REVIEW

Chloride in intensive care units: a key electrolyte [version 1; referees: 3 approved]

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Abstract
Over the past few years, chloride has joined the league of essential electrolytes for critically ill patients. Dyschloremia can occur secondary to various etiologic factors before and during patient admission in the intensive care unit. Some cases are disease-related; others, treatment-related. Chloride abnormalities were shown in animal models to have adverse effects on arterial blood pressure, renal blood flow, and inflammatory markers, which have led to several clinical investigations. Hyperchloremia was studied in several settings and correlated to different outcomes, including death and acute kidney injury. Baseline hypochloremia, to a much lesser extent, has been studied and associated with similar outcomes. The chloride content of resuscitation fluids was also a subject of clinical research. In this review, we describe the effect of dyschloremia on outcomes in critically ill patients. We review the major studies assessing the chloride content of resuscitation fluids in the critically ill patient.
Introduction
Chloride constitutes 70% of the negative ion content of the body. The principal dietary chloride intake is in the form of salt and thus nutritional deficiencies of chloride are rare. Chloride and sodium have a significant role in maintaining osmolarity, acid-base balance, and electro-neutrality of body fluids. The various mechanisms and hormones that regulate sodium and volume balance also regulate chloride concentration, including the renin-angiotensin-aldosterone system, sympathetic nervous system, atrial natriuretic peptide, and other factors affecting renal blood flow. The chloride ion distributes in all body fluid compartments and mainly in the extracellular fluid compartment of plasma and interstitial fluid. Its concentration in the intracellular fluid compartment is less than in extracellular fluid.

Chloride is frequently reported among other daily laboratory values obtained for critically ill patients. However, it attracts only minimal attention beyond its role in acid-base calculations. Interestingly, some reports indicate that dyschloremia may be associated with harmful effects. In animal models, hyperchloremic acidosis has been shown to have deleterious effects, such as an increase in inflammatory markers in animal models of sepsis and a reduction in mean arterial pressure in septic rats when pH and chloride levels have changed. In other animal experiments, high chloride concentration was associated with increased renal vasoconstriction and reductions in renal blood flow and glomerular filtration rate.

In recent years, these findings have led to growing interest in the interplay of chloride and its effect for the critically ill patient. Both hypochloremia and hyperchloremia have been associated with worse clinical outcomes, including death and acute kidney injury (AKI). The chloride concentration in resuscitation fluids in the intensive care unit (ICU) was determined to be a clinically relevant field of research. In this review, we outline the role of chloride in the critically ill patient and discuss the recent literature behind that role.

Dyschloremia in the ICU
Hypochloremia in the ICU can be due to pathophysiologic processes related to the illness or secondary to therapeutic interventions. The leading causes of hypochloremia are related to gastrointestinal or renal losses of chloride ions (Table 1). Renal losses of the chloride ion can occur in the clinical setting of diuretic use or, less commonly, in renal disorders such as Bartter syndrome. Gastrointestinal losses can occur through losses of chloride-rich fluids (for example, vomiting). Hypochloremia can also develop with excess water gains (for example, syndrome of inappropriate antidiuretic hormone secretion and congestive heart failure). The reported prevalence of hypochloremia has varied according to the clinical setting and patient population. The general ICU setting, different studies have reported an incidence between 6.7% and 37%. Among patients with heart failure, the reported incidence varied from 13% to 23%

Hyperchloremia, in contrast to hypochloremia, has been in the medical spotlight recently. The rates of occurrence of hyperchloremia in the ICU vary widely according to study population and time of measurement. Mechanisms leading to the development of hyperchloremia include the iatrogenic mechanism from excessive chloride administration during resuscitation with chloride-rich solutions. Excessive water loss, either net water loss or in excess of chloride loss, in addition to increased renal reabsorption of chloride, is another causative mechanism. (Table 2)

Associations of dyschloremia and outcomes in the ICU
Hypochloremia has gained minimal attention in the literature, and its related data are scarce. Tani and colleagues reported the association of hypochloremia with increased ICU length of stay and death in a mixed surgical and medical ICU setting. The authors, following multivariate analysis, stated that hypochloremia was not an independent predictor of mortality. Nonetheless, they showed a significant correlation between hypochloremia and higher Acute Physiology and Chronic Health Evaluation scores. In another report, Kimura and colleagues found that hypochloremia within

Table 1. Causes of hypochloremia.

| Mechanism                  | Loss location       | Example                                      |
|----------------------------|---------------------|----------------------------------------------|
| Chloride loss              | Gastrointestinal    | Vomiting                                    |
|                            |                     | Gastric fluid drainage                      |
|                            |                     | High-volume ileostomy drainage              |
| Renal                      |                     | Diuretic use                                 |
|                            |                     | Bartter syndrome                            |
|                            |                     | Gitelman syndrome                           |
| Excess water gain          | Congestive heart failure | Infusion of hypotonic solutions             |
| (compared with chloride)   | Syndrome of inappropriate antidiuretic hormone |                                         |
| Excess sodium gain         |                     | Infusion of sodium bicarbonate              |
| (compared with chloride)   |                     |                                             |
the first 48 hours postoperatively was independently associated with an increased mortality rate compared with patients who had normal chloride levels, even after adjustment for illness severity. Shao and colleagues looked into the relationship of dyschloremia—hypochloremia and hyperchloremia—and AKI, as well as other outcomes, in a large cohort of ICU patients. In this cohort, the incidence of hypochloremia before ICU admission was high and reported as 37%. They found that baseline hypochloremia (serum chloride of less than 94 mmol/L) was an independent risk factor for the development of AKI compared with normochloremia. They also noted longer ICU and hospital lengths of stay as well as increased mortality rate in the presence of hypochloremia. In another study, authors demonstrated an association between hypochloremia and longer use of non-invasive ventilation in patients with exacerbation of chronic obstructive pulmonary disease. Not only hypochloremia but the rate of increase in chloride level has been found to be associated with worse outcomes among hospitalized patients.

Many recent studies highlighted the potential effects of hyperchloremia on patient outcomes. The association between hyperchloremia and death in adult critically ill patients was first reported in 2011; Boniatti and colleagues noted that, in a prospective cohort of 175 patients, the addition of serum chloride to multiple logistic regression models improved the accuracy of the models to assess the risk of death. Various other reports have further highlighted the association between hyperchloremia with worse outcomes. Neyra and colleagues found that, among hyperchloremic patients with severe sepsis or septic shock, a higher chloride level at 72 hours after ICU admission was associated with a higher mortality rate. They also noted an increase in death (odds ratio of 1.37) with each 5 mEq/L increase in chloride level among those patients. Interestingly, they did not find a relationship between ICU admission chloride level and death. Likewise, in trauma patients, hyperchloremia 48 hours after ICU admission and a change in chloride levels were independent predictive factors of the 30-day mortality rate. Other reports found similar associations with minimal differences. After non-cardiac surgery, for patients with normal preoperative serum chloride level, death was associated with postoperative hyperchloremia; and in a mixed ICU population, higher mortality rates were associated with ICU admission hyperchloremia though not with patients undergoing elective cardiac surgery.

Of the earlier reports on AKI and hyperchloremia, Zhang and colleagues found an association between maximum chloride level and AKI incidence. However, chloride level on ICU admission was not associated with AKI development. They also found that mean chloride levels were higher among patients who had AKI. Shao and colleagues also found an association of hyperchloremia and AKI. Another study found an increase in AKI rate among septic patients with a moderate increase in serum chloride (a change of at least 5 mmol/L) even without hyperchloremia. However, not all studies revealed such a direct relationship. A study

### Table 2. Causes of hyperchloremia.

| Mechanism                                           | Loss location          | Example                                      |
|-----------------------------------------------------|------------------------|----------------------------------------------|
| Chloride administration                             | Chloride-rich intravenous fluids | Total parenteral nutrition                    |
| Water loss (true water loss or relative to chloride)| Renal                  | Diabetes insipidus                           |
|                                                     |                        | Diuretic use                                 |
|                                                     |                        | Osmotic diuresis                             |
|                                                     |                        | Postobstructive diuresis                     |
| Extrarenal                                          | Fever                  |                                               |
|                                                     |                        | Hypermetabolic state                         |
|                                                     |                        | Diarrhea                                     |
|                                                     |                        | Burns                                        |
|                                                     |                        | Exercise and severe dehydration              |
| Definitive or relative increase in tubular chloride reabsorption | Renal tubular acidosis |                                               |
|                                                     |                        | Renal failure                                |
|                                                     |                        | Acetazolamide use                            |
|                                                     |                        | Ureteral diversion procedure                 |
|                                                     |                        | Post-hypocapnia                              |
of patients with ST-elevation myocardial infarction undergoing percutaneous interventions failed to demonstrate a similar association between hyperchloremia and AKI\textsuperscript{29}.

Use of chloride-rich fluids in the ICU

The choice of the optimal crystalloid fluid in the ICU has been debated lately. The interplay of chloride imbalance and critical illness has been a driver of such conversation. Randomized controlled trials have addressed the conundrum of using chloride-rich solutions (0.9% saline) or more chloride restriction and balanced crystalloid solutions (for example, Ringer’s lactate and PlasmaLyte)\textsuperscript{26–28}. Several patient populations have been studied, and various outcomes, such as death, AKI, nutrition, and even coagulopathy and transfusion requirements, have been addressed. Several published randomized clinical trials relayed the effect of chloride concentration in resuscitation fluids and the outcomes of critically ill patients. Unfortunately, most of the older published trials had small sample sizes (<100 patients)\textsuperscript{26,27} or included patients with less severity of illness.

Yunos and colleagues\textsuperscript{29} performed a prospective, open-label, sequential period trial showing that the use of chloride-restrictive intravascular fluid strategy for resuscitation, versus a chloride-rich strategy, reduced AKI incidence and the need for renal replacement therapy (RRT) among ICU patients. However, the authors did not find a positive correlation with ICU or hospital death or lengths of stays. They also did not report chloride levels in their patients; therefore, a clear association between baseline dyschloremia and a change in chloride level could not be established. In another study\textsuperscript{30}, 150 patients who underwent cadaveric renal transplant were randomly assigned to receive normal saline or an acetate-buffered, balanced crystalloid during and after transplant surgery. The research arm receiving the balanced crystalloid had less hyperchloremia and acidosis and required fewer catecholamines. These trials raised concerns about the potential harmful associations with the use of chloride-rich solutions.

Within the past two years, three very relevant trials which provided valuable perspectives on this topic were published. In 2015, Young and colleagues\textsuperscript{31} published the results of the SPLIT (0.9% Saline vs. PlasmaLyte 148 for ICU Fluid Therapy) trial, a randomized double-blinded controlled trial on the use of saline versus a buffered crystalloid (PlasmaLyte 148; Baxter Healthcare Ltd). They enrolled 2,278 ICU patients, of whom 2,092 were included in the primary analysis. These investigators did not find a significant difference between treatment arms in the development of AKI, which was their primary outcome. They also did not find a significant difference in hospital death or RRT. Although this is probably the largest randomized trial on this topic to date, the authors did not report chloride levels. In addition, the average positive fluid balance was slightly less than 2 L, and most of the enrollees were surgical patients with fewer comorbidities. Because an adverse effect of a high chloride level on kidney function is mainly reported in sicker patients with higher serum chloride concentrations, an explanation for this study’s negative findings is the demographic characteristics of the enrolled patients and the limited exposure to the potentially nephrotoxic intravascular solution (with high chloride concentration) in the intervention arm.

The isotonic Solution Administration Logistical Testing (SALT) trial was published in 2017\textsuperscript{32}. This was a pilot trial for a much larger, pragmatic, cluster-randomized, multiple-crossover study aiming to enroll 14,000 patients. The study involves alternating crystalloid assignment to different ICUs on a monthly basis following a cluster-randomized crossover design. The primary outcome of the larger project will be major adverse kidney events by hospital discharge or day 30 (MAKE 30), including in-hospital mortality, receipt of new RRT, or persistent renal dysfunction defined as a final inpatient serum creatinine value of at least 200% of the baseline serum creatinine concentration. The pilot enrolled close to a thousand patients and revealed that the selected design could produce well-balanced groups with separation in the type of crystalloid received. Their patient-centered outcomes showed no difference between the groups in the rate of MAKE 30. Comparing the patient populations of the SALT and SPLIT trials is noteworthy as the patients in the SALT trial were admitted to the ICU mainly for sepsis or respiratory failure as opposed to mostly surgical patients in the SPLIT trial. Nonetheless, both studies had low fluid administration volumes. In the SALT and SPLIT trials, the median volumes of crystalloid received in both arms were less than 1,500 and 2,000 mL, respectively. Interestingly, in the subgroup analysis of patients who received larger volumes, the SALT investigators did find a significant difference in the rate of MAKE 30 between treatment arms.

The Limiting Intravenous Chloride to Reduce AKI (LICRA) trial is among the latest evidence on this topic\textsuperscript{33}. The investigators studied the effect of limiting chloride load in patients who underwent cardiac surgery. They designed a prospective multiple sequential period study which included the use of chloride-rich fluids during the first and last periods. Normal saline and 4% albumin were considered to be fluids with high chloride content (used in the first and fourth periods). They included Hartmann’s solution and 20% albumin in the second period and PlasmaLyte and 20% albumin in the third period. Fluid administration was controlled during the perioperative and early postoperative periods. The average volume administration was close to 5 L of crystalloid and colloid. However, the average chloride load was higher in the chloride-rich group. They found no difference among the groups in their co-primary outcomes of change in serum creatinine on postoperative day 5 and AKI stage 2 or 3 development according to the Kidney Disease: Improving Global Outcomes (KDIGO) creatinine AKI definition criteria\textsuperscript{34}. Likewise, the groups did not differ in the incidence of postoperative RRT, hospital mortality, or ICU length of stay. Hyperchloremia and acidemia occurred more frequently in the chloride-rich group, while the chloride-limited group developed more alkalemia, hypokalemia, and hyponatremia. Interestingly, more than 60% of patients in the chloride-restricted strategy developed hyperchloremia.

Conclusions

In a review of the currently available literature on dyschloremia in the ICU, one should remember that most studies are retrospective or small. In some of the larger studies on the use of normal saline, chloride levels were not reported\textsuperscript{26,27}. The studies looking into associations of hyperchloremia and outcomes were very heterogeneous with different measured associations and various
outcomes. The association between hyperchloremia and death was not always observed or reported. Furthermore, associated electrolyte imbalances from fluid resuscitation—whether the perceived worse outcomes such as death or AKI are related to hyperchloremia per se or to rapid chloride loading with its associated acid-base imbalance—have yet to be carefully examined. Dyschloremia reflects a pathologic process or is a result of therapeutic interventions. Close monitoring of chloride concentration among critically ill patients who undergo multiple interventions may be considered as an important step. In addition, isolation of the dyschloremia effect in the absence of the driving cause may be challenging and less informative.

Following the examination of the body of literature about the consequences of chloride-rich versus more balanced solutions on critically ill patients, we noted that earlier studies suggested that the use of balanced fluids may be associated with less AKI and need for RRT. However, the more recent trials failed to show a significant effect on death or AKI. The use of low volumes of intravenous fluids administered in treatment arms of the SALT and SPLIT trials among patients with less comorbid conditions may explain the failure to observe such relationships. In contrast to these trials, the LICRA trial involved the use of a larger volume of fluid administration yet did not reveal any significant difference in study outcomes, keeping in mind hyperchloremia occurred in more than half of the patients in the chloride-restricted arm.

What seems to be an acceptable general practice among intensivists is to avoid chloride-rich solutions in non-hypochloremic patients. Although patients with hypovolemic metabolic alkalosis or intracranial hypertension may benefit from higher chloride concentration during fluid resuscitation, those who have hyperchloremia, increased risk of AKI, or metabolic acidosis may be harmed by chloride-rich solutions. Clinicians intuitively favor the use of physiologic solutions when resuscitating a critically ill patient. However, to date, no robust data indicate a clear benefit from this strategy. We suggest that, during intravenous fluid resuscitation, clinicians treat different solutions as other medications and consider the benefits and potential adverse effects before prescribing any solution.

Future research
Prospective trials with more precise design may clarify the answer related to the impact of chloride changes on patient outcomes. These can include the use of chloride level to guide fluid therapy, prospective investigations to assess the impact of dyschloremia at baseline or resultant from therapeutic interventions, study of the potential role of chloride-rich fluids in hypochloremic or normochloremic patients during early resuscitation, and studying the effects of different fluid management strategies in each specific group of patients rather than heterogeneous populations in the hospital or ICUs. Such research would result in more relevant conclusions.

Competing interests
The authors declare that they have no competing interests.

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References

1. Berenk K, van Hulsteijn LH, Gans RO: Chloride: the queen of electrolytes? Eur J Intern Med. 2012;23(3):203–11. PubMed Abstract | Publisher Full Text
2. Yunos NM, Bellorom R, Story D, et al.: Bench-to-bedside review: Chloride in critical illness. Crit Care. 2010; 14(4): 226. PubMed Abstract | Publisher Full Text | Free Full Text
3. Institute of M: Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate. % @ 978-0-309-09169-5. Washington, DC %G English: The National Academies Press; 2005. Reference Source
4. Langer T, Ferrari M, Zazzeron L, et al.: Effects of intravenous solutions on acid-base equilibrium: from crystalloids to colloids and blood components. Anesth Analg. 2014; 119(5): 550–60. PubMed Abstract | Publisher Full Text
5. Kellum JA, Song M, Almasi E: Hyperchloremic acidosis increases circulating inflammatory molecules in experimental sepsis. Chest. 2006; 130(4): 962–7. PubMed Abstract | Publisher Full Text
6. Kellum JA, Song M, Venkatakrishnan R: Effects of hyperchloremic acidosis on arterial pressure and circulating inflammatory molecules in experimental sepsis. Chest. 2004; 126(1): 543–8. PubMed Abstract | Publisher Full Text
7. Wilcox CS: Regulation of renal blood flow by plasma chloride. J Clin Invest. 1983; 71(3): 726–35. PubMed Abstract | Publisher Full Text | Free Full Text
8. Bulivant EM, Wilcox CS, Welch WJ: Intrarenal vasoconstriction during hyperchloremia: role of thromboxane. Am J Physiol. 1989; 256(1 Pt 2): F152–7. PubMed Abstract
9. Zazzeron L, Ottolino D, Scotti E, et al.: Real-time urinary electrolyte monitoring after furosemide administration in surgical ICU patients with normal renal function. Ann Intensive Care. 2016; 6(1): 72. PubMed Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation
10. Shao M, Li G, Sarvottam K, et al.: Dyschloremia Is a Risk Factor for the Development of Acute Kidney Injury in Critically Ill Patients. PLoS One. 2016; 11(8): e0160322. PubMed Abstract | Publisher Full Text | Free Full Text
11. Kimura S, Matsumoto S, Muto N, et al.: Association of serum chloride concentration with outcomes in postoperative critically ill patients: a retrospective observational study. J Intensive Care. 2014; 2(1): 39. PubMed Abstract | Publisher Full Text | Free Full Text
12. Tanii M, Morimoto H, Takatsu F, et al.: The incidence and prognostic value of hypochloremia in critically ill patients. ScientificWorldJournal. 2012; 2012: 474185. PubMed Abstract | Publisher Full Text | Free Full Text
13. Van Regenmortel N, Verbrugghe W, Van den Wyngaert T, et al.: Impact of chloride and strong ion difference on ICU and hospital mortality in a mixed intensive care population. Ann Intensive Care. 2016; 6(1): 91. PubMed Abstract | Publisher Full Text | Free Full Text
14. Ter Maaten JM, Darmman K, Hanberg JS, et al.: Hypochloremia, Diuretic Resistance, and Outcome in Patients With Acute Heart Failure. Circ Heart Fail. 2016; 9(8): pii: e003109. PubMed Abstract | Publisher Full Text | F1000 Recommendation
15. Testani JM, Hanberg JS, Arroyo JP, et al.: Hypochloremia is strongly and independently associated with mortality in patients with chronic heart failure.
24. Patel N, Baker SM, Walters RW, et al.: Serum hyperchloremia as a risk factor for acute kidney injury in patients with ST-segment elevation myocardial infarction undergoing percutaneous coronary intervention. Proc (Bayl Univ Med Cent). 2016; 29(1): 7–11. PubMed Abstract | Publisher Full Text | F1000 Recommendation

25. Grodin JL, Verbrugg F, Ellis SG, et al.: Importance of Abnormal Chloride Homeostasis in Stable Chronic Heart Failure. Circ Heart Fail. 2016; 9(1): e002453. PubMed Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

26. Raghunathan K, Mursy PT, Beattie WS, et al.: Choice of fluid in acute illness: what should be given? An international consensus. Br J Anaesth. 2014; 113(5): 772–83. PubMed Abstract | Publisher Full Text

27. Reddy S, Weinberg L, Young P.: Crystalloid fluid therapy. Crit Care. 2016; 20: 59. PubMed Abstract | Publisher Full Text | Free Full Text | F1000 Recommendation

28. Langer T, Santini A, Scotti E, et al.: Intravenous balanced solutions: from physiology to clinical evidence. Anaesth Intensivether. 2015; 47(Spec No): s78–88. PubMed Abstract | Publisher Full Text | F1000 Recommendation

29. Yunus NM, Bellomo R, Hegarty C, et al.: Association between a chloride-liberal vs chloride-restrictive intravenous fluid administration strategy and kidney injury in critically ill adults. JAMA. 2012; 308(15): 1566–72. PubMed Abstract | Publisher Full Text | F1000 Recommendation

30. Potura E, Lindner G, Biesenbach P, et al.: An acetate-buffered balanced crystalloid versus 0.9% saline in patients with end-stage renal disease undergoing cadaveric renal transplantation: a prospective randomized controlled trial. Anesth Analg. 2015; 120(1): 123–9. PubMed Abstract | Publisher Full Text | F1000 Recommendation

31. Young P, Beasley R, et al.: Effect of a Buffered Crystalloid Solution vs Saline on Acute Kidney Injury Among Patients in the Intensive Care Unit: The SPLIT Randomized Clinical Trial. JAMA. 2015; 314(16): 1701–10. PubMed Abstract | Publisher Full Text | F1000 Recommendation

32. Semler MW, Wanderer JP, Ehrenfeld JM, et al.: Balanced Crystalloids versus Saline in the Intensive Care Unit. The SALT Randomized Trial. Am J Respir Crit Care Med. 2017; 195(10): 1362–72. PubMed Abstract | Publisher Full Text | F1000 Recommendation

33. McLeroy D, Murphy D, Kasza J, et al.: Effects of restricting perioperative use of intravenous chloride on kidney injury in patients undergoing cardiac surgery: the LICRA pragmatic controlled clinical trial. Intensive Care Med. 2017; 43(6): 795–806. PubMed Abstract | Publisher Full Text | F1000 Recommendation

34. Section 2: AKI Definition. Kidney Int Suppl. (2011); 2(1): 19–36. PubMed Abstract | Publisher Full Text | Free Full Text
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