategy.

INTRODUCTION

Fluids have been widely used in critically ill patients to optimize hemodynamics[1], to enhance renal protection from contrast[2], globins[3], and uric acid[4], to offer caloric intake[5] and as an adjunct for medication dilution[6]. During the first hours of shock syndromes, isotonic fluids can stabilize arterial pressure and perfusion and are lifesaving at times. Furthermore, to reach physiological hemodynamic targets, a large amount of intravenous fluids may be required. Some fasting patients receive infusions of one to three liters of dextrose in water with added electrolytes, mainly sodium, chloride and potassium, to avoid hypoglycemia, dehydration and electrolyte deficiency. Renal protection in critically ill patients is of huge importance, and hyperhydration is frequently used to enhance urine output and to avoid renal tubular cell injury by the retention of toxic substances at high concentrations. Finally, many drugs require a large amount of fluids with electrolytes to be safely administered.

Fluids and electrolytes are responsible for a large amount of volume that is infused in critically ill patients and are commonly associated with reduced urine output and renal electrolyte excretion failure, particularly chloride-rich solutions. This combination is even more accentuated in the first hours of critical illness[1,7] or in the presence of acute kidney injury (AKI)[8-10]. Ultimately, the inadequate management of fluids and electrolytes in critically ill patients culminates in hydroelectrolytic overload, which causes physiological derangements and worse outcomes[11]. This manuscript describes the mechanisms, pathophysiology, and potential consequences of fluid and electrolyte overload and provides a combined bedside approach to avoid it.

ELECTROLYTE OVERLOAD

Primary electrolytes in basic human physiology

Sodium and chloride are the main determinants of colloidosmotic forces in human plasma and interstitial space because they account for 80% of the osmolality of these fluids[12]. Plasma non-permeable proteins attract positively charged ions and repel negatively charged ions, leading to a passive transmembrane distribution of anions to preserve plasma and interstitial space electroneutrality, known as the Gibbs-Donnan effect. A steady-state is achieved when the plasmatic osmolality is 1 mOsm/L greater than the interstitial space, and the capillary hydrostatic pressure opposes the osmotic movement of the water into the intravascular space[13].

Even at a constant interstitial space osmolality, to maintain cell volume, the transport of osmotically active substances across the cell membrane (mainly sodium and potassium) counterbalances the intracellular osmotic forces imposed by high-molecular-weight anionic proteins (Double-Donnan effect)[14].

One of the main roles of electrolytes and their homeostasis is the distribution of fluids throughout the human body. Colloidosmotic and hydrostatic pressures are the main forces influencing the fluid distribution between intravascular and interstitial spaces, whereas changes in intra or extracellular osmolality are in general followed by water movement and determine the changes in cell volume[14].

Sodium overload

Sodium is the main cation of solutions infused into critically ill patients. The 0.9% saline solution has 154 mEq/L of sodium, that is, one liter of 0.9% saline infusion carries 3.4 g of sodium, which represents approximately eight 100 g packages of commercially available potato chips, a huge amount of the electrolyte[15]. Nevertheless, sodium renal excretion is largely impaired in critically ill patients,[10] particularly in patients with AKI[8].

In a sample of septic patients, for instance, the mean isotonic fluid intake was 5000 mL during the first 24 h in the ICU, with a urine output of 2000 mL during the same period and a mean sodium urinary concentration of 55 mEq/L[16]. In this casuistic, the total amount of sodium infused was 770 mEq in the 24 h period analyzed with a concomitant sodium excretion of 110 mEq, resulting in a positive fluid and sodium balance of 3000 mL and 660 mEq, respectively. Because of the large sodium distribution volume in adults (49 L to 70 kg), the expected effect of the remaining 660 mEq of sodium and 3000 mL of water in patients with a pre-infusion sodium concentration of 145 mEq/L is approximately 4.0 mEq/L[17]. Notably, patients with established kidney injuries were excluded from the Stelfox *et al*[18] study, and consequently the sodium overload effect in patients with AKI is expected to be even more striking. To exemplify this finding, Table 1 shows a water and electrolyte cumulative evolution of a mono-compartment mathematical model of a post-resuscitation phase with low urinary sodium and chloride, similar to the septic patients of Noritomi's study.

Other groups have also described resuscitation fluids as a contributing factor to ICU-acquired hypernatremia with a dose-response effect: the greater the saline infusion, the worse the hypernatremia condition[19]. However, other sources of saline contribute to sodium loading in critically ill patients and may be a modifiable risk factor, such as normal saline used to dilute parenteral drugs and to keep catheters open[20]. Finally, in Australia and New Zealand, a point-prevalence study demonstrated that sodium administration in excess

Table 1 Closed mono-compartment mathematical marginal model simulating the body water space of distribution						
Variables	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5
Patient's resulting variables						
Na^+ (mEq/L)	140	142	148	151	146	144
Cl^- (mEq/L)	100	108	114	117	113	111
Fluid balance (mL)	-	6000	0	800	800	0
Cumulative fluid balance (mL)	-	6000	6000	6800	7600	7600
Distribution water volume and electrolyte data						
Vd (L)	36	42	42	43	44	44
Total mass of Na^+ (mEq)	5040	5964	6216	6493	6424	6336
Total mass of Cl^- (mEq)	3600	4536	4788	5031	4972	4884
Fluids output						
Diuresis (mL)	-	2000	1200	1200	1200	2000
Urinary Na^+ (mEq/L)	-	30	50	70	90	110
Urinary Cl^- (mEq/L)	-	30	50	70	90	110
Fluids input						
Volume	6000	2000	2000	2000	2000	2000
Na^+ (mEq/L)	154	154	154	0	0	0
Cl^- (mEq/L)	154	154	154	0	0	0

The main assumptions of this model are the absence of feces, sudoresis, renal replacement therapy, and the absence of Gibbs-Donnan effect. This patient was resuscitated with 4000 mL of 0.9% saline and received additional 2000 mL of 0.9 fluids during the Day 0. He received an amount of 0.9% saline during day 1 and day 2, afterwards the same 2000 mL of volume was infused without electrolytes due to hypernatremia. Vd: Denotes distribution volume.

of recommended daily requirements (*i.e.*, 1-2 mmol/kg) was fairly common, with the major sources being maintenance fluids (30.9%), fluid boluses (16.3%) and drug boluses (12.3%)[21].

Hypernatremia is present at hospital admission and at ICU admission in 2% and 7% of patients, respectively[22,23]. By contrast, up to 27% of patients in the ICU develop hypernatremia during their ICU stay[18]. In a speculative view, this higher incidence of hypernatremia in critically ill patients might be explained by sodium overload. Critical illness related hypernatremia is associated with disease severity, kidney injury and dysfunction, mechanical ventilation and ICU length-of-stay[18]. Finally, hypernatremia is associated with higher in-hospital mortality[18,22,24,25] and it has been considered in several ICUs as a quality-of-care marker[26,27]. Recently, a group also retrospectively noted that correcting this abnormality ultimately resulted in better survival[28].

Chloride overload
Chloride is the main anion of fluids used in critical care settings, and its concentration is well correlated to the sodium concentration to maintain the electroneutrality of solutions[29]. The 0.9% saline solution, Ringer's lactate solution, and Plasmalyte contain 154, 109 and 98 mEq/L of chloride, respectively[15]. Because the serum chloride concentration is approximately 100 mEq/L, it is expected that a 0.9% saline infusion potentially increases the serum chloride concentration. In septic patients, Park *et al*[30] showed that 2000 ± 300 mL of a 0.9% saline infusion promptly resulted in a disproportionate elevation of serum chloride in comparison to the sodium concentration (Figure 1). Of note, this disproportionate elevation occurred in spite of equal chloride and sodium

concentrations in the 0.9% saline solution that was infused[15,30].

The principle of the unequal chloride and sodium concentration elevations is based on the fact that the initial serum chloride concentration is lower than the initial sodium concentration. Therefore, the same infused amount in mEq/L of sodium and chloride is expected to have a greater effect on the ion with the lower serum concentration - in this case, chloride (Figure 2).

Kellum *et al*[31] demonstrated in a canine model of endotoxemia that only one-third of the post-volume infusion of chloride associated acidosis could be explained by exogenous chloride. The authors attributed this fact to an extravascular to intravascular chloride shift that was driven by differences in the transmembrane potential and the Gibbs-Donnan effect secondary to the fluid challenge. This same finding of chloride elevation was observed in humans with severe sepsis and septic shock[16]. Therefore, one can expect an intrinsic chloride elevation in patients with systemic inflammation, which is amplified by a chloride-rich fluid infusion, such as the many previously described sources of normal saline that are infused in critically ill patients.

In addition to these sources of chloride, the renal excretion of chloride is also impaired, similarly to sodium excretion, during the initial phase of critical illness[9,10], particularly in patients with AKI[8]. The net result is a positive balance of chloride (Table 1), and an increased serum chloride concentration results in a hyperchloremic metabolic acidosis[16,32]. This is also called "SID acidosis" and is not related to outcomes in mixed critically ill patients[33]. However, specifically in septic patients, initial hyperchloremic acidosis is associated with a higher mortality[16].
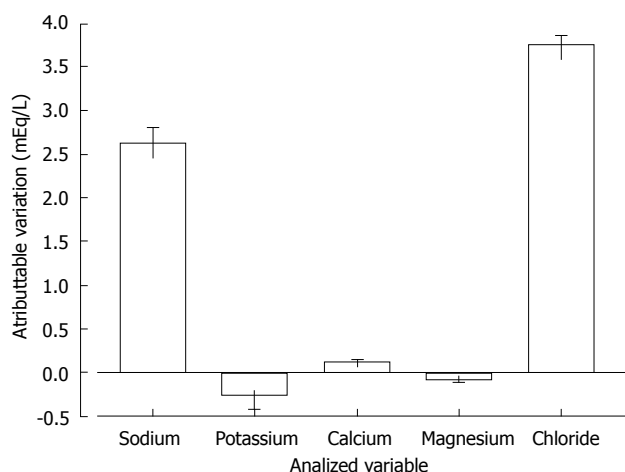
Figure 1 Variation of plasma electrolytes concentration immediately after 2000 ± 300 mL infusion of 0.9% saline in septic patients. Adapted from Park *et al*[30].

Figure 2 A monocompartimental model of intravascular 0.9% saline infusion, simulating the extracellular volume modification. To the initial distribution volume (Vd) = 36 L (approximately 60% of body mass of 60 kg), the total AMMOUNT of Cl^- and Na^+ were 3420 and 5040 mEq respectively. The infusion of 4000 mL of 0.9% saline results in additional 616 mEq of Cl^- and Na^+ to the total QUANTITY of extracellular electrolytes, that is, 4036 and 5656 mEq of Cl^- and Na^+ respectively. The new total AMMOUNT of electrolytes are distributed in a new Vd of 40 (36 + 4) liters, resulting in the new concentrations, where the chloride elevation was more striking than the sodium elevation.
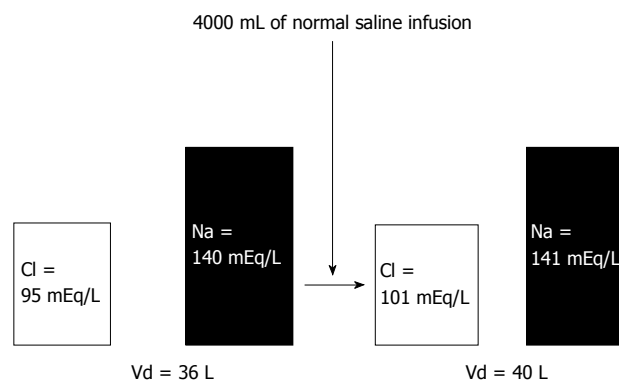
Pathophysiology

Renal consequences: Electrolyte overload may have detrimental effects on renal function, particularly chloride overload. Animal studies suggest that chloride may influence renal blood flow (RBF), which is mediated primarily by its effects on afferent and intrarenal arterial vessels[34,35]. In canine experiments, the renal infusion of solutions containing chloride, such as 0.9% saline or NH_4Cl, led to reductions in the total RBF and GFR in both denervated and *in situ* kidneys[34]. In an animal model of sepsis, unbalanced solutions worsened sepsis-induced AKI[36]. Other experiments confirmed that extracellular chloride is essential for contraction in renal afferent arterioles[37,38]. In humans, an infusion of 2 L of 0.9% saline over 1 h was associated with a reduction in the RBF velocity and renal cortical tissue perfusion measured by magnetic resonance imaging (MRI); these changes were not observed after a similar infusion of a balanced crystalloid[39]. Moreover, studies in healthy volunteers have shown a delayed urine output with saline compared to a balanced solution[40].

An infusion of hypertonic solutions containing chloride into the renal artery causes a biphasic response in renal vascular resistance[34]. Hyperosmolality leads to an abrupt renal vasodilatation and consequent increase in RBF. After 1-5 min, vasodilation is reversed, and RBF and GFR decrease below pre-infusion levels. The second phase is absent in hypertonic solutions that do not contain chloride.

In vitro, the entry of chloride from elevated tubular chloride concentrations into epithelial renal cells causes the depolarization of the basolateral membrane[41]. Increased NaCl concentrations in the macula densa stimulate ATP release, resulting in the extracellular formation of adenosine, which is involved in the signal transmission of the tubule-glomerular feedback response, increasing afferent arteriolar resistance and reducing GFR[35,42].

Clinically, Yunos *et al*[43] translated this experimental knowledge to a large population of critically ill patients in a prospective open-label sequential period pilot study. After a control period and a wash-out phase, the use of chloride-rich intravenous fluids was restricted; this resulted in decreased chloride administration (694 to 496 mmol/patient) and led to better renal outcomes even after adjustment for covariates, including less high-severity AKI [OR = 0.52 (95%CI: 0.37-0.75); *P* < 0.001] and the reduced use of renal replacement therapy [OR = 0.52 (95%CI: 0.33-0.81); *P* = 0.004][43].

Acid-base consequences: Large volume resuscitation is commonly required in patients with sepsis and trauma. These patients may receive crystalloid infusions of many times their plasma volumes. Because the chloride concentration in 0.9% saline is approximately 50% higher than the plasma values, the chloride load associated with these volumes is significant. As previously described in this review, the chloride load associated with normal saline, which is a solution with a strong ion difference (SID) of 0, may be one of the main determinants of acidosis induced by fluids, along with chloride shifts that may occur in patients with sepsis (and other inflammatory states) and the Gibbs-Donnan effect after fluid challenges. These chloride loads and shifts interact with the patient's renal function, leading to both more AKI and subsequently lower chloride excretion, which might affect the kidney's recovery.

In surgical patients, when 0.9% saline was used as the primary intraoperative solution, significantly more acidosis was observed on completion of the surgery. These patients required larger amounts of bicarbonate to achieve predetermined measurements of base deficit and were associated with the use of larger amounts of blood products[44]. In another trial, a 0.9% saline infusion was compared to a balanced electrolyte and glucose solution. Two-thirds of the patients in the 0.9% saline

group but none of the patients in the balanced fluid group developed hyperchloremic metabolic acidosis, and the hyperchloremic acidosis was associated with reduced gastric mucosal perfusion on gastric tonometry[45].

Although the effects of chloride are well studied, little is known about the potential contributions of sodium to the metabolic acid-base state. In a sample of 51 critically ill patients, a rise in serum sodium levels during the development of hypernatremia was accompanied by an increasing pH, serum bicarbonate, and standard base excess, and consequently metabolic alkalosis[46]. In addition, the development of metabolic alkalosis correlated with the SID but not with the absolute serum sodium concentrations, indicating that the increase in the serum sodium-to-chloride ratio led to the development of metabolic alkalosis[47].

Inflammatory response: Fluid and electrolyte overload may also influence cytokine production and the inflammatory response. In an animal model of hyperchloremic acidosis induced by dilute HCl infusion, moderate (SBE, - 5 to - 10) and severe (SBE, - 10 to - 15) acidosis significantly increased cytokine expression in a dose-dependent fashion in normotensive septic rats[48]. These results are consistent with *in vitro* studies showing that HCl influences cytokine production in LPS-stimulated cells[49], and pH interferes in nitric oxide[50] and tumor necrosis-α production[51] by macrophages in cell models. Interestingly, acidosis etiology may determine the inflammatory response pattern. Hyperchloremic acidosis is essentially pro-inflammatory as assessed by the increased NO release and the IL-6-to-IL-10 ratio, whereas lactic acidosis is associated with an anti-inflammatory pattern[49].

Hemodynamic consequences: Chloride overload and its consequent hyperchloremic acidosis may have direct and independent deleterious effects on hemodynamics and survival. In an endotoxic shock model in rats, moderate and severe acidosis that was generated by HCl infusion induced a significant drop in blood pressure. This change in blood pressure was correlated with increases in plasma chloride concentrations and to a lesser degree with a decrease in pH[52]. Furthermore, saline solution resuscitation was associated with a significantly shorter survival time compared to a balanced electrolyte solution containing starch in a similar animal model. Survival time was negatively correlated with both the decrease in pH and the increase in serum chloride following the initial resuscitation. The decrease in pH appeared to have been brought on by changes in chloride, lactate, and $PaCO_2$. However, lactate values were not different between the groups, and the changes in $PaCO_2$ were not correlated with survival time. Thus, hyperchloremic acidosis, rather than acidosis in general, was strongly and independently associated with early mortality in these animals[53].

FLUID OVERLOAD

Pathophysiology

The renal compartment syndrome: The human body is composed of different organ systems. Lungs are, perhaps, the most affected organs by fluid overload, followed by encapsulated organs such as the kidneys. Experimental and clinical evidence from more than 30 years ago links the development of renal edema with oliguria and the perpetuation of ischemic AKI[54]. This could be explained by reduced perfusion pressure through the kidneys as a result of higher central venous pressure, which has been better described in the context of cardiorenal syndromes[55,56]. In addition to heart failure, patients with systemic inflammatory response syndrome (SIRS) may also develop interstitial edema and subsequently increases in interstitial pressure, leading to lower perfusion pressure, particularly in encapsulated organs such as the kidney[57].

In animal models, Burnett *et al*[58] also demonstrated that an increase in renal venous pressure associated with volume expansion led to higher interstitial pressures and decreased sodium excretion in association with a decreased RBF and glomerular filtration rate. Recently, Cruces *et al*[59] experimentally described a model that provided even more support of the existence of a renal compartment. In their work, pressure had a nonlinear dependence on volume in the intact kidney, whereas the decapsulated kidney followed a linear pressure-volume curve, thus corroborating the hypothesis that kidney hypoperfusion might be explained by a reduced perfusion pressure. Clinical evidence supporting the role of interstitial edema to worse kidney outcomes will be discussed later in this review.

Pulmonary consequences: Derangements in the capillary permeability, which occurs in SIRS, combined with an increased hydrostatic pressure, as induced by aggressive fluid resuscitation, results in major interstitial edema that can lead to important clinical consequences.

Fluid overload increases hydrostatic pressure, leading to fluid accumulation in the lungs. Studies in mice have shown that the leakage occurs in the bronchiole, and the backflow of fluids leads to alveolar edema[60]. There is a reabsorption of fluids in the interstitial space and, because the accumulated fluids are drained across the lymphatic vessels to the thoracic duct and superior vena cava, alterations in systemic venous pressure, which occurs during fluid overload, result in impaired lymphatic drainage and consequently pulmonary edema[61], leading to a gas exchange impairment.

The high hydrostatic pressure not only causes fluid leakage but also generates mechanical stress injury to capillary walls, leading to the impairment of the mechanisms of fluid reabsorption[62] and alveolo-capillary barrier damage[63,64]. This damage causes

ultrastructural changes in the capillary, altering permeability to proteins and activating the inflammatory response[65], which compromises gas exchange[66].

Hypoxemia resulting from impaired gas exchange leads to lung regional blood flow redistribution. As demonstrated by Ruff *et al*[67], fluid overload leads to an inversion of the pulmonary perfusion pattern, with decreased blood flow to the pulmonary dependent regions and increased blood flow to the non-dependent regions, most likely because of hypoxic vasoconstriction.

The clinical features of pulmonary edema are not restricted to oxygenation but are a result of decreased pulmonary ventilation as well. In 1922, Drinker had described a tidal volume reduction of 40%-70% in an induced pulmonary edema animal model[68], and a subsequent study has shown that a negative fluid balance strategy improved lung compliance and arterial oxygenation[69].

Considering Starling's equation in which pulmonary edema is a result of colloidosmotic and hydrostatic forces, one approach to this clinical problem is to lower filling pressures. Despite concerns regarding lowering cardiac output and oxygen delivery, current evidence shows that a conservative fluid strategy improves the oxygenation index and number of ventilation-free days without compromising hemodynamics or other organ functions[11,70].

Other organ consequences: Other organs might be affected by fluid overload in addition to the lungs and kidneys. Worse outcomes of the skin and the recovery of soft tissue wounds after surgery have been described, and the trial of Brandstrup *et al*[71] showed that a more conservative approach on fluids achieved better outcomes, particularly regarding surgical complications.

Gastrointestinal complications, such as ileum and anastomotic leakages, can also be increased because of interstitial edema associated with accumulated fluids during critical illness or major surgeries[72]. This might lead to delays in the administration of nutritional needs and worsen the possibility of achieving an adequate enteral nutrition intake.

The liver is also an encapsulated organ, and interstitial edema could lead to a sort of compartment syndrome. In shock states, in addition to hypoperfusion, a high central venous pressure is required for the development of ischemic hepatitis[73]. High venous pressures are usually secondary to a low cardiac output in patients with congestive heart failure, but it can also occur in fluid overloaded patients with SIRS who develop myocardial dysfunction.

From a broader perspective, abdominal compartment syndrome can be seen as another preventable complication of fluid overload. This syndrome would be an extreme situation regarding fluid overload states and can be either primary or secondary. In this case, fluid overload contributes to the development of abdominal compartment syndrome, leading to deleterious effects on many organ systems, including hemodynamic (as a result of reduced venous return), renal (as a result of increased renal venous pressure) and even respiratory system mechanics (by reducing the thoracic wall compliance)[74].

Other organ systems have more limited evidence associating fluid overload with worse outcomes. Although the brain could be considered an encapsulated organ, in general ICU patients whose blood-brain barrier is considered intact, fluid overload will most likely not lead to a significant cerebral edema that will develop into intracranial hypertension. However, it might be associated with an increased incidence of delirium[75], which is associated with worse outcomes.

Acid-base water effect: Despite the effect of electrolytes on acid-base status, water itself might influence the acid-base status. Some experimental evidence from *in vitro* studies suggests that the dilution of plasma with distilled water changes many electrolyte concentrations, but because the ensuing proportions are maintained regarding the SID, $PaCO_2$ and weak anions, there is no significant difference in the pH[76]. However, in a mathematical modeling approach validated thereafter with human plasma, Gattinoni *et al*[77] demonstrated that water itself, when in an open system, leads to acidosis, mainly because of the reaction of CO_2 with H_2O. The same group later described a possible rule that would regulate pH changes during crystalloid infusion, with interesting results. Mainly, the baseline $[HCO_3^-]$ values would dictate the pH response to a crystalloid solution whose (SID) would be the main determinant of the direction of the pH change[78]. As an example, giving a patient both 0.9% saline [(SID) = 0] or dextrose in water [(SID) = 0] can lead to worsened acidemia, depending on the patient's renal function and pulmonary function to counteract these effects. However, 0.9% saline comes with an added cost, which is that of electrolyte overload, as we have discussed.

Observational evidence correlating fluid overload with worse outcomes

Fluid overload or cumulative fluid balances have been associated with worse outcomes in many scenarios, including in patients with sepsis[79], cancer[80], and surgical patients[81], and during weaning from mechanical ventilation[82] and at discharge from the ICU[83].

A sub analysis of the VASST trial, which included patients with septic shock who were on vasopressors, reported that a positive fluid balance at both 12 h and 4 d after the onset of shock was associated with worse outcomes. Interestingly, the patients with CVP values below 8 mmHg at 12 h after septic shock onset had improved survival compared to patients with higher values of CVP[79], which are recommended by the surviving sepsis campaign during the first hours of resuscitation[84]. More provocative are the findings of Murphy *et al*[85], who studied a cohort of patients with septic shock who thereafter developed acute respiratory distress syndrome (ARDS), in which they hypothesized whether an adequate initial

fluid resuscitation strategy and a conservative late fluid management strategy were associated with improved survival[85]. In this cohort, the patients who achieved both adequate initial fluid resuscitation and conservative late fluid management had the lowest mortality. Interestingly, the patients who achieved a conservative late fluid management but not adequate initial fluid resuscitation had lower mortality rates than those who achieved adequate initial fluid resuscitation but not conservative late fluid management. This appears to provide a lesson regarding this population: trying to optimize hemodynamics later in the course of the disease is most likely deleterious, whereas achieving negative fluid balances, *i.e.*, actively de-resuscitating patients even if the initial resuscitation was not deemed adequate, appears to be successful, particularly for patients with ARDS[11]. In patients with ARDS, a large observational cohort also demonstrated that more positive fluid balances are associated with worse outcomes[86].

In patients being weaned from mechanical ventilation, data demonstrate that a 24-h negative fluid balance on the day of the spontaneous breathing trial and a cumulative negative fluid balance were associated with better weaning outcomes[82]. In another cohort of elderly patients, both negative fluid balances and decreasing values of central venous pressure were associated with better weaning outcomes[87]. A higher cumulative fluid balance, even after ICU discharge, was also associated with worse outcomes during hospitalization[83].

In patients with AKI, positive fluid balances have also been associated with worse outcomes. In a sub analysis of a European cohort of general ICU patients who developed AKI, a positive mean fluid balance was an independent risk factor for 60-d mortality[88]. In a sub analysis of the RENAL study, the authors investigated the effect of fluid balance on the outcomes of patients with many different statistical approaches, and they consistently found an association between negative mean daily fluid balances and improved clinical outcomes[89].

Many of these conditions in which fluid overload has been shown to be deleterious share a common feature: the presence of SIRS and the risk of multiple organ dysfunction syndrome, which can manifest clinically as shock along with AKI, ARDS and many other possible organ dysfunctions, septic or non-septic in origin[90]. What remains to be established is whether fluid overload is only a biomarker[91] that puts patients under an increased risk of death or an iatrogenic condition from critical care that should be considered in daily care and actively treated and avoided. This is a question to be answered with randomized controlled trials.

Randomized controlled trials correlating fluid overload with worse outcomes

Some randomized controlled trials in critically ill patients attempted to address whether a conservative fluid management approach would result in better outcomes for patients instead of a liberal approach, testing the hypothesis that fluid overload is not only a biomarker but is also a modifiable risk factor for worsening organ dysfunctions and death. In each trial, the fluid-restrictive protocols were different; however, the greatest objective in all of the studies was to withdraw fluids from the patients and/or to avoid giving unnecessary fluids.

In patients admitted to an intensive care unit who required a pulmonary artery catheter, Mitchell *et al*[70] compared an extravascular lung-water based strategy against a wedge pressure-based strategy for the treatment of 101 patients. Regardless of the protocol used, in the extravascular lung-water based strategy, the cumulative fluid balance was 142 ± 3632 mL compared to 2239 ± 3695 mL in the other group. The conservative strategy led to better outcomes in this group although mortality was unchanged.

In patients undergoing high-risk colorectal surgery, Brandstrup *et al*[71] also tested another conservative strategy for fluid management during the perioperative state and achieved a significantly lower fluid balance in these patients, yielding a lower rate of complications after surgery, many of which included surgical wound repair and cardiopulmonary complications.

In the landmark FACTT trial, which included two different protocols for the fluid management of patients with ARDS, patients in the conservative group achieved a negative fluid balance throughout the course of the disease, whereas patients in the liberal group progressively accumulated more fluids during their ICU stay. The primary outcome (mortality) was not different between the groups. However, the conservative group achieved a higher number of ventilator-free days and ICU-free days but had less vasopressor free-days, along with a slight trend towards a lower dialysis requirement through day 60 ($P = 0.06$)[11]. This trial demonstrated an interesting point: when using a conservative fluid management strategy, one will likely require vasopressors for a longer period but paradoxically at the benefit of being able to breathe without the ventilator sooner and being discharged from the ICU sooner. The cumulative fluid balance of both arms of the FACTT study is shown in Figure 3, as is the fluid balance of the ALVEOLI[92] and ARMA[93] studies about protective mechanical ventilation in ARDS patients.

Finally, during weaning from mechanical ventilation in a mixed ICU population, it has been demonstrated that a brain natriuretic peptide-driven strategy for fluid withdrawal resulted in more negative cumulative fluid balances [median, - 180 (-2556; 2832) *vs* - 2320 (-4735 to 738), $P < 0.001$], resulting in more ventilator-free days, although without impact on mortality[94].

These trials, although conducted in different clinical scenarios, share an interesting feature. In the population of patients at risk of developing new organ failures (such as patients during high-risk surgery) or with ongoing organ failures (such as patients with ARDS) or even
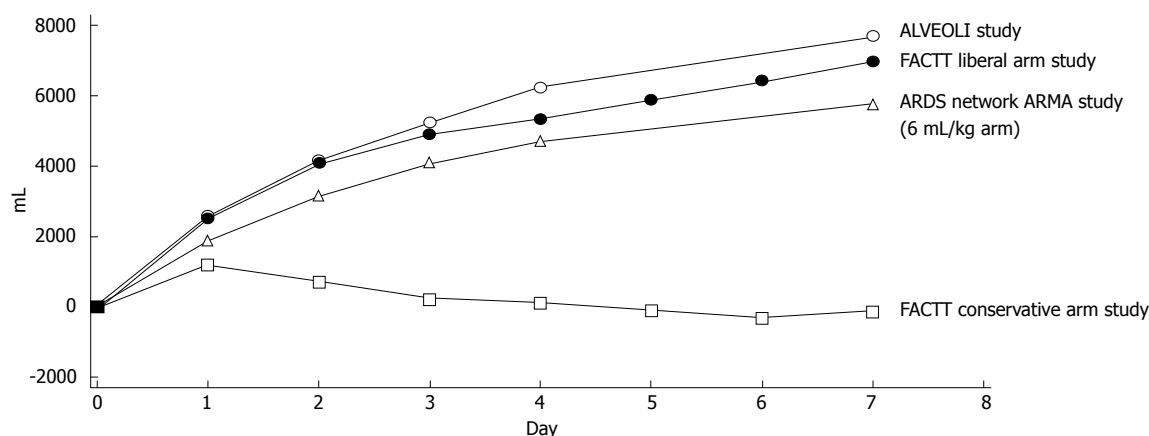
Figure 3 Cumulative fluid balances of the acute respiratory distress syndrome network group studies. The FACTT conservative fluid strategy arm returned to the neutral fluid balance within the first three days after randomization. The former strategy did not result in better survival, however patients were ventilated for less time and spent less time in the ICU in the conservative group. Adapted from Wiedemann *et al*[11]. ARDS: Acute respiratory distress syndrome; ICU: Intensive care unit.

during recovery of the critical illness, a conservative strategy led to better outcomes. Whether this can be extrapolated to all clinical scenarios remains to be answered.

The kidney paradox (oliguria worsened by fluid challenge)

Oliguria is usually considered a marker of decreased cardiac output, and a fluid challenge is often considered in an attempt to increase the cardiac preload and enhance cardiac output, which would ultimately enhance organ perfusion. However, after the optimization of hemodynamic parameters, some patients will still develop AKI and may have persistent oliguria on the ensuing days. Hence, after the first hours of resuscitation, oliguria should be interpreted as a marker of organ dysfunction but should not be seen as a marker of low cardiac output and does not necessarily indicate the need for volume expansion.

In this context of oliguria and a high risk of fluid overload, an added fluid challenge may worsen urine output and even renal function, as we have discussed previously in this review; most of the time, this will contribute to fluid and electrolyte overload. Clinically, Van Biesen *et al*[95] demonstrated in a cohort of septic patients with AKI that additional fluid therapy failed to improve renal function, and other studies have shown an association between a positive fluid balance and worse outcomes in patients with AKI[91], in addition to a decreased likelihood of renal recovery[88,96]. Another implication of increasing cumulative fluid balances in this context is the potential underestimation of the diagnosis or severity of AKI because of an increased creatinine distribution volume[97].

Therefore, this kidney paradox should be avoided in which clinicians attempt to enhance urinary output through repeated fluid challenges to avoid worsening kidney injury; these actions may in fact lead to more fluid accumulation and ultimately a worse outcome.

A BEDSIDE PATIENT-TAILORED APPROACH

To avoid potentially deleterious complications associated with fluid and electrolyte overload (Table 2), a patient-tailored approach is necessary to result in better outcomes for the individual patient. This will involve some aspects of fluid resuscitation, maintenance fluids, other sources of electrolytes and water and, ultimately, an active de-resuscitation strategy that may aim at the fluid balance and, if performed adequately will also remove the excessive loads of sodium and chloride. Here we describe how clinicians can address this situation at the bedside.

Judicious resuscitation

During the acute phase of resuscitation, fluids should be used judiciously to achieve an adequate perfusion. This encompasses four distinct aspects of fluid resuscitation: timing, type, amount and avoidance of the kidney paradox[98].

Resuscitation with fluids should be performed during the appropriate timing for this action, which occurs during the onset of the injury (intra-operative states) or soon after it (first hours after septic shock, major surgery or other acute physiological insults)[1]. There is no evidence that fluid resuscitation after these first moments will lead to better results. In fact, as we have discussed so far, the evidence points in the opposite direction.

In general, balanced solutions should be the fluids of choice in patients with shock states because they carry a lower chloride load, lead to less acid-base disturbances and most likely to better organ dysfunction outcomes, particularly for the kidneys, as shown in the study by Yunos *et al*[43].

The proper amount of fluid for acute care resuscitation is another critical component of judicious resuscitation. A recently published cohort of septic patients from

Table 2 Potential complications of fluids and electrolytes overload

Organ system	Complication	Main modifiable risk factor	Pathophysiological mechanism
Central nervous system	Delirium	Hypernatremia	Excessive sodium load Kidneys inability to excrete excess sodium load
Renal/ metabolic	Worse recovery of renal function	Cumulative fluid balance/higher CVP	Renal edema, reduced perfusion pressure
	Worsening acute kidney injury	Unbalanced solutions	Chloride-induced renal vasoconstriction
	Worsening acidemia	Unbalanced solutions	Solution SID relative to plasma SID Kidneys inability to excrete excess chloride load
Respiratory	Impaired gas exchange	Cumulative fluid balance/higher	Lung edema
	Altered pulmonar and chest wall mechanics	CVP/higher EVLW	
	Increased work of breathing		
Gastrointestinal	Ileum	Cumulative fluid balance	Bowel edema
	Hepatic congestion	Higher CVP	Hepatic congestion
	Increased intra-abdominal pressure (may induce by itself more organ dysfunctions)	Cumulative fluid balance	Visceral edema (bowel, renal, *etc.*), ascites
Hemostasis	Increased bleeding	Unbalanced solutions	Acidemia secondary to chloride load
Wound healing	Impaired wound healing	Cumulative fluid balance	Local edema
Hemodynamics	Worse microcirculatory blood flow	Higher CVP	Reduced perfusion pressure

CVP: Central venous pressure; SID: Strong ion difference; EVLW: Extravascular lung water.

Australia and New Zealand, which yielded impressive mortality outcomes, demonstrated that patients received approximately 3 L of fluids during the first hours of resuscitation[99]. Furthermore, in the recently published PROCESS trial, in patients who received more fluids (approximately 1 L more) in one of the three study arms, there were more cases of new onset renal failure than the usual care group[7]. With this in mind, particularly in cases of septic shock, after an initial fluid challenge of 20-30 mL/kg, we favor an earlier use of vasopressors and the avoidance of repeated fluid expansion in patients with vasodilatatory states, particularly in those with adequate perfusion parameters who are no longer fluid-responsive[100].

Another issue to be considered is to avoid the "kidney paradox". In oliguric patients, one should strongly consider avoiding repeated volume expansions after the first hours of resuscitation because this will most likely lead to higher filling pressures and more fluid accumulation despite a possibly increased urine output. In patients who further develop anuria, fluid challenges might be even more deleterious.

Acid-base monitoring during resuscitation
During the resuscitation phase of critical illness, in addition to usual hemodynamic monitoring, it is important to monitor potentially deleterious effects of fluids and electrolytes on the acid-base status. As previously discussed, both fluid composition and quantity can influence acid-base status[98]. Through acid-base monitoring, one can identify at an earlier stage metabolic complications occurring during resuscitation. If possible, one should attempt to quantify which component of metabolic acidosis is worse during acute resuscitation because they carry different prognostic significances[16].

Active de-resuscitation
After a judicious resuscitation strategy, active de-resuscitation should be considered to avoid the deleterious effects of continuous fluid accumulation when the patient does not passively excrete the excess amount of water and electrolytes. This can be achieved both with diuretics, which have been shown to be safe in the context of AKI, or with an earlier indication of hemodialysis, as defended by some authors, when the former cannot control fluid overload[101]. To achieve a safe withdrawal of fluids and electrolytes, some factors must be considered:

Fluid removal rate: either with dialysis or diuretics, the fluid removal rate should be titrated to the patient hemodynamic status to avoid underfilling during this phase[102]. If tolerated, there will likely be no deleterious effects of fluid withdrawal, even in the presence of vasopressors or inotropic drugs.

Intermittent *vs* continuous infusion of diuretics: in critically ill patients, the continuous infusion of diuretics was not extensively studied. Better evidence from other clinical situations has not demonstrated any consistent advantage of one way of administering diuretics over another, except for higher doses of diuretics in intermittent therapy for the same fluid balance achievement compared to continuous infusion diuretic therapy[103,104]. As long as a target diuresis is achieved, there will likely be no differences among these treatments.

Association of albumin to furosemide: although albumin was not associated with better outcomes in patients with septic shock[105] or for fluid resuscitation in general ICU patients[106], in patients with ARDS, a better hemodynamic tolerance during fluid withdrawal was achieved with the combination of albumin and furosemide[107] and could be a useful adjunct during the active de-resuscitation phase.

Monitoring and treating metabolic complications: the use of diuretics is associated with more metabolic disturbances, including hypernatremia, hypokalemia and metabolic alkalosis[11]. To counteract these disturbances,

we favor the use of acetazolamide if the patient develops metabolic alkalosis, thiazide diuretics and increases in free water reposition if hypernatremia ensues and the aggressive reposition of electrolytes to avoid extreme electrolyte disturbances. We refer the reader to the trial by Mekontso Dessap *et al*[94], which proposed a method to do this safely with a combination of diuretics.

Consideration for an earlier indication of renal replacement therapy in oliguria should be part of an active de-resuscitation strategy because some patients will develop stage Ⅲ AKI[108], will be unresponsive to diuretics and, during this process, will accumulate fluids progressively, which has been consistently shown to be associated with worse outcomes in this specific population[88,89,96].

Although pulmonary edema is a common trigger for fluid withdrawal, it is a late and potentially deadly consequence of fluid overload. Hence, during this phase of active fluid withdrawal, some very simple monitoring strategies can be used.

Central venous pressure, although recently receiving discredit as a guide to fluid loading[109], was used in the largest randomized controlled trial on conservative fluid strategies[11]. In this regard, although there are many physiological states that can influence its isolated value, higher CVP values have been associated with worse outcomes in many conditions, including septic shock[79], likely not only because of fluid overload but also because of the associated significant effect of heart dysfunction on its values. Therefore, it can be an adjunct for active de-resuscitation strategies, and a goal towards lower CVP values (*e.g.*, down to < 4 mmHg in adequately perfused patients without vasopressors) is a simple way to monitor this strategy.

An even simpler solution is to focus on fluid balance. Although daily weights would potentially be better, these values are also prone to error when measuring patients on ICU beds[110], and we believe that fluid balance, although imperfect, appears to be a simple bedside target of active de-resuscitation. Therefore, reaching even to negative fluid balances during the first days of critical illness onset and, as soon as possible, aiming at more negative fluid balances until reaching a cumulative fluid balance of approximately zero during the ICU stay appears to be a good approach.

In addition to active fluid withdrawal, one should avoid the unnecessary entrance of fluids and electrolytes in the form of electrolyte reposition, drugs dilution and as caloric intake on a daily basis because as we have previously discussed, these are important sources of sodium, chloride and water. In this regard, we favor using hypertonic glucose solutions if deemed necessary for minimum caloric intake (when the enteral route is not available for feeding) and the avoidance of maintenance fluids when there are no clinically relevant fluid losses (*e.g.*, ileostomy). Finally, electrolytes, antimicrobials and other drugs should be diluted in the minimum necessary amount of fluids and preferentially in 5% dextrose in water[20].

With all this evidence combined, it appears that a judicious initial fluid resuscitation followed by a conservative fluid management approach will lead to better outcomes in patients in many different shock states, including in patients with sepsis and patients with other causes of non-septic SIRS. As we have discussed, hypernatremia is associated with worse outcomes, along with hyperchloremic acidosis in some scenarios and also progressive cumulative fluid balances. Many of the studies in this regard examined these issues separately, whereas these may be different aspects of the same problem: that of fluid and electrolyte overload.

CONCLUSION

Although there are no adequate prospective experimentally designed studies that have shown that fluids are essential in the treatment of critically ill patients, fluids are used liberally among ICU patients, and fluid accumulation is very common throughout the course of a patient's ICU stay. In this review, we provided evidence of the potentially deleterious effects of fluids and electrolytes on many organ systems, how to monitor for these complications and how to manage this increasingly recognized clinical problem. Currently, we favor a more conservative approach regarding fluid management strategies in general ICU patients, although a randomized controlled trial addressing this issue is mandatory to shed light on this discussion, along with deeper mechanistic studies to understand the relative contributions of each component of fluid therapy.

REFERENCES

1   **Rivers E**, Nguyen B, Havstad S, Ressler J, Muzzin A, Knoblich B, Peterson E, Tomlanovich M. Early goal-directed therapy in the treatment of severe sepsis and septic shock. *N Engl J Med* 2001; **345**: 1368-1377 [PMID: 11794169 DOI: 10.1056/NEJMoa010307]

2   **Eisenberg RL**, Bank WO, Hedgock MW. Renal failure after major angiography can be avoided with hydration. *AJR Am J Roentgenol* 1981; **136**: 859-861 [PMID: 6784516 DOI: 10.2214/ajr.136.5.859]

3   **Gunal AI**, Celiker H, Dogukan A, Ozalp G, Kirciman E, Simsekli H, Gunay I, Demircin M, Belhan O, Yildirim MA, Sever MS. Early and vigorous fluid resuscitation prevents acute renal failure in the crush victims of catastrophic earthquakes. *J Am Soc Nephrol* 2004; **15**: 1862-1867 [PMID: 15213274 DOI: 10.1097/01. ASN.0000129336.09976.73]

4   **Davidson MB**, Thakkar S, Hix JK, Bhandarkar ND, Wong A, Schreiber MJ. Pathophysiology, clinical consequences, and treatment of tumor lysis syndrome. *Am J Med* 2004; **116**: 546-554 [PMID: 15063817 DOI: 10.1016/j.amjmed.2003.09.045]

5   **van den Berghe G**, Wouters P, Weekers F, Verwaest C, Bruyninckx F, Schetz M, Vlasselaers D, Ferdinande P, Lauwers P, Bouillon R. Intensive insulin therapy in critically ill patients. *N Engl J Med* 2001; **345**: 1359-1367 [PMID: 11794168 DOI: 10.1056/ NEJMoa011300]

6   **Nemec K**, Kopelent-Frank H, Greif R. Standardization of infusion solutions to reduce the risk of incompatibility. *Am J Health Syst Pharm* 2008; **65**: 1648-1654 [PMID: 18714112 DOI: 10.2146/ ajhp070471]

7   **Yealy DM**, Kellum JA, Huang DT, Barnato AE, Weissfeld LA, Pike F, Terndrup T, Wang HE, Hou PC, LoVecchio F, Filbin MR, Shapiro NI, Angus DC. A randomized trial of protocol-based care

for early septic shock. *N Engl J Med* 2014; **370**: 1683-1693 [PMID: 24635773 DOI: 10.1056/NEJMoa1401602]

8   **Maciel AT**, Park M, Macedo E. Physicochemical analysis of blood and urine in the course of acute kidney injury in critically ill patients: a prospective, observational study. *BMC Anesthesiol* 2013; **13**: 31 [PMID: 24112801 DOI: 10.1186/1471-2253-13-31]

9   **Maciel AT**, Park M. Urine assessment in the critically ill: a matter of both quantity and quality. *Rev Bras Ter Intensiva* 2013; **25**: 184-185 [PMID: 24213079 DOI: 10.5935/0103-507X.20130032]

10   **Maciel AT,** Park M, Macedo E. Urinary electrolyte monitoring in critically ill patients: a preliminary observational study. *Rev Bras Ter Intensiva* 2012; **24**: 236-245 [PMID: 23917824 DOI: 10.1590/S0103-507X2012000300006]

11   **National Heart, Lung, and Blood Institute Acute Respiratory Distress Syndrome (ARDS) Clinical Trials Network**; Wiedemann HP, Wheeler AP, Bernard GR,Thompson BT, Hayden D, deBoisblanc B, Connors AF Jr, Hite RD, Harabin AL. Comparison of two fluid-management strategies in acute lung injury. *N Engl J Med* 2006; **354**: 2564-2575 [PMID: 16714767 DOI: 10.1056/NEJMoa062200]

12   **Guyton AC,** Hall JE. The body fluid compartments: extracellular and intracellular fluids; interstitial fluid and edema. In: Guyton AC, Hall JE, editors. Textbook of Medical Physiology. 10th ed. Philadelphia, PA: Saunders, 2000: 250-264

13   **Nguyen MK**, Kurtz I. Quantitative interrelationship between Gibbs-Donnan equilibrium, osmolality of body fluid compartments, and plasma water sodium concentration. *J Appl Physiol* (1985) 2006; **100**: 1293-1300 [PMID: 16357067 DOI: 10.1152/japplphysiol.01274.2005]

14   **Lang F**, Busch GL, Ritter M, Völkl H, Waldegger S, Gulbins E, Häussinger D. Functional significance of cell volume regulatory mechanisms. *Physiol Rev* 1998; **78**: 247-306 [PMID: 9457175]

15   **Guidet B**, Soni N, Della Rocca G, Kozek S, Vallet B, Annane D, James M. A balanced view of balanced solutions. *Crit Care* 2010; **14**: 325 [PMID: 21067552 DOI: 10.1186/cc9230]

16   **Noritomi DT**, Soriano FG, Kellum JA, Cappi SB, Biselli PJ, Libório AB, Park M. Metabolic acidosis in patients with severe sepsis and septic shock: a longitudinal quantitative study. *Crit Care Med* 2009; **37**: 2733-2739 [PMID: 19885998 DOI: 10.1097/CCM.0b013e3181a59165]

17   **Adrogué HJ**, Madias NE. Aiding fluid prescription for the dysnatremias. *Intensive Care Med* 1997; **23**: 309-316 [PMID: 9083234 DOI: 10.1007/s001340050333]

18   **Stelfox HT**, Ahmed SB, Khandwala F, Zygun D, Shahpori R, Laupland K. The epidemiology of intensive care unit-acquired hyponatraemia and hypernatraemia in medical-surgical intensive care units. *Crit Care* 2008; **12**: R162 [PMID: 19094227 DOI: 10.1186/cc7162]

19   **Van De Louw A**, Shaffer C, Schaefer E. Early intensive care unit-acquired hypernatremia in severe sepsis patients receiving 0.9% saline fluid resuscitation. *Acta Anaesthesiol Scand* 2014; **58**: 1007-1014 [PMID: 25039806 DOI: 10.1111/aas.12368]

20   **Choo WP**, Groeneveld AB, Driessen RH, Swart EL. Normal saline to dilute parenteral drugs and to keep catheters open is a major and preventable source of hypernatremia acquired in the intensive care unit. *J Crit Care* 2014; **29**: 390-394 [PMID: 24603000 DOI: 10.1016/j.jcrc.2014.01.025]

21   **Bihari S**, Peake SL, Seppelt I, Williams P, Bersten A; George Institute for Global Health; Australian and New Zealand Intensive Care Society Clinical Trials Group. Sodium administration in critically ill patients in Australia and New Zealand: a multicentre point prevalence study. *Crit Care Resusc* 2013; **15**: 294-300 [PMID: 24289511]

22   **Arampatzis S**, Frauchiger B, Fiedler GM, Leichtle AB, Buhl D, Schwarz C, Funk GC, Zimmermann H, Exadaktylos AK, Lindner G. Characteristics, symptoms, and outcome of severe dysnatremias present on hospital admission. *Am J Med* 2012; **125**: 1125.e1-1125.e7 [PMID: 22939097 DOI: 10.1016/j.amjmed.2012.04.041]

23   **Funk GC**, Lindner G, Druml W, Metnitz B, Schwarz C, Bauer P, Metnitz PG. Incidence and prognosis of dysnatremias present on

ICU admission. *Intensive Care Med* 2010; **36**: 304-311 [PMID: 19847398 DOI: 10.1007/s00134-009-1692-0]

24   **Lindner G**, Funk GC, Schwarz C, Kneidinger N, Kaider A, Schneeweiss B, Kramer L, Druml W. Hypernatremia in the critically ill is an independent risk factor for mortality. *Am J Kidney Dis* 2007; **50**: 952-957 [PMID: 18037096 DOI: 10.1053/j.ajkd.2007.08.016]

25   **Vandergheynst F**, Sakr Y, Felleiter P, Hering R, Groeneveld J, Vanhems P, Taccone FS, Vincent JL. Incidence and prognosis of dysnatraemia in critically ill patients: analysis of a large prevalence study. *Eur J Clin Invest* 2013; **43**: 933-948 [PMID: 23869476 DOI: 10.1111/eci.12123]

26   **Lindner G**, Funk GC. Hypernatremia in critically ill patients. *J Crit Care* 2013; **28**: 216.e11-216.e20 [PMID: 22762930 DOI: 10.1016/j.jcrc.2012.05.001]

27   **Lindner G**. "Hypernatremia in the intensive care unit--an iatrogenic complication?". *J Crit Care* 2013; **28**: 214-215 [PMID: 23337488 DOI: 10.1016/j.jcrc.2012.11.017]

28   **Darmon M**, Pichon M, Schwebel C, Ruckly S, Adrie C, Haouache H, Azoulay E, Bouadma L, Clec'h C, Garrouste-Orgeas M, Souweine B, Goldgran-Toledano D, Khallel H, Argaud L, Dumenil AS, Jamali S, Allaouchiche B, Zeni F, Timsit JF. Influence of early dysnatremia correction on survival of critically ill patients. *Shock* 2014; **41**: 394-399 [PMID: 24667611 DOI: 10.1097/SHK.0000000000000135]

29   **Berend K**, van Hulsteijn LH, Gans RO. Chloride: the queen of electrolytes? *Eur J Intern Med* 2012; **23**: 203-211 [PMID: 22385875 DOI: 10.1016/j.ejim.2011.11.013]

30   **Park M,** Calabrich A, Maciel A, Zampieri F, Taniguchi L, Souza C, Barboza C, Nassar Junior AP, Azevedo L. Physicochemical characterization of metabolic acidosis induced by normal saline resuscitation of patients with severe sepsis and septic shock. *Rev Bras Ter intensiva* 2011; **23**: 176-182 [DOI: 10.1590/S0103-507X2011000200010]

31   **Kellum JA**, Bellomo R, Kramer DJ, Pinsky MR. Etiology of metabolic acidosis during saline resuscitation in endotoxemia. *Shock* 1998; **9**: 364-368 [PMID: 9617887 DOI: 10.1097/00024382-199805000-00009]

32   **Maciel AT**, Park M. Differences in acid-base behavior between intensive care unit survivors and nonsurvivors using both a physicochemical and a standard base excess approach: a prospective, observational study. *J Crit Care* 2009; **24**: 477-483 [PMID: 19327958 DOI: 10.1016/j.jcrc.2009.01.005]

33   **Boniatti MM**, Cardoso PR, Castilho RK, Vieira SR. Is hyperchloremia associated with mortality in critically ill patients? A prospective cohort study. *J Crit Care* 2011; **26**: 175-179 [PMID: 20619601 DOI: 10.1016/j.jcrc.2010.04.013]

34   **Wilcox CS**. Regulation of renal blood flow by plasma chloride. *J Clin Invest* 1983; **71**: 726-735 [PMID: 6826732 DOI: 10.1172/JCR110820]

35   **Imig JD**, Passmore JC, Anderson GL, Jimenez AE. Chloride alters renal blood flow autoregulation in deoxycorticosterone-treated rats. *J Lab Clin Med* 1993; **121**: 608-613 [PMID: 8454943]

36   **Zhou F**, Peng ZY, Bishop JV, Cove ME, Singbartl K, Kellum JA. Effects of fluid resuscitation with 0.9% saline versus a balanced electrolyte solution on acute kidney injury in a rat model of sepsis*. *Crit Care Med* 2014; **42**: e270-e278 [PMID: 24335444 DOI: 10.1097/CCM.0000000000000145]

37   **Jensen BL**, Ellekvist P, Skøtt O. Chloride is essential for contraction of afferent arterioles after agonists and potassium. *Am J Physiol* 1997; **272**: F389-F396 [PMID: 9087683]

38   **Hansen PB**, Jensen BL, Skott O. Chloride regulates afferent arteriolar contraction in response to depolarization. *Hypertension* 1998; **32**: 1066-1070 [PMID: 9856975 DOI: 10.1161/01.HYP.32.6.1066]

39   **Chowdhury AH**, Cox EF, Francis ST, Lobo DN. A randomized, controlled, double-blind crossover study on the effects of 2-L infusions of 0.9% saline and plasma-lyte® 148 on renal blood flow velocity and renal cortical tissue perfusion in healthy volunteers. *Ann Surg* 2012; **256**: 18-24 [PMID: 22580944 DOI: 10.1097/SLA.0b013e318256be72]

40   **Reid F**, Lobo DN, Williams RN, Rowlands BJ, Allison SP.

(Ab)normal saline and physiological Hartmann's solution: a randomized double-blind crossover study. *Clin Sci* (Lond) 2003; **104**: 17-24 [PMID: 12519083 DOI: 10.1042/CS20020202]

41 **Bell PD**, Lapointe JY, Cardinal J. Direct measurement of basolateral membrane potentials from cells of the macula densa. *Am J Physiol* 1989; **257**: F463-F468 [PMID: 2782426]

42 **Ren Y**, Garvin JL, Liu R, Carretero OA. Role of macula densa adenosine triphosphate (ATP) in tubuloglomerular feedback. *Kidney Int* 2004; **66**: 1479-1485 [PMID: 15458441 DOI: 10.1111/j.1523-1755.2004.00911.x]

43 **Yunos NM**, Bellomo R, Hegarty C, Story D, Ho L, Bailey M. Association between a chloride-liberal vs chloride-restrictive intravenous fluid administration strategy and kidney injury in critically ill adults. *JAMA* 2012; **308**: 1566-1572 [PMID: 23073953 DOI: 10.1001/jama.2012.13356]

44 **Waters JH**, Gottlieb A, Schoenwald P, Popovich MJ, Sprung J, Nelson DR. Normal saline versus lactated Ringer's solution for intraoperative fluid management in patients undergoing abdominal aortic aneurysm repair: an outcome study. *Anesth Analg* 2001; **93**: 817-822 [PMID: 11574339 DOI: 10.1097/00000539-200110000-00004]

45 **Wilkes NJ**, Woolf R, Mutch M, Mallett SV, Peachey T, Stephens R, Mythen MG. The effects of balanced versus saline-based hetastarch and crystalloid solutions on acid-base and electrolyte status and gastric mucosal perfusion in elderly surgical patients. *Anesth Analg* 2001; **93**: 811-816 [PMID: 11574338 DOI: 10.1097/00000539-200110000-00003]

46 **Lindner G**, Schwarz C, Grüssing H, Kneidinger N, Fazekas A, Funk GC. Rising serum sodium levels are associated with a concurrent development of metabolic alkalosis in critically ill patients. *Intensive Care Med* 2013; **39**: 399-405 [PMID: 23160772 DOI: 10.1007/s00134-012-2753-3]

47 **Hofmann-Kiefer KF**, Chappell D, Jacob M, Schülke A, Conzen P, Rehm M. [Hypernatremic alkalosis. Possible counterpart of hypercloremic acidosis in intensive care patients?]. *Anaesthesist* 2009; **58**: 1210-1215 [PMID: 19911108 DOI: 10.1007/s00101-009-1640-y]

48 **Kellum JA**, Song M, Almasri E. Hyperchloremic acidosis increases circulating inflammatory molecules in experimental sepsis. *Chest* 2006; **130**: 962-967 [PMID: 17035425 DOI: 10.1378/chest.130.4.962]

49 **Kellum JA**, Song M, Li J. Lactic and hydrochloric acids induce different patterns of inflammatory response in LPS-stimulated RAW 264.7 cells. *Am J Physiol Regul Integr Comp Physiol* 2004; **286**: R686-R692 [PMID: 14695114 DOI: 10.1152/ajpregu.00564.2003]

50 **Bellocq A**, Suberville S, Philippe C, Bertrand F, Perez J, Fouqueray B, Cherqui G, Baud L. Low environmental pH is responsible for the induction of nitric-oxide synthase in macrophages. Evidence for involvement of nuclear factor-kappaB activation. *J Biol Chem* 1998; **273**: 5086-5092 [PMID: 9478960 DOI: 10.1074/jbc.273.9.5086]

51 **Heming TA**, Davé SK, Tuazon DM, Chopra AK, Peterson JW, Bidani A. Effects of extracellular pH on tumour necrosis factor-alpha production by resident alveolar macrophages. *Clin Sci* (Lond) 2001; **101**: 267-274 [PMID: 11524044 DOI: 10.1042/CS20010139]

52 **Kellum JA**, Song M, Venkataraman R. Effects of hyperchloremic acidosis on arterial pressure and circulating inflammatory molecules in experimental sepsis. *Chest* 2004; **125**: 243-248 [PMID: 14718447 DOI: 10.1378/chest.125.1.243]

53 **Kellum JA**. Fluid resuscitation and hyperchloremic acidosis in experimental sepsis: improved short-term survival and acid-base balance with Hextend compared with saline. *Crit Care Med* 2002; **30**: 300-305 [PMID: 11889298 DOI: 10.1097/00003246-200202000-00006]

54 **Stone HH**, Fulenwider JT. Renal decapsulation in the prevention of post-ischemic oliguria. *Ann Surg* 1977; **186**: 343-355 [PMID: 407854 DOI: 10.1097/00000658-197709000-00012]

55 **Bock JS**, Gottlieb SS. Cardiorenal syndrome: new perspectives. *Circulation* 2010; **121**: 2592-2600 [PMID: 20547939 DOI: 10.1161/CIRCULATIONAHA.109.886473]

56 **Damman K**, van Deursen VM, Navis G, Voors AA, van Veldhuisen DJ, Hillege HL. Increased central venous pressure is associated

with impaired renal function and mortality in a broad spectrum of patients with cardiovascular disease. *J Am Coll Cardiol* 2009; **53**: 582-588 [PMID: 19215832 DOI: 10.1016/j.jacc.2008.08.080]

57 **Legrand M**, Dupuis C, Simon C, Gayat E, Mateo J, Lukaszewicz AC, Payen D. Association between systemic hemodynamics and septic acute kidney injury in critically ill patients: a retrospective observational study. *Crit Care* 2013; **17**: R278 [PMID: 24289206 DOI: 10.1186/cc13133]

58 **Burnett JC**, Knox FG. Renal interstitial pressure and sodium excretion during renal vein constriction. *Am J Physiol* 1980; **238**: F279-F282 [PMID: 7377299]

59 **Cruces P**, Salas C, Lillo P, Salomon T, Lillo F, Hurtado DE. The renal compartment: a hydraulic view. *Intensive Care Medicine Experimental* 2014; **2**: 26 [DOI: 10.1186/s40635-014-0026-x]

60 **Yoneda K**. Anatomic pathway of fluid leakage in fluid-overload pulmonary edema in mice. *Am J Pathol* 1980; **101**: 7-16 [PMID: 7446703]

61 **Laine GA**, Allen SJ, Katz J, Gabel JC, Drake RE. Effect of systemic venous pressure elevation on lymph flow and lung edema formation. *J Appl Physiol* (1985) 1986; **61**: 1634-1638 [PMID: 3781976]

62 **West JB**, Mathieu-Costello O. Vulnerability of pulmonary capillaries in heart disease. *Circulation* 1995; **92**: 622-631 [PMID: 7634477 DOI: 10.1161/01.CIR.92.3.622]

63 **West JB**. Invited review: pulmonary capillary stress failure. *J Appl Physiol* (1985) 2000; **89**: 2483-2489; discussion 2497 [PMID: 11090605]

64 **Tsukimoto K**, Mathieu-Costello O, Prediletto R, Elliott AR, West JB. Ultrastructural appearances of pulmonary capillaries at high transmural pressures. *J Appl Physiol* (1985) 1991; **71**: 573-582 [PMID: 1718936]

65 **De Pasquale CG**, Arnolda LF, Doyle IR, Grant RL, Aylward PE, Bersten AD. Prolonged alveolocapillary barrier damage after acute cardiogenic pulmonary edema. *Crit Care Med* 2003; **31**: 1060-1067 [PMID: 12682473 DOI: 10.1097/01.CCM.0000059649.31659.22]

66 **Guazzi M**. Alveolar-capillary membrane dysfunction in heart failure: evidence of a pathophysiologic role. *Chest* 2003; **124**: 1090-1102 [PMID: 12970042 DOI: 10.1378/chest.124.3.1090]

67 **Ruff F**, Caubarrere I, Salem A, Dubois F, Duroux P. [Regional distribution of pulmonary perfusion during fluid overload in man]. *Ann Anesthesiol Fr* 1975; **16** Spec No 2-3: 164-168 [PMID: 9861]

68 **Drinker CK**, Peabody FW, Blumgart HL. The effect of pulmonary congestion on the on the ventilation of the lungs. *J Exp Med* 1922; **35**: 77-95 [PMID: 19868589 DOI: 10.1084/jem.35.1.77]

69 **Bone RC**. Treatment of adult respiratory distress syndrome with diuretics, dialysis, and positive end-expiratory pressure. *Crit Care Med* 1978; **6**: 136-139 [PMID: 350486 DOI: 10.1097/00003246-197805000-00002]

70 **Mitchell JP**, Schuller D, Calandrino FS, Schuster DP. Improved outcome based on fluid management in critically ill patients requiring pulmonary artery catheterization. *Am Rev Respir Dis* 1992; **145**: 990-998 [PMID: 1586077 DOI: 10.1164/ajrccm/145.5.990]

71 **Brandstrup B**, Tønnesen H, Beier-Holgersen R, Hjortsø E, Ørding H, Lindorff-Larsen K, Rasmussen MS, Lanng C, Wallin L, Iversen LH, Gramkow CS, Okholm M, Blemmer T, Svendsen PE, Rottensten HH, Thage B, Riis J, Jeppesen IS, Teilum D, Christensen AM, Graungaard B, Pott F. Effects of intravenous fluid restriction on postoperative complications: comparison of two perioperative fluid regimens: a randomized assessor-blinded multicenter trial. *Ann Surg* 2003; **238**: 641-648 [PMID: 14578723 DOI: 10.1097/01.sla.0000094387.50865.23]

72 **Macafee DA**, Allison SP, Lobo DN. Some interactions between gastrointestinal function and fluid and electrolyte homeostasis. *Curr Opin Clin Nutr Metab Care* 2005; **8**: 197-203 [PMID: 15716800 DOI: 10.1097/00075197-200503000-00015]

73 **Seeto RK**, Fenn B, Rockey DC. Ischemic hepatitis: clinical presentation and pathogenesis. *Am J Med* 2000; **109**: 109-113 [PMID: 10967151 DOI: 10.1016/S0002-9343(00)00461-7]

74 **Kirkpatrick AW**, Roberts DJ, De Waele J, Jaeschke R, Malbrain ML, De Keulenaer B, Duchesne J, Bjorck M, Leppaniemi A, Ejike JC, Sugrue M, Cheatham M, Ivatury R, Ball CG, Reintam Blaser A,

Regli A, Balogh ZJ, D'Amours S, Debergh D, Kaplan M, Kimball E, Olvera C. Intra-abdominal hypertension and the abdominal compartment syndrome: updated consensus definitions and clinical practice guidelines from the World Society of the Abdominal Compartment Syndrome. *Intensive Care Med* 2013; **39**: 1190-1206 [PMID: 23673399 DOI: 10.1007/s00134-013-2906-z]

75   **Prowle JR**, Echeverri JE, Ligabo EV, Ronco C, Bellomo R. Fluid balance and acute kidney injury. *Nat Rev Nephrol* 2010; **6**: 107-115 [PMID: 20027192 DOI: 10.1038/nrneph.2009.213]

76   **Haskins SC**, Hopper K, Rezende ML. The acid-base impact of free water removal from, and addition to, plasma. *J Lab Clin Med* 2006; **147**: 114-120 [PMID: 16503240 DOI: 10.1016/j.lab.2005.04.011]

77   **Gattinoni L**, Carlesso E, Maiocchi G, Polli F, Cadringher P. Dilutional acidosis: where do the protons come from? *Intensive Care Med* 2009; **35**: 2033-2043 [PMID: 19763537 DOI: 10.1007/s00134-009-1653-7]

78   **Carlesso E**, Maiocchi G, Tallarini F, Polli F, Valenza F, Cadringher P, Gattinoni L. The rule regulating pH changes during crystalloid infusion. *Intensive Care Med* 2011; **37**: 461-468 [PMID: 21152898 DOI: 10.1007/s00134-010-2095-y]

79   **Boyd JH**, Forbes J, Nakada TA, Walley KR, Russell JA. Fluid resuscitation in septic shock: a positive fluid balance and elevated central venous pressure are associated with increased mortality. *Crit Care Med* 2011; **39**: 259-265 [PMID: 20975548 DOI: 10.1097/CCM.0b013e3181feeb15]

80   **de Almeida JP**, Palomba H, Galas FR, Fukushima JT, Duarte FA, Nagaoka D, Torres V, Yu L, Vincent JL, Auler JO, Hajjar LA. Positive fluid balance is associated with reduced survival in critically ill patients with cancer. *Acta Anaesthesiol Scand* 2012; **56**: 712-717 [PMID: 22621427 DOI: 10.1111/j.1399-6576.2012.02717.x]

81   **Walsh SR**, Walsh CJ. Intravenous fluid-associated morbidity in postoperative patients. *Ann R Coll Surg Engl* 2005; **87**: 126-130 [PMID: 15826425 DOI: 10.1308/147870805X28127]

82   **Upadya A**, Tilluckdharry L, Muralidharan V, Amoateng-Adjepong Y, Manthous CA. Fluid balance and weaning outcomes. *Intensive Care Med* 2005; **31**: 1643-1647 [PMID: 16193330 DOI: 10.1007/s00134-005-2801-3]

83   **Lee J**, de Louw E, Niemi M, Nelson R, Mark RG, Celi LA, Mukamal KJ, Danziger J. Association between fluid balance and survival in critically ill patients. *J Intern Med* 2014; **277**: 468-477 [PMID: 24931482 DOI: 10.1111/joim.12274]

84   **Dellinger RP**, Levy MM, Rhodes A, Annane D, Gerlach H, Opal SM, Sevransky JE, Sprung CL, Douglas IS, Jaeschke R, Osborn TM, Nunnally ME, Townsend SR, Reinhart K, Kleinpell RM, Angus DC, Deutschman CS, Machado FR, Rubenfeld GD, Webb SA, Beale RJ, Vincent JL, Moreno R. Surviving sepsis campaign: international guidelines for management of severe sepsis and septic shock: 2012. *Crit Care Med* 2013; **41**: 580-637 [PMID: 23353941 DOI: 10.1097/CCM.0b013e31827e83af]

85   **Murphy CV**, Schramm GE, Doherty JA, Reichley RM, Gajic O, Afessa B, Micek ST, Kollef MH. The importance of fluid management in acute lung injury secondary to septic shock. *Chest* 2009; **136**: 102-109 [PMID: 19318675 DOI: 10.1378/chest.08-2706]

86   **Sakr Y**, Vincent JL, Reinhart K, Groeneveld J, Michalopoulos A, Sprung CL, Artigas A, Ranieri VM; Sepsis Occurence in Acutely Ill Patients Investigators. High tidal volume and positive fluid balance are associated with worse outcome in acute lung injury. *Chest* 2005; **128**: 3098-3108 [PMID: 16304249 DOI: 10.1378/chest.128.5.3098]

87   **Epstein CD**, Peerless JR. Weaning readiness and fluid balance in older critically ill surgical patients. *Am J Crit Care* 2006; **15**: 54-64 [PMID: 16391315]

88   **Payen D**, de Pont AC, Sakr Y, Spies C, Reinhart K, Vincent JL; Sepsis Occurrence in Acutely Ill Patients (SOAP) Investigators. A positive fluid balance is associated with a worse outcome in patients with acute renal failure. *Crit Care* 2008; **12**: R74 [PMID: 18533029 DOI: 10.1186/cc6916]

89   **RENAL Replacement Therapy Study Investigators;** Bellomo R, Cass A, Cole L, Finfer S, Gallagher M, Lee J, Lo S, McArthur C, McGuiness S, Norton R, Myburgh J, Scheinkestel C, Su S. An observational study fluid balance and patient outcomes in the Randomized Evaluation of Normal vs. Augmented Level of Replacement Therapy trial. *Crit Care Med* 2012; **40**: 1753-1760 [PMID: 22610181 DOI: 10.1097/CCM.0b013e318246b9c6]

90   **Dulhunty JM**, Lipman J, Finfer S; Sepsis Study Investigators for the ANZICS Clinical Trials Group. Does severe non-infectious SIRS differ from severe sepsis? Results from a multi-centre Australian and New Zealand intensive care unit study. *Intensive Care Med* 2008; **34**: 1654-1661 [PMID: 18504549 DOI: 10.1007/s00134-008-1160-2]

91   **Bagshaw SM**, Brophy PD, Cruz D, Ronco C. Fluid balance as a biomarker: impact of fluid overload on outcome in critically ill patients with acute kidney injury. *Crit Care* 2008; **12**: 169 [PMID: 18671831 DOI: 10.1186/cc6948]

92   **Brower RG**, Lanken PN, MacIntyre N, Matthay MA, Morris A, Ancukiewicz M, Schoenfeld D, Thompson BT. Higher versus lower positive end-expiratory pressures in patients with the acute respiratory distress syndrome. *N Engl J Med* 2004; **351**: 327-336 [PMID: 15269312 DOI: 10.1056/NEJMoa032193]

93   Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. The Acute Respiratory Distress Syndrome Network. *N Engl J Med* 2000; **342**: 1301-1308 [PMID: 10793162 DOI: 10.1056/NEJM200005043421801]

94   **Mekontso Dessap A**, Roche-Campo F, Kouatchet A, Tomicic V, Beduneau G, Sonneville R, Cabello B, Jaber S, Azoulay E, Castanares-Zapatero D, Devaquet J, Lellouche F, Katsahian S, Brochard L. Natriuretic peptide-driven fluid management during ventilator weaning: a randomized controlled trial. *Am J Respir Crit Care Med* 2012; **186**: 1256-1263 [PMID: 22997204 DOI: 10.1164/rccm.201205-0939OC]

95   **Van Biesen W**, Yegenaga I, Vanholder R, Verbeke F, Hoste E, Colardyn F, Lameire N. Relationship between fluid status and its management on acute renal failure (ARF) in intensive care unit (ICU) patients with sepsis: a prospective analysis. *J Nephrol* 2005; **18**: 54-60 [PMID: 15772923]

96   **Bouchard J**, Soroko SB, Chertow GM, Himmelfarb J, Ikizler TA, Paganini EP, Mehta RL; Program to Improve Care in Acute Renal Disease (PICARD) Study Group. Fluid accumulation, survival and recovery of kidney function in critically ill patients with acute kidney injury. *Kidney Int* 2009; **76**: 422-427 [PMID: 19436332 DOI: 10.1038/ki.2009.159]

97   **Macedo E**, Bouchard J, Soroko SH, Chertow GM, Himmelfarb J, Ikizler TA, Paganini EP, Mehta RL; Program to Improve Care in Acute Renal Disease Study. Fluid accumulation, recognition and staging of acute kidney injury in critically-ill patients. *Crit Care* 2010; **14**: R82 [PMID: 20459609 DOI: 10.1186/cc9004]

98   **McDermid RC**, Raghunathan K, Romanovsky A, Shaw AD, Bagshaw SM. Controversies in fluid therapy: Type, dose and toxicity. *World J Crit Care Med* 2014; **3**: 24-33 [PMID: 24834399 DOI: 10.5492/wjccm.v3.i1.24]

99   **Peake SL**, Bailey M, Bellomo R, Cameron PA, Cross A, Delaney A, Finfer S, Higgins A, Jones DA, Myburgh JA, Syres GA, Webb SA, Williams P. Australasian resuscitation of sepsis evaluation (ARISE): A multi-centre, prospective, inception cohort study. *Resuscitation* 2009; **80**: 811-818 [PMID: 19467755 DOI: 10.1016/j.resuscitation.2009.03.008]

100   **Marik PE**. Early management of severe sepsis: concepts and controversies. *Chest* 2014; **145**: 1407-1418 [PMID: 24889440 DOI: 10.1378/chest.13-2104]

101   **Uchino S**, Doig GS, Bellomo R, Morimatsu H, Morgera S, Schetz M, Tan I, Bouman C, Nacedo E, Gibney N, Tolwani A, Ronco C, Kellum JA; Beginning and Ending Supportive Therapy for the Kidney (B.E.S.T. Kidney) Investigators. Diuretics and mortality in acute renal failure. *Crit Care Med* 2004; **32**: 1669-1677 [PMID: 15286542 DOI: 10.1097/01.CCM.0000132892.51063.2F]

102   **Prowle JR**, Kirwan CJ, Bellomo R. Fluid management for the prevention and attenuation of acute kidney injury. *Nat Rev Nephrol* 2014; **10**: 37-47 [PMID: 24217464 DOI: 10.1038/nrneph.2013.232]

103   **Ostermann M**, Alvarez G, Sharpe MD, Martin CM. Frusemide administration in critically ill patients by continuous compared to

bolus therapy. *Nephron Clin Pract* 2007; **107**: c70-c76 [PMID: 17890871 DOI: 10.1159/000108641]

104 **Felker GM,** Lee KL, Bull DA, Redfield MM, Stevenson LW, Goldsmith SR, LeWinter MM, Deswal A, Rouleau JL, Ofili EO, Anstrom KJ, Hernandez AF, McNulty SE, Velazquez EJ, Kfoury AG, Chen HH, Givertz MM, Semigran MJ, Bart BA, Mascette AM, Braunwald E, O'Connor CM. Diuretic strategies in patients with acute decompensated heart failure. *N Engl J Med* 2011; **364**: 797-805 [PMID: 21366472 DOI: 10.1056/NEJMoa1005419]

105 **Caironi P**, Tognoni G, Masson S, Fumagalli R, Pesenti A, Romero M, Fanizza C, Caspani L, Faenza S, Grasselli G, Iapichino G, Antonelli M, Parrini V, Fiore G, Latini R, Gattinoni L. Albumin replacement in patients with severe sepsis or septic shock. *N Engl J Med* 2014; **370**: 1412-1421 [PMID: 24635772 DOI: 10.1056/NEJMoa1305727]

106 **Finfer S,** Bellomo R, Boyce N, French J, Myburgh J, Norton R; SAFE Study Investigators. A comparison of albumin and saline for fluid resuscitation in the intensive care unit. *N Engl J Med* 2004; **350**: 2247-2256 [PMID: 15163774 DOI: 10.1056/NEJMoa040232]

107 **Martin GS**, Moss M, Wheeler AP, Mealer M, Morris JA, Bernard GR. A randomized, controlled trial of furosemide with or without albumin in hypoproteinemic patients with acute lung injury. *Crit Care Med* 2005; **33**: 1681-1687 [PMID: 16096441 DOI: 10.1097/01.CCM.0000171539.47006.02]

108 **Mehta RL,** Kellum JA, Shah SV, Molitoris BA, Ronco C, Warnock DG, Levin A; Acute Kidney Injury Network. Acute Kidney Injury Network: report of an initiative to improve outcomes in acute kidney injury. *Crit Care* 2007; **11**: R31 [PMID: 17331245 DOI: 10.1186/cc5713]

109 **Marik PE**, Cavallazzi R. Does the central venous pressure predict fluid responsiveness? An updated meta-analysis and a plea for some common sense. *Crit Care Med* 2013; **41**: 1774-1781 [PMID: 23774337 DOI: 10.1097/CCM.0b013e31828a25fd]

110 **Schneider AG**, Baldwin I, Freitag E, Glassford N, Bellomo R. Estimation of fluid status changes in critically ill patients: fluid balance chart or electronic bed weight? *J Crit Care* 2012; **27**: 745. e7-745.12 [PMID: 22341728 DOI: 10.1016/j.jcrc.2011.12.017]

Baishideng®

Published by **Baishideng Publishing Group Inc**
8226 Regency Drive, Pleasanton, CA 94588, USA
Telephone: +1-925-223-8242
Fax: +1-925-223-8243
E-mail: bpgoffice@wjgnet.com
Help Desk: http://www.wjgnet.com/esps/helpdesk.aspx
http://www.wjgnet.com