Current role of high dose vitamin C in sepsis management: A concise review

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Abstract

Sepsis and septic shock are common diagnoses for patients requiring intensive care unit admission and associated with high morbidity and mortality. In addition to aggressive fluid resuscitation and antibiotic therapy, several other drugs have been tried as adjuvant therapies to reduce the inflammatory response and improve outcomes. Vitamin C has been shown to have several biological actions, including anti-inflammatory and immunomodulatory effects, which may prove beneficial in sepsis management. Initial trials showed improved patient outcomes when high dose vitamin C was used in combination with thiamine and hydrocortisone. These results, along with relative safety of high-dose (supra-physiological) vitamin C, encouraged physicians across the globe to add vitamin C as an adjuvant therapy in the management of sepsis. However, subsequent large-scale randomised control trials could not replicate these results, leaving the world divided regarding the role of vitamin C in sepsis management. Here, we discuss the rationale, safety profile, and the current clinical evidence for the use of high-dose vitamin C in the management of sepsis and septic shock.

Key Words: Ascorbic acid; Critical care; Infection; Sepsis; Septic shock; Vitamin C

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Core Tip: High-dose vitamin C is increasingly used in varied clinical conditions including sepsis and septic shock. Even though a few initial studies showed remarkable improvements in outcomes, later studies failed to replicate these effects. Through this article, we wish to review the rationale and current clinical evidence for use of vitamin C in the management of patients with sepsis and septic shock.

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INTRODUCTION

Vitamin C, or ascorbic acid, is a water-soluble vitamin that acts as an anti-oxidant and as a co-factor for multiple enzymes. For a long time, vitamin C deficiency has been associated with the occurrence of scurvy disease. However, in recent years, vitamin C has been established to have different biochemical effects and has been increasingly used in varied clinical conditions that include severe acute pancreatitis, sepsis, and cancer[1-3]. Being a water-soluble vitamin, vitamin C is generally considered to be safe even at high dosages. Although no clear guidelines or recommendations exist for the administration of vitamin C, it is still being used to manage these diseases, even in critically-ill patients. Mortality associated with sepsis and septic shock remains high though the disease, its prognosis, and management procedures are well established earlier. Intravenous fluid resuscitation and hemodynamic support, early administration of appropriate antibiotics, source control, and organ support form the mainstay of therapy[4]. Over the years, various therapeutic methods that include activated protein C, ulinastatin, and vitamin C have been tested as adjuvant therapies to improve the outcomes[2,5,6]. However, these therapies failed to achieve any significant and meaningful outcome and their role in sepsis management remains ambiguous[4]. In this background, the aim of the current review is to discuss the scientific rationale behind the usage of high-dose vitamin C (HDVC) in patients with sepsis and septic shock and evaluate its clinical evidence.

RATIONALE

In general, normal serum contains more than 50 μmol/L vitamin C[7]. However, acutely-ill patients exhibit a rapid reduction in their vitamin C levels, while critically-ill patients, especially those with sepsis, show extremely low vitamin C levels (below 11 μmol/L), in spite of the recommended enteral and parenteral nutritional intakes[8]. Moreover, commonly-employed organ-support intensive care unit (ICU) interventions like continuous renal replacement therapy (CRRT) also reduce the levels of water-soluble vitamins like vitamin C[9].

Vitamin C exhibits several biochemical effects that may potentially benefit the management of patients with sepsis and septic shock (Table 1)[10,11]. Sepsis results in the release of several reactive oxygen species (ROS) which are capable of causing severe injury to lipids, proteins, and nucleic acid that in turn results in endothelial and mitochondrial dysfunction, cell death, and ultimately multiple organ dysfunction syndrome (MODS). Vitamin C exerts its anti-oxidant effects by scavenging these ROS. Further, it also helps in recycling other anti-oxidants like vitamin E and tetrahydrobiopterin (BH4). Thus, it plays a major role in preventing oxidative damage and cell death[12,13].

Sepsis tends to reduce the functions of adenosine triphosphate (ATP) and causes bioenergetic failure of mitochondria, secondary to oxidative damage caused by mitochondrial ROS and alterations in fatty acid metabolism[14]. Vitamin C exhibits anti-oxidant effect and prevents the oxidative damage, and it also helps in carnitine production that improves fatty acid metabolism in mitochondria[15]. These actions may be helpful in the prevention of cell death, leading to septic cardiomyopathy and MODS.

Sepsis causes microvascular dysfunction which reduces the arteriolar reactivity to vasoconstrictors. This phenomenon results in vasodilation and shock. Vitamin C acts as a co-factor for the enzymes that are required for the synthesis of catecholamines and vasopressors. Thus, it enhances the synthesis of these enzymes and improves arteriolar sensitivity to vasopressors by inhibiting endothelial expression of inducible nitric oxide synthase (iNOS). In addition, vitamin C also has several immuno-modulatory and anti-inflammatory effects that help in abating cytokine storm associated with sepsis-induced MODS[10,11,16].

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Table 1 Biological effects of vitamin C

| Biological effects of vitamin C | Mechanisms of action |
|--------------------------------|-----------------------|
| Antioxidant properties         | Reduced production of reactive oxygen species; Reduced production of endothelial nitric oxide |
| Prevention of mitochondrial dysfunction | Reduction of oxidation injury; Reduces apoptosis |
| Prevention of septic cardiomyopathy | Reduction of oxidation injury; Increased carnitine synthesis; Reduces apoptosis |
| Prevention of micro and macro vascular dysfunction | Acts as a co-factor for synthesis of catecholamines (epinephrine, norepinephrine) and vasopressin; Inhibition of iNOS expression |
| Anti-inflammatory effects       | Suppresses activation of nuclear factor kappa-B (NF-κB); Inhibits tumor necrosis factor-α; Reduces pro-inflammatory cytokines like high mobility group box 1; Lowers histamine levels |
| Immune enhancing effects       | T-cell maturation and modulation; Improves neutrophil chemotaxis and phagocytosis; Enhances oxidative killing; Promotes proliferation of lymphocytes; Stimulates interferon production; Increased antibody production |

CLINICAL STUDIES

Several randomised controlled trials (RCTs) have been conducted in recent years to explore the plausibility of clinical benefits, achieved from the antioxidative effect of vitamin C, in reducing sepsis-induced tissue injury (Table 2). The authors conducted a systematic search using keywords such as ‘Vitamin C’ OR ‘Ascorbic acid’ AND Sepsis OR “Septic Shock” in PubMed and Google Scholar and found a total of 17 RCTs suitable for the current analysis. Out of the 17, five were about the application of vitamin C alone in patients with sepsis[17-21]. The current study followed a heterogeneous design with different doses of vitamin C monotherapy vs combination therapy with thiamine and hydrocortisone and the timing of administration.

Isolated vitamin C therapy

Out of the RCTs considered, five compared vitamin C with placebo in patients with sepsis. Different doses were used in the studies under consideration[17-21]. All the studies, except one, failed to infer any clinically meaningful difference with the usage of vitamin C[18]. The CITRIS-ALI trial compared vitamin C (at a dose of 50 mg/kg q6h) with a placebo in patients with sepsis and acute respiratory distress syndrome. No significant difference was found in the mean change of sequential organ failure assessment (SOFA) scores between the groups considered, from baseline to 96 h. The changes in C-reactive protein (CRP) and thrombomodulin levels, at 168 h, were also statistically non-significant. In terms of subgroup analysis, the 28-d mortality rate (without adjustment for multiple comparisons) was found to be significantly lower in the vitamin C group (29.8% vs 46.3%; P = 0.05)[17].

The largest and the most recently published LOVIT study was a phase III, multicentre RCT that involved 35 medical-surgical ICUs which spanned across Canada, France, and New Zealand. The study included patients with suspected or proven infection and those who were on vasopressor support. Vitamin C was intravenously administered once for 6 h, at a dosage of 50 mg/kg, up to 96 h to 429 patients in the intervention group. On the other hand, a placebo was administered to 434 patients who belonged to the control group. The administration of thiamine and glucocorticoids was left to the clinical discretion of the treating physician. The primary outcome, i.e., a composite of death or persistent organ dysfunction at 28 d, was significantly higher in the intervention (vitamin C) group vs the control group [44.5% vs 38.5%; risk ratio: 1.21; 95% confidence interval (CI): 1.04-1.40; P = 0.01]. However, no significant difference was found in the individual components of composite primary outcome: Mortality or persistent organ dysfunction, organ dysfunction-free days at 28 d, SOFA scores at pre-defined time intervals from days 1-8, 6-mo survival, and health-related quality of life. The study outcomes not only inferred the lack of benefit but also provided insights on possible harm caused by high dosage administration of vitamin C in patients with sepsis and septic shock[20].

Vitamin C as a part of combination therapy

Marik et al.[22] conducted a single-centre retrospective study involving 47 patients. This study compared cocktail therapy that included hydrocortisone, ascorbic acid, and thiamine (HAT) with a control group (standard care) among patients with severe sepsis and septic shock. The authors recorded a low hospital mortality rate in the treatment group (8.5% vs 40.4%, P < 0.001). The dosage regimen was as follows: Vitamin C at 1.5 g/h q6h, hydrocortisone at 50 mg q6h, and thiamine at 200 mg/12 h. Moreover, the mean duration of the vasopressors, used for shock, was also significantly shorter in the intervention arm (18.3 h vs 54.9 h, P = 0.001)[22]. This observational study started a debate on the suggested possible benefits of cocktail therapy among patients with septic shock. Subsequently, multiple RCTs were conducted to validate the findings of this study.
| No. | Title                                                                 | Ref.             | Acronym   | Country of origin | Study design | Sample size in control arm | Sample size in intervention arm | Intervention summary                                                                 | Results in brief                                                                                                                                                                                                 |
|-----|----------------------------------------------------------------------|------------------|-----------|-------------------|--------------|-----------------------------|---------------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | **Studies using isolated vitamin C**                                 |                  |           |                   |              |                             |                                  |                                                                                      |                                                                                                                                                                                                                  |
| 1   | Intravenous Vitamin C in Adults with Sepsis in the Intensive Care Unit | Lamontagne et al[20], 2022 | LOVIT Trial | Canada            | RCT          | 437                         | 435                              | Intravenous vitamin C (at a dose of 50 mg/kg body weight) 6 hourly for 96 h           | This trial reported significantly higher composite primary outcome (risk of mortality OR persistent organ dysfunction at 28 d) in vitamin C group. One patient had a severe hypoglycemic episode and another had a serious anaphylaxis event. |
| 2   | Intravenous vitamin C administration to patients with septic shock: a pilot randomised controlled trial | Rosengrave et al[19], 2022 |           | New Zealand       | RCT          | 20                          | 20                              | Intravenous vitamin C (at a dose of 25 mg/kg of body weight every 6 h) for up to 96 h, or until death or discharge | Treatment with intravenous vitamin C did not result in reduction of mean dose and duration of vasopressor infusion. Both the groups were comparable for rise in inflammatory markers, length of ICU stay, length of hospital stay, and mortality. |
| 3   | Early use of high-dose vitamin C is beneficial in treatment of sepsis | Lv et al[18], 2020 |           | China             | RCT          | 56                          | 61                              | Intravenous vitamin C 3.0 g in 5% dextrose (100 ml/time, 2 times/d)                  | Treatment with vitamin C resulted in a significant reduction in the 28-d mortality. There was a significant reduction in SOFA score at 72 h and duration of vasopressor use, also there was increased clearance of procalcitonin. |
| 4   | Effect of Vitamin C Infusion on Organ Failure and Biomarkers of Inflammation and Vascular Injury in Patients With Sepsis and Severe Acute Respiratory Failure: The CITRIS-ALI Randomized Clinical Trial | Fowler et al [17], 2019 | CITRIS-ALI | United States     | RCT          | 83                          | 84                              | Intravenous infusion of vitamin C (50 mg/kg in dextrose 5% in water, n = 84) every 6 h for 96 h | There was no significant difference in SOFA score at 96 h, and levels of marker of inflammation (CRP) and vascular injury (thrombomodulin) at 168 h. |
| 5   | Effect of vitamin C administration on neutrophil apoptosis in septic patients after abdominal surgery | Ferrón-Celma et al[21], 2008 |           | Spain             | PD interventions RCT study | 10                          | 10                              | The vitamin C group received 450 mg/d of the vitamin in 3 doses                         | Vitamin C treatment in postoperative septic abdominal surgery patients have an antiapoptotic effect on peripheral blood neutrophils, reducing caspase-3 and PARP levels, and increasing BCL-2 levels. However this effect is not maintained all the time. |
|     | **Studies using vitamin C in combination therapy**                   |                  |           |                   |              |                             |                                  |                                                                                      |                                                                                                                                                                                                                  |
| 6   | Effect of Supplementation of Vitamin C and Thiamine on the Outcome in Sepsis: South East Asian Region | Ap et al[27], 2022 |           | India             | RCT          | 20                          | 20 + 20 + 20                     | Intervention group received vitamin C, thiamine, both, and neither, respectively. Vitamin C (2 g 8 hourly) and thiamine (200 mg 12 hourly) were given intravenously for 5 d | Intervention with vitamin C and thiamine did not reduce mortality. The vitamin C level and thiamine level were significantly lower than those in healthy controls. |
| 7   | Biomarker Analysis for Combination Therapy of Vitamin C and Thiamine   | Park et al[34], 2022 | Post hoc ATESP | South Korea       | RCT (post hoc analysis) | 52                          | 45                              | Intravenous vitamin C (50 mg/kg, maximum single dose 5 g) and thiamine                | Baseline biomarker levels (IL-6, IL-10, AP2, and S100) at 72 h were not significantly different                                                                                                         |
1. **Usefulness of Antioxidants as Adjunct Therapy for Septic Shock: A Randomized Controlled Trial**

   | Study Title | Institution | Country | Design | N | Type | Key Interventions |
   |-------------|-------------|---------|--------|---|------|------------------|
   | Fujii et al. [23], 2020 | VITMAINS | Japan | RCT | 107 | 109 | Intravenous vitamin C (1.5 g every 6 h), hydrocortisone (50 mg every 6 h), and thiamine (200 mg every 12 h), given in intervention group and intravenous for 4 d |

2. **Vitamin C and Hydrocortisone on Ventilator- and Vasopressor-Free Days in Patients With Sepsis: The VICTAS Randomized Clinical Trial**

   | Study Title | Institution | Country | Design | N | Type | Key Interventions |
   |-------------|-------------|---------|--------|---|------|------------------|
   | Sevransky JE et al. [25], 2021 | VICTAS Trial | United States | RCT | 252 | 249 | Vitamin C (1.5 g), thiamine (100 mg), and hydrocortisone (50 mg) every 6 h |

3. **Combination therapy with ascorbic acid, corticosteroids, and thiamine in early phase of septic shock.**

   - **Intravenous combination of vitamin C (1.5 g every 6 h), thiamine (200 mg every 12 h), and hydrocortisone (50 mg every 6 h) within 6 h of onset of septic shock admission**

   - **Intravenous vitamin C (1.5 g every 6 h), hydrocortisone (50 mg every 6 h), and thiamine (200 mg every 12 h), given in intervention group and intravenous for 4 d**

   - **Vitamin C (50 mg/kg, maximum single dose 3 g) and thiamine (200 mg) administration every 12 h for a total of 48 h**

   - **Parenteral vitamin C (1500 mg), hydrocortisone (50 mg), and thiamine (100 mg) every 6 h for 4 d**

   - **Vitamin C (50 mg/kg, maximum single dose 3 g) and thiamine (200 mg) administration every 12 h for a total of 48 h intravenously**

   - **Ascorbic acid 1500 mg q6h, thiamine 200 mg every 12 h, and hydrocortisone 50 mg q6h for a maximum of 4 d**

   - **Intravenous vitamin C (1.5 g every 6 h), hydrocortisone (50 mg every 6 h), and thiamine (200 mg every 12 h), given in intervention group and intravenous**

   - **Findings from this trial suggest that combination therapy does not lead to rapid resolution of septic shock in comparison to hydrocortisone alone with no significant improvement in overall mortality**
The VITAMINS trial, a multicentric RCT involving 211 patients, evaluated the effectiveness of a combination of vitamin C (1.5 g q6h), thiamine (200 mg q12h), and hydrocortisone (50 mg q6h) in patients suffering from septic shock. To conduct primary analysis, 107 patients were recruited for the intervention arm and 104 patients under the control arm. The eligibility criteria for this study were as follows: A primary diagnosis of septic shock with an acute increase in SOFA score by two points or more, a lactate level > 2 mmol/L, and the requirement for vasopressor support for at least 2 h, prior to enrolment. The study found no significant difference between the groups in terms of primary outcome, duration of time alive, and vasopressor-free days until day 7 (122.1 (76.3–145.4 h) vs 124.6 (82.1–147.0 h), P = 0.83). Among the secondary outcomes too, no significant difference was found in 28 d, 90 d, ICU-, or hospital-mortality between the groups. Further, the two groups also exhibited similar secondary outcomes like vasopressor-free days, mechanical ventilation-free days, and renal replacement-free days. While SOFA scores got reduced by day 3 in both the groups, the decline was marginally higher in the intervention group. In this study, two patients had adverse events (fluid overload and hyperglycemia, one each) in the intervention group[23].

A multicentre RCT (ACTS trial) was conducted among 205 septic shock patients randomised into either a placebo (n = 102) or an intervention arm (n = 103) with intravenous vitamin C (1500 mg q6h), hydrocortisone (50 mg q6h), and thiamine (100 mg q6h) for 4 d. No significant change was observed in SOFA score (difference between baseline and SOFA score at 72 h) between intervention vs placebo (-0.8; 95%CI: -1.7 to 0.2; P = 0.12). Further, no significant difference was found in the secondary outcomes too, such as incidence of acute kidney injury (AKI) and ventilator-free days. Shock-free days were found to be higher in the intervention group (median difference of 1 d; 95%CI: 0.2-1.8 d; P < 0.01)[24].

In another multicentric RCT (VICTAS trial) conducted among patients with sepsis and septic shock (n = 252), a cocktail of vitamin C (1.5 g q6h), thiamine (100 mg q6h), and hydrocortisone (50 mg q6h) was used, commencing within 4 h of randomization for 4 d. On the other hand, a matching placebo was
administered in the control group \((n = 249)\). The trial was prematurely terminated due to the lack of funding though the actual plan was to recruit 2000 patients. No significant difference was found in terms of primary outcomes such as ventilator- and vasopressor-free days for the first 30 d \([25\text{ d (0-29 d)}\text{ vs }26\text{ d (0-28 d)}]\); \(P = 0.85\). Further, no significant difference was found between 30-d mortality between the groups \((22\% \text{ vs }24\%)\). In addition to these, no serious adverse events were reported during the study. This study, although terminated early, did not reveal any difference with vitamin C cocktail in patients with sepsis, including respiratory or cardiovascular dysfunction\[25\].

Similar findings were reported in another multi-center RCT (ATESS trial) conducted in South Korea. Patients with septic shock in emergency department were randomized to receive either vitamin C (50 mg/kg) and thiamine (200 mg q6h for 48 h) in the intervention arm \((n = 53)\) or placebo \((n = 58)\) in the control group. Hydrocortisone (200 mg/d) and intravenous vasopressin infusion were administered in both the arms of patients who required high dosage norepinephrine. No statistically significant difference was found in the primary outcome whereas the SOFA score \(P\text{-value of difference between the baseline and 72-h score) significantly changed between the intervention and placebo groups}\[3,\ (-1 \text{ to } 5)\text{ vs }3,\ (0-4), \ P = 0.96\]. Further, there was no significant difference between the intervention arm and placebo in baseline vitamin C or thiamine levels. After the treatment, vitamin C and thiamine levels were found to have increased in the intervention group. However, there was no significant difference observed in any of the secondary outcomes, including mortality at day 7, 28, or 90, shock reversal, ventilator-free days, incidence of AKI, and reduction of CRP or procalcitonin\[26\].

Several non-randomized trials have also been conducted earlier to evaluate the role of vitamin C, either as a single entity or as a part of combination therapy, in the management of sepsis \(\text{(Table 3)}\).

### Meta-analysis of vitamin C in sepsis

Various systematic reviews and meta-analyses have been published on vitamin C in sepsis, with conflicting results on the short-term mortality \(\text{(Table 4)}\). However, no effect was found in the trials with long-term mortality. A recent metaanalysis by Agarwal et al\[44\], with 41 RCTs and 4915 patients (including recently published LOVIT trial), explored the effect of intravenous vitamin C as monotherapy or combination therapy among hospitalized patients with severe infection. With low-certainty evidence, there was a trend towards reduced in-hospital mortality \[21 RCTs, 2762 patients, risk ratio \(\text{(RR)}\) = 0.88 \(\text{(95\%CI, 0.73-1.06)}\)] and early mortality \[34 RCTs, 4366 patients, \(\text{RR} = 0.83 \text{ (0.71-0.98)}\)\] with vitamin C. However, on sensitivity analysis involving published trials which were blinded and with a low risk of bias, the impact of vitamin C was attenuated with no statistical significance. The RR of hospital mortality \(\text{(6 RCTs, 1371 patients)}\) was 1.07 \(\text{(0.92-1.24)}\), with moderate certainty evidence; that of 30-day mortality \(\text{(9 RCTs, 2057 patients)}\) was 0.88 \(\text{(0.71-1.10)}\), with low certainty evidence; and that of early mortality \(\text{(11 RCTs, 2214 patients)}\) was 0.88 \(\text{(0.73-1.06)}\), with low certainty evidence. With moderate certainty evidence, increased 90-d mortality was suggested in five RCTs, including 1722 patients \(\text{(RR} = 1.07, 0.94-1.21)\). The reason for heterogeneity was that few trials with large treatment effects were either single centre, or had small sample size. The RR of early mortality in trials reporting 90-d mortality was 1.05 \(\text{(0.91-1.21)}\). Among the adverse events, there were no major adverse events, except an increased risk of hypoglycemia \(\text{(1 RCT, 862 patients, RR} = 1.20 \text{ (0.69-2.08)}\)\), with moderate certainty of evidence. The result of other secondary outcomes was mixed with reduction of duration and use of mechanical ventilation and increased risk of AKI or need of RRT, based on low-certainty evidence. No credible subgroup effects were observed related to cointerventions \(\text{(monotherapy vs combined therapy)}\), dose of vitamin C, or the type of infection \(\text{(SARS-CoV-2 vs others)}\) \[44\].

### DOSING

Different authors have tried several different dosing regimens. Higher doses of intravenous vitamin C are also being prescribed regularly, with doses up to 100 g/d used to manage patients with sepsis\[30\]. Even “high-dose” is not clearly defined and is arbitrarily considered a dose of more than 2-10 g/d in adults, by different authors\[57, 58\].

The current literature suggests using six-hourly dosage for vitamin C in order to alleviate the deficiency, achieve steady plasma levels rapidly, and maintain normal serum levels. This dosing schedule may also be able to rapidly normalize the neutrophil ascorbic acid levels\[36, 39\]. Even though intravenous formulations are generally preferred in critically ill patients, especially those in shock, and may rapidly increase the serum vitamin C levels, no difference in clinical efficacy has been reported between intravenous and oral formulations of vitamin C\[39, 60\].

### ADVERSE EFFECTS

As a water-soluble vitamin, vitamin C is generally considered safe, even when used at high doses. Most
### Table 3 Non randomized studies of vitamin C in sepsis

| No. | Title                                                                 | Ref. | Country of origin | Study design | Sample size in control arm | Sample size in intervention arm | Intervention summary                                                                 | Results in brief                                                                 |
|-----|------------------------------------------------------------------------|------|-------------------|--------------|----------------------------|--------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| 1   | High dose intravenous vitamin C treatment in Sepsis: associations with acute kidney injury and mortality | McCune et al[35], 2021 | United States     | Cohort study (retrospective cohort) | 1178                       | 212                             | Cohort of patients who have received at least one dose of 1.5 g IV vitamin C       | Vitamin C therapy was associated with significant chances of AKI and death.     |
| 2   | Effect of high-dose intravenous vitamin C on point-of-care blood glucose level in septic patients: a retrospective, single-center, observational case series | He et al[38], 2020 | China             | Observational case series | 82                           |                                 | Patients with septic shock on admission received 100 mg/kg/d, while other patients received <100 mg/kg/d | High-dose vitamin C therapy may interfere with point-of-care glucose testing results. |
| 3   | Pharmacokinetic data support 6-hourly dosing of intravenous vitamin C to critically ill patients with septic shock | Hudson EP et al[36], 2019 | Australia         | Observational PK study | 11                           |                                 | Patients received 1.5 g intravenous vitamin C every 6 h                           | Injectable vitamin C 1.5 g every 6 h helps in correction of vitamin C deficiency and hypovitaminosis C, and it also provides appropriate dosing schedule for vitamin C supplementation in septic shock. |
| 4   | Accuracy of Point-of-Care Blood Glucose Level Measurements in Critically Ill Patients with Sepsis Receiving High-Dose Intravenous Vitamin C | Smith et al[37], 2018 | United States     | Observational PK study | 5                            |                                 | Patients who have received vitamin C 1500 mg intravenously two or more doses and had point of care blood glucose checked and laboratory venous BG levels measured within 1 h of each other during vitamin C therapy | The accuracy and agreement of POC BG did not have significant interreference during vitamin C treatment in sepsis. |
| 5   | Phase I safety trial of intravenous ascorbic acid in patients with severe sepsis | Fowler et al[39], 2014 | United States     | Phase I safety trial | 24 total in 1:1:1 ratio |                                 | Patients with severe sepsis in the medical intensive care unit were randomized 1:1:1 to receive intravenous infusions every 6 h for 4 d of ascorbic acid: Lo-AscA (50 mg/kg/24 h, n = 8), or Hi-AscA (200 mg/kg/24 h, n = 8), or placebo (5% dextrose/water, n = 8) | Intravenous vitamin C infusion is safe and tolerated well and may have a positive impact on endothelial injury, the extent of multiple organ failure, and levels of inflammatory biomarkers. |
| 6   | Adding vitamin C to hydrocortisone lacks benefit in septic shock: a historical cohort study | Chang et al[40], 2020 | Canada            | Cohort study (retrospective cohort) | 88                           | 52                             | Retrospective cohorts of vitamin C with hydrocortisone and hydrocortisone therapies for 72 h were compared in patients with sepsis or septic shock | Outcomes for hospital mortality, ICU mortality, ventilator free days, vasopressor free days, dialysis use, and duration of ICU admission were comparable between the groups. |
| 7   | Hydrocortisone, Vitamin C, and Thiamine for the Treatment of Severe Sepsis and Septic Shock: A Retrospective Before-After Study | Marik et al[22], 2017 | United States     | Cohort study (before and after study) | 47                           | 47                             | Intra-venous vitamin C (1.5 g q12h for 4 d or until ICU discharge), hydrocortisone (50 mg q12h for 7 d or until ICU discharge followed by a taper over 3 d) as well as intravenous thiamine (200 mg q12h for 4 d or until ICU discharge) | Results of this study suggest that the early use of intravenous vitamin C, together with corticosteroids and thiamine, prevents progressive organ dysfunction, including acute kidney injury, and reduces the mortality of patients with severe sepsis and septic shock. |
|     | Other studies                                                           |      |                   |              |  |  |  |  |
|   | Plasma Cortisol, Aldosterone, and Ascorbic Acid Concentrations in Patients with Septic Shock Do Not Predict Treatment Effect of Hydrocortisone on Mortality. A Nested Cohort Study | Cohen et al [42], 2020 | Australia and NZ | Cohort Study (nested cohort study) | Levels of total and free plasma cortisol and aldosterone were measured along with quantitatively measured vitamin C levels | In patients with septic shock, plasma aldosterone and ascorbic acid concentrations are not associated with outcome. |
|---|---|---|---|---|---|---|
| 9 | Vitamin C levels amongst initial survivors of out of hospital cardiac arrest | Gardner et al [43], 2020 | United States | Observational study | 34 | 25 post arrest, 25 post sepsis | Observational |
| 10 | Hypovitaminosis C and vitamin C deficiency in critically ill patients despite recommended enteral and parenteral intakes | Carr et al [41], 2017 | New Zealand | Observational study | 20 | 24 | Patients with septic shock and non-septic aetiology |
| 11 | Colistin-associated Acute Kidney Injury in Severely Ill Patients: A Step Toward a Better Renal Care? A Prospective Cohort Study | Dalfino et al [41], 2015 | Italy | Cohort (prospective cohort) | 39 non AKI | 31 AKI | Intervention cohort patients have received colistin at a median daily dose of 9 million IU |

AKI: Acute kidney injury; Hi-AscA: High dose ascorbic acid; ICU: Intensive care unit; Lo-AscA: Low dose ascorbic acid; POC BG: Point of care blood glucose.

of the large trials evaluating the efficacy of vitamin C have not assessed adverse effects as a primary objective. Hence, the data regarding adverse events has largely come from case reports, case series, and meta-summary of case reports[61]. Most commonly reported side effects are mild and include interference with laboratory tests, lethargy, fatigue, phlebitis, glycemic disturbances (hypo- or hyperglycemia), hypernatremia, muscle cramps, nausea, vomiting, headache, altered mental status, syncope, methemoglobinemia, oxalosis, and renal stones. However, rarely patients may develop life-threatening complications like haemolysis, AKI, and disseminated intravascular coagulation[62,63]. The probability of developing complications is reported to be higher in patients with glucose-6-phosphate dehydrogenase (G6PD) deficiency and in those with underlying renal dysfunction[61]. Even though vitamin C has anti-oxidant properties, when used at higher doses, it may deplete the intra-erythrocyte glutathione stores and cause oxidative stress. Patients with G6PD deficiency are unable to replenish these glutathione stores and develop haemolysis secondary to oxidative damage[64,65].

**DISCUSSION**

Despite a pathophysiological rationale, the current clinical evidence does not support the use of vitamin C in sepsis. Indeed, there was a trend towards harm observed in the LOVIT trial. However, the primary outcome was composite, and its components did not reach statistical significance. The harm was not seen in other RCTs. In the LOVIT trial, the intervention arm had more patients in shock and on invasive mechanical ventilation at the baseline compared to the control arm. This imbalance in baseline characteristics between the groups may explain the higher incidence of organ dysfunction. Furthermore, despite excluding patients staying > 24 h in ICU, the time gap between the actual onset of sepsis and administration of vitamin C is unclear[20].
### Table 4 Meta-analyses of trials on vitamin C in sepsis

| No. | Title                                                                 | Ref.            | Country of origin | Study design    | Included studies | Included sample size | Intervention summary                                                                 | Results in brief                                                                                                                                                                                                 |
|-----|------------------------------------------------------------------------|-----------------|-------------------|-----------------|------------------|----------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | IV Vitamin C in Critically Ill Patients: A Systematic Review and Meta-Analysis | Patel et al [45], 2022 | United States     | Meta-analysis   | 15 RCTs          | 2490 participants    | Compared intravenous vitamin C at high and low doses with placebo among pooled study participants | Intravenous vitamin C therapy is associated with a trend toward reduced overall mortality. Data further reveals that High-dose IV vitamin C was associated with a significant reduction in overall mortality. None of the included trials reported an increase in adverse events related to IV vitamin C therapy. |
| 2   | Efficacy of intravenous vitamin C intervention for septic patients: A systematic review and meta-analysis based on randomized controlled trials | Li et al [47], 2021 | China             | Meta-analysis of RCTs | 10 RCTs          | 1400 patients        | Studies that have intravenous vitamin C supplementation were included                 | Data from this meta-analysis reports improved SOFA score within 72 h but no significant improvement in short term (28-30 d) mortality, long term mortality (90 d), hospital stay, ventilator-free days, ICU-stay in sepsis or septic shock patients. |
| 3   | Effect of vitamin C in critically ill patients with sepsis and septic shock: A meta-analysis | Feng et al [48], 2021 | China             | Meta-analysis of RCTs | 9 RCTs           | 584 patients         | Studies with vitamin C treatment in critically sick sepsis and septic shock patients were included | Data from this study finds significant differences in 28-d mortality and dose of vasopressors. However, the ICU length of stay was the same between the two groups. |
| 4   | Efficacy of vitamin C in patients with sepsis: An updated meta-analysis | Wei et al [46], 2020 | China             | Meta-analysis    | 6 RCTs and 6 observational studies | 1176 in control group | This analysis included data from RCTs and observational studies that evaluated the effect of vitamin C in patients with sepsis | This study reports no significant improvement in 28-d or in-hospital mortality. There was also no difference in vasopressor duration and ICU or hospital stay. |
| 5   | Thiamine, Ascorbic Acid, and Hydrocortisone As a Metabolic Resuscitation Cocktail in Sepsis: A Meta-Analysis of Randomized Controlled Trials With Trial Sequential Analysis | Assouline B et al [49], 2021 | Switzerland     | Meta-analysis   | 8 RCTs           | 1335 patients        | Combination of thiamine, ascorbic acid, and hydrocortisone compared to patients with sepsis or septic shock | Data in this study was homogenous and intervention led to improved change in SOFA score at 72 h; however, there was no difference in ICU mortality and renal composite outcome (incidence of AKI 3 or need for Renal replacement therapy). |
| 6   | The Efficacy of vitamin C, thiamine, and corticosteroid therapy in adult sepsis patients: a systematic review and meta-analysis | Somagutta et al [50], 2021 | United States     | Meta-analysis   | 15 studies (8 RCTs and 7 cohort studies) | 67349 patients       | Combination of HAT treatment in patients with sepsis                                | Meta-analysis from RCTs concluded that hospital mortality, ICU stay, hospital stay, and renal replacement therapy was not significant. Results from cohort studies have also concluded that hospital mortality, ICU mortality, ICU length of stay, length of hospital stay, change in SOFA score, the use of renal replacement therapy, or vasopressor duration was not significant. |
| 7   | Vitamin C, Thiamine, and Hydrocortisone in the Treatment of Sepsis: A Meta-Analysis and Trial Sequential Analysis of Randomized Controlled Trials | Zayed et al [51], 2021 | United States     | Meta-analysis   | 6 RCTs           | 839 patients         | Vitamin C, thiamine, and steroid in combination for sepsis and septic shock          | Data from this study concluded that there is no significant difference in long term mortality, ICU mortality, incidence of acute kidney injury, hospital length of stay, ICU length of stay, and ICU free days on day 28 between the intervention and control groups. However, there was a significant reduction in SOFA score on 3rd day. |
| Study ID | Title                                                                 | Country       | Design          | No. of Participants | Results and Findings                                                                                                                                 |
|---------|----------------------------------------------------------------------|---------------|-----------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| 8       | Mortality in septic patients treated with vitamin C: a systematic meta-analysis | Germany       | Meta-analysis   | 3133 patients       | Vitamin C 1.5 g every 6 h, and 100 mg thiamine every 6 h, and 50 mg hydrocortisone every 6 h. However, initiation and duration of the intervention differed considerably within the studies. |
| 9       | Effect of adjunctive vitamin C, glucocorticoids, and vitamin B1 on longer-term mortality in adults with sepsis or septic shock: a systematic review and a component network meta-analysis | Japan         | Meta-analysis   | 10257 patients     | Compared networked interventions of very high dose vitamin C, high dose vitamin C, vitamin B1, and glucocorticoids.                                      |
| 10      | Steroid, ascorbic acid, and thiamine in adults with sepsis and septic shock: a systematic review and component network meta-analysis | Hong Kong     | Meta-analysis   | 9898 patients      | Additive network meta-analysis was performed, adding vitamin C, glucose corticoid, and thiamine sequentially.                                           |
| 11      | Effect of Combined Hydrocortisone, Ascorbic Acid and Thiamine for Patients with Sepsis and Septic Shock: A Systematic Review and Meta-Analysis | China         | Meta-analysis   | 1559 participants  | This study compared hydrocortisone, thiamine, and ascorbic acid use to usual care or hydrocortisone.                                                                 |
| 12      | Thiamine combined with vitamin C in sepsis or septic shock: a systematic review and meta-analysis | China         | Systematic review and meta-analysis | 868 patients      | Thiamine combined with vitamin C in patients with sepsis or septic shock.                                                                                          |

HAT: Hydrocortisone; ascorbic acid and thiamine combination; ICU: Intensive care unit; IV: Intravenous; RCT: Randomized control trial; SOFA: Sequential organ failure assessment score.

We know that sepsis is a syndrome and has proven to be a graveyard of various therapies modulating inflammation. The role of vitamin C, if there is, may be in the initial phase of hyperinflammation or cytokine storm associated with release of ROS. Besides, these RCTs used the heterogeneous cohort and failed to consider the sepsis phenotypes based on the level of inflammation. Finally, baseline vitamin C levels were not measured in all the trials, and a fixed dose therapy without measuring therapeutic levels may have caused inconsistent results.

In the absence of current evidence showing any clinical benefits, the recent surviving sepsis guidelines suggest against using vitamin C for managing patients with sepsis and septic shock[4]. The clinical practice at our institute is also in accordance to these latest recommendations and we refrain from making vitamin C a part of our routine sepsis management regimen. The future may be the individualization of these therapies using different disease models based on the aetiology of sepsis, illness severity, and degree of inflammation.
FURTHER TRIALS

Presently, there are more than 30 ongoing clinical trials to evaluate the effect of vitamin C in the management of sepsis and septic shock, in different parts of the world. These trials are evaluating the role of different doses (up to 12 g/d), different patient populations (alcoholic hepatitis, acute lung injury, and patients on invasive mechanical ventilation), and different combinations (along with steroids, thiamine, pyridoxine, or cyanocobalamine). Many of these are randomized multi-center trials (CEMVIS, REVISTA-DOSE, and C-EASIE) which may shed light on many of the unanswered questions regarding the utility of vitamin C in sepsis management. Ongoing studies in different cohorts, like patients with COVID-19 (LOVIT-COVID and REMAP-CAP), burn (VICTORY), post-cardiac arrest (VITaCCA), and/or cardiac surgery patients (advanceCSX) may answer the question of whether vitamin C can produce clinically meaningful outcomes in more specific patient populations.

CONCLUSION

Theoretically, vitamin C has been established to protect cells from oxidative damage, reduce inflammatory response, maintain immune functions, and increase the hemodynamic reserve. All these biological actions may be beneficial in the management of sepsis and septic shock. However, in the aftermath of recent interests and several multi-center trials, it can be concluded that there is still a lack of strong evidence to prove its clinical benefits. Contrary to popular belief, use of intravenous HDVC may rarely be associated with adverse effects like haemolysis, especially in vulnerable patients like those with G6PD deficiency or underlying renal dysfunction. Hence, routine use of HDVC is presently not recommended in the management of sepsis or septic shock.

FOOTNOTES

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REFERENCES

1. Gao L, Chong E, Pendharkar S, Phillips A, Ke L, Li W, Windsor JA. The Challenges and Effects of Ascorbic Acid Treatment of Acute Pancreatitis: A Systematic Review and Meta-Analysis of Preclinical and Clinical Studies. *Front Nutr* 2021; 8: 734558 [PMID: 34765629 DOI: 10.3389/fnut.2021.734558]

2. Martimbianco ALC, Pacheco RL, Bagattini ÂM, de Fátima Carreira Moreira Padovez R, Azvedo LCP, Riera R. Vitamin C-based regimens for sepsis and septic shock: Systematic review and meta-analysis of randomized clinical trials. *J Crit Care* 2022; 71: 154099 [PMID: 35763993 DOI: 10.1016/j.jcrc.2022.154099]

3. Zasowska-Nowak A, Nowak PJ, Ciałkowska-Rysz A. High-Dose Vitamin C in Advanced-Stage Cancer Patients. *Nutrients* 2021; 13 [PMID: 33652579 DOI: 10.3390/nu13030735]

4. Evans L, Rhodes A, Alhazzani W, Antonelli M, Coopersmith CM, French C, Machado FR, McIntyre L, Ostermann M, Prescott HC, Schorr C, Simpson S, Joost Wiersinga W, Alshamsi F, Angus DC, Arabi Y, Azvedo L, Beale R, Beilman G, Belley-Cote E, Burly L, Cecconi M, Centofanti J, Yataco AC, De Waele J, Dellingner RP, Doi K, Du B, Estenssoro E, Ferrer R, Gomersall C, Hodgson C, Möller MH, Iwashyna T, Jacob S, Kleinpell R, Klompas M, Koh Y, Kumar A, Kwizera A, Lobo S, Masur H, McGloughlin S, Mehta S, Mehta Y, Mer M, Nunnally M, Oczkowski S, Osborn T, Papananassoglou E, Perner A, Puskarich M, Roberts J, Schweickert W, Seckel M, Sevransky J, Sprung CL, Welte T, Zimmerman J, Levy M. Executive Summary: Surviving Sepsis Campaign: International Guidelines for the Management of Sepsis and Septic Shock.
5 Ranieri VM, Thompson BT, Barie PS, Dhainaut JF, Douglas IS, Finfer S, Gárdlund B, Marshall JC, Rhodes A, Artigas A, Payen D, Tenhunen J, Al-Khalidi HR, Thompson V, Janes J, Macias WL, Vangerow B, Williams MD. PROWESS-SHOCK Study Group. Drotrecogin alfa (activated) in adults with septic shock. N Engl J Med 2012; 366: 2055-2064 [PMID: 22616830 DOI: 10.1056/NEJMoa122290]

6 Wang H, Liu B, Tang Y, Chang P, Yao L, Huang B, Lodato RF, Liu Z. Improvement of Sepsis Prognosis by Ulinastatin: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. Front Pharmacol 2019; 10: 1370 [PMID: 31349646 DOI: 10.3389/fphar.2019.01370]

7 European Food Safety Authority Panel on Dietetic Products, Nutrition and Allergies. Scientific opinion on dietary reference values for vitamin C. EFSAs J 2013; 11: 3418 [DOI: 10.2903/j.efsa.2013.3418]

8 Carr AC, Rosengrave PC, Bayer S, Chambers S, Mehtrens J, Shaw GM. Hypovitaminosis C and vitamin C deficiency in critically ill patients despite recommended enteral and parenteral intakes. Crit Care 2017; 21: 300 [PMID: 29228951 DOI: 10.1186/s13054-017-1891-y]

9 Hyaluronidase therapy for acute myocardial infarction: results of a randomized, blinded, multicenter trial. MILIS Study Group. Am J Cardiol 1986; 57: 1236-1243 [PMID: 2872794 DOI: 10.1016/0002-9149(86)90392-3]

10 Carr AC, Shaw GM, Fowler AA, Natarajan R. Ascorbate-dependent vasopressor synthesis: a rationale for vitamin C administration in severe sepsis and septic shock? Crit Care 2015; 19: 418 [PMID: 26612352 DOI: 10.1186/s13054-015-1131-2]

11 Marik PE. Vitamin C for the treatment of sepsis: The scientific rationale. Pharmacol Ther 2018; 189: 63-70 [PMID: 29684467 DOI: 10.1016/j.pharmthera.2018.04.007]

12 Wilson JX. Mechanism of action of vitamin C in sepsis: ascorbate modulates redox signaling in endothelium. Biofactors 2009; 35: 5-13 [PMID: 19319840 DOI: 10.1002/biof.7]

13 Peng Y, Kwok KH, Yang PH, Ng SS, Liu J, Wong OG, He ML, Kung HF, Lin MC. Ascorbic acid inhibits ROS production, NF-kappa B activation and prevents ethanol-induced growth retardation and microencephaly. Neuropharmacology 2005; 48: 426-434 [PMID: 15721175 DOI: 10.1016/j.neuropharm.2004.10.015]

14 Kornberg MD, Levine M. New concepts in the biology and biochemistry of ascorbic acid. Science 2018; 360: 449-453 [PMID: 29599194 DOI: 10.1126/science.aan4665]

15 Levine M. New concepts in the biology and biochemistry of ascorbic acid. N Engl J Med 1986; 314: 892-902 [PMID: 35230161 DOI: 10.1056/NEJM198603141401407]

16 Lavillegrand JR, Raia L, Urbina T, Hariri G, Gabarre P, Bonny Y, Bigé N, Baudel JL, Brunelle A, Dupre T, Guidet B, Maury E, Ait-Oufella H. Vitamin C improves microvascular reactivity and peripheral tissue perfusion in septic shock patients. Crit Care 2022; 26: 25 [PMID: 35062987 DOI: 10.1186/s13054-022-03891-8]

17 Fowler AA 3rd, Truitt WD, Hite RD, Morris PE, DeWilde C, Prayde A, Fisher B, Thacker LR 2nd, Natarajan R, Brophy DF, Sculthorpe R, Nanchal R, Syed A, Sturgill J, Martin GS, Sevransky J, Kashiouris M, Hamman S, Egan KF, Hastings A, Spencer W, Tench S, Mehkiri O, Bindas J, Duggal A, Graf J, Zellner S, Yanny L, McPolin C, Hollith T, Kramer D, Ojielo C, Damm T, Cassidy E, Wieliczko A, Huilquent M. Effect of Vitamin C Infusion on Organ Failure and Biomarkers of Inflammation and Vascular Injury in Patients With Sepsis and Severe Acute Respiratory Failure: The CITRIS-ALI Randomized Controlled Trial. JAMA 2019; 322: 1261-1270 [PMID: 31573637 DOI: 10.1001/jama.2019.11825]

18 Ly SJ, Zhang GH, Xia JM, Yu H, Zhao F. Early use of high-dose vitamin C is beneficial in treatment of sepsis. Ir J Med Sci 2021; 190: 1183-1188 [PMID: 33904466 DOI: 10.1007/s11845-020-02394-1]

19 Rosemberg J, Specker E, Willimans J, Mehtrens T, Morgan S, Doyle T, Van Der Heyden K, Van Der Heyden B, Carr AC. Intravenous vitamin C administration to patients with septic shock: a pilot randomised controlled trial. Crit Care 2022; 26: 30573968 [PMID: 10.1186/s13054-022-03900-w]

20 Lamontagne F, Masse MH, Menard J, Sprague S, Pinto R, Heyland DK, Cook DJ, Battista MC, Day AG, Guyatt GH, Battista MC, Day AG, Guyatt GH, Hoeven DJ, Heyland DK, Cook DJ, Fazio VW. Vitamin C for the treatment of sepsis: The scientific rationale. JAMA 2012; 308: 1261-1270 [PMID: 35704292 DOI: 10.1056/NEJMoa2200644]

21 Ferron-Celma I, Mansilla A, Hassan L, Garcia-Navarro A, Comino AM, Bueno P, Ferron JA. Effect of vitamin C administration on neutrophil apoptosis in septic patients after abdominal surgery. J Surg Res 2009; 153: 224-230 [PMID: 18952228 DOI: 10.1016/j.jss.2008.04.024]

22 Marik PE, Khangoora V, Rivera R, Hooper MH, Catravas J. Hydrocortisone, Vitamin C, and Thiamine for the Treatment of Severe Sepsis and Septic Shock: A Retrospective Before-After Study. Chest 2017; 151: 1229-1238 [PMID: 27940189 DOI: 10.1016/j.chest.2016.11.036]

23 Fuji T, Lueht J, Young PJ, Frei DR, Eastwood GM, French CJ, Deane AM, Shehabi Y, Hajjar LA, Oliveira G, Udy AA, Shaw GM, Fowler AA, Natarajan R. Ascorbate-dependent vasopressor synthesis: a rationale for vitamin C administration in sepsis. Crit Care Med 2020; 48: 892-902 [PMID: 31590997 DOI: 10.1016/j.ccm.2019.22176]

24 Moskowitz A, Huang DT, Hou PC, Gong J, Doshi PB, Grossestreuer AV, Anderson LW, Ngo L, Sherwin RL, Berg KM, Chase M, Cocchi MN, McCannon JB, Hershey M, Hilewitz A, Korotun M, Becker LB, Otero RM, Udoman J, Sen A, Donnini MW; ACTS Clinical Trial Investigators. Effect of Ascorbic Acid, Corticosteroids, and Thiamine on Organ Injury in Septic Shock: The ACTS Randomized Clinical Trial. JAMA 2020; 324: 642-650 [PMID: 32809003 DOI: 10.1001/jama.2020.11946]
Sevranisky JE, Rothman RE, Hager DN, Bernard GR, Brown SM, Buchman TG, Busse LW, Coopersmith CM, DeWilde C, Ely EW, Eyzaguirre LM, Fowler AA, Gaieski DF, Gong MN, Hall A, Hinson JS, Hooper MH, Kelen GD, Khan A, Levine MA, Lewis RJ, Lindsell CJ, Martin JS, McGlothlin A, Moore BL, Nagert KL, Nwosu S, Polito CC, Rice TW, Ricketts EP, Rudolph CC, Sanfilippo F, Viele K, Martin GS, Wright DW. VICTAS Investigators. Effect of Vitamin C, Thiamine, and Hydrocortisone on Ventilator- and Vasopressor-Free Days in Patients With Sepsis: The VICTAS Randomized Clinical Trial. Jama 2021;325:742-750 [PMID:33620456 DOI:10.1001/jama.2020.24505]

Hwang SY, Ryoo SM, Park JE, Jo YH, Jung DH, Suh GJ, Kim T, Kim YJ, Kim S, Cho H, Jo LJ, Chung SP, Choi SH, Shin TG, Kim WY. Korean Shock Society (KoSS). Combination therapy of vitamin c and thiamine for septic shock: a multicentre, double-blinded, randomized, controlled study. Intensive Care Med 2020; 46: 2015-2025 [PMID:32780166 DOI:10.1007/s00134-020-06191-3]

Ap GR, Daga MK, Mawari G, Koner BC, Singh VK, Kumar N, Rohatgi I, Mishra R. Effect of Supplementation of Vitamin C and Thiamine on the Outcome in Sepsis: South East Asian Region. J Assoc Physicians India 2022; 70: 11-12 [PMID:35438278]

Aisa-Alvarez A, Soto ME, Guarner-Lans V, Camarena-Alejo G, Franco-Granillo J, Martinez-Rodriguez EA, Gamboa Ávila R, Manzano Pech L, Pérez-Torres I. Usefulness of Antioxidants as Adjuvant Therapy for Septic Shock: A Randomized Clinical Trial. Medicina (Kaunas) 2020; 56: [PMID:33213070 DOI:10.3390/medicina56101691]

Iglesias J, Vassallo AV, Patel PV, Sullivan JB, Cavanaugh J, Elbaga Y. Outcomes of Metabolic Resuscitation Using Ascorbic Acid, Thiamine, and Glucocorticoids in the Early Treatment of Sepsis: The ORANGES Trial. Chest 2020; 158: 164-173 [PMID:32194058 DOI:10.1016/j.chest.2020.02.049]

Wani SJ, Mufti SA, Jan RA, Shah SU, Qadri SM, Khan UH, Bugdadi F, Mefhooz N, Kouli PA. Combination of vitamin C, thiamine and hydrocortisone added to standard treatment in the management of sepsis: results from an open label randomised controlled clinical trial and a review of the literature. Infect Dis (Lond) 2020; 52: 271-278 [PMID:31990246 DOI:10.1080/23744235.2020.1718200]

Galley HF, Howdle PD, Walker BE, Webster NR. The effects of intravenous antioxidants in patients with septic shock. Free Radic Biol Med 1997; 23: 768-774 [PMID:9296454 DOI:10.1016/S0891-5849(97)00059-2]

Chang P, Liao Y, Guan J, Guo Y, Zhao M, Hu J, Zhou J, Wang H, Cen Z, Tang Y, Liu Z. Combined Treatment With Hydrocortisone, Vitamin C, and Thiamine for Sepsis and Septic Shock: A Randomized Controlled Trial. Chest 2020; 158: 174-182 [PMID:32243943 DOI:10.1016/j.chest.2020.02.065]

Mohamed ZU, Prasannan P, Moni M, Edathadathil F, Prasanna P, Menon A, Nair S, Greeshma CR, Sathyapalan DT, Menon V. Vitamin C Therapy for Routine Care in Sepsis (ViCTOR) Trial: Effect of IntraVenous Vitamin C, Thiamine, and Hydrocortisone Administration on Inpatient Mortality in Patients with Sepsis. Indian J Crit Care Med 2020; 24: 653-661 [PMID:33024370 DOI:10.5005/jp-journals-10071-23517]

Park JE, Jo YH, Hwang SY, Kim WY, Ryoo SM, Jung DH, Kim T, Kim YJ, Kim S, Cho H, Lee GT, Chung SP, Choi SH, Shin TG, Suh GJ, Korean Shock Society (KoSS) Investigators. Biomarker Analysis for Combination Therapy of Vitamin C and Thiamine in Septic Shock: A Post-Hoc Study of the ATESS Trial. Shock 2022; 57: 81-87 [PMID:34482319 DOI:10.1097/SHK.0000000000018589]

McCune TR, Toeppe AJ, Sheehan BE, Sherani MSK, Peri ST, Dodani S. High dose intravenous vitamin c treatment in sepsis: associations with acute kidney injury and mortality. BMC Nephrol 2021; 22: 387 [PMID:34800992 DOI:10.1186/s12882-021-02599-1]

Hudson EP, Collie JT, Fuji T, Luethi N, Udy AA, Doherty S, Eastwood G, Yanase F, Naorungroj T, Bitker L, Abdelhamid YA, Greaves RF, Deane AM, Bellomo R. Pharmacokinetic data support 6-hourly dosing of intravenous vitamin c to critically ill patients with septic shock. Crit Care Resusc 2019; 21: 236-242 [PMID:31778629]

Smith KE, Brown CS, Manning BM, May T, Riker RR, Lerwick PA, Hayes TL, Fraser GL. Accuracy of Point-of-Care Blood Glucose Level Measurements in Critically Ill Patients with Sepsis Receiving High-Dose Intravenous Vitamin C. Pharmacotherapy 2018; 38: 1155-1161 [PMID:30230568 DOI:10.1002/phar.2182]

He J, Zheng G, Qian X, Sheng H, Chen B, Zhao B, Chen E, Mao X, Bian X. Effect of high-dose intravenous vitamin c on point-of-care blood glucose level in septic patients: a retrospective, single-center, observational case series. Curr Med Res Opin 2021; 37: 555-565 [PMID:33568093 DOI:10.1080/03007995.2021.1887832]

Fowler AA 3rd, Syed AA, Knowslon S, Sculthorpe R, Farthing C, DeWilde C, Farthing CA, Larus TL, Martin E, Brophy DF, Gupta S; Medical Respiratory Intensive Care Unit Nursing, Fisher BJ, Natarajan R. Phase I safety trial of intravenous ascorbic acid in patients with severe sepsis. J Transl Med 2014; 12: 32 [PMID:24484547 DOI:10.1186/1479-5876-12-32]

Chang K, Harbin M, Shuster C, Griesdale DEG, Foster D, Sweet D, Wood MD, Dhingra VK. Adding vitamin C to hydrocortisone lacks benefit in septic shock: a historical cohort study. Can J Anaesth 2020; 67: 1798-1805 [PMID:32959746 DOI:10.1007/s12630-020-01814-1]

Dalfino L, Puntillo F, Ondok MJ, Mosca A, Monno R, Coppolecchia S, Spada ML, Bruno F, Brienza N. Colistin-Associated Acute Kidney Injury in Severely Ill Patients: A Step Toward a Better Renal Care? Clin Infect Dis 2015; 61: 1771-1777 [PMID:26354965 DOI:10.1093/cid/cv1717]

Cohen J, Bellomo R, Billot L, Burrell LM, Evans DM, Finfer S, Hammond NE, Li Q, Liu D, McArthur C, McWhinney B, Moore I, Myburgh J, Peake S, Pretorius C, Rajbhandari D, Rhodes A, Saxena M, Ungerer JPI, Young MJ, Venkatesh B, Plasma Cortisol, Aldosterone, and Ascorbic Acid Concentrations in Patients with Septic Shock Do Not Predict Treatment Effect of Hydrocortisone on Mortality. A Nested Cohort Study. Am J Respir Crit Care Med 2020; 202: 700-707 [PMID:32396775 DOI:10.1164/rcrm.202002-0281OC]

Gardner R, Liu X, Wang Y, Cole A, Heyrickson S, Dommo MW, Moskovitz A. Vitamin C levels amongst initial survivors of out of hospital cardiac arrest. Resuscitation 2020; 156: 190-193 [PMID:32946985 DOI:10.1016/j.resuscitation.2020.09.005]

Agarwal A, Basmajj J, Fernando SM, Ge FZ, Xiao Y, Faisal H, Honarmand K, Hylands M, Lau VI, Lewis K, Couban R, Lamontagne F, Adhikari NK. Parenteral Vitamin C in Patients with Severe Infection: A Systematic Review. NEJM Evidence 2022 ahead of print. [DOI:10.1056/NEJMed.2200105]

Patel JJ, Ortiz-Reyes A, Dhalwai R, Clarke J, Hill A, Stoppe C, Lee ZY, Heyland DK. IV Vitamin C in Critically Ill
Patients: A Systematic Review and Meta-Analysis. Crit Care Med 2022; 50: e304-e312 [PMID: 34637420 DOI: 10.1097/CMM.0000000000005320]

Wei XB, Wang ZH, Xiao XL, Guo WX, Wen JY, Qin TH, Wang SH. Efficacy of vitamin C in patients with sepsis: An updated meta-analysis. Eur J Pharmacol 2020; 868: 172889 [PMID: 31870831 DOI: 10.1016/j.ejphar.2019.172889]

Li T, Zeng J, Li DH, Yang GY, Wang K, Deng HF, Jiang H. Efficacy of intravenous patients with septic shock: A systematic review and meta-analysis based on randomized controlled trials. Am J Emerg Med 2021; 50: 242-250 [PMID: 34416515 DOI: 10.1016/j.ajem.2021.08.012]

Feng F, Yang H, Yang W, Li M, Chang X, Chen Y. Effect of vitamin C in critically ill patients with sepsis and septic shock: A meta-analysis. Sci Prog 2021; 104: 36850421998175 [PMID: 33787414 DOI: 10.1177/0036850421998175]

Assouline B, Faivre A, Verissimo T, Sangla F, Berchtold L, Giraud R, Bendjelid K, Sgardello S, Elia N, Pugin J, de Seigneuws S, Legouis D. Thiamine, Ascorbic Acid, and Hydrocortisone As a Metabolic Resuscitation Cocktail in Sepsis: A Meta-Analysis of Randomized Controlled Trials With Trial Sequential Analysis. J Crit Care 2021; 49: 2112-2120 [PMID: 34582409 DOI: 10.1016/j.jcc.2021.07.030]

Somagutta MKR, Pormento MKL, Khan MA, Hamdan A, Hange N, Ke M, Pagad S, Jain MS, Lingarajah S, Sharma V, Kaur J, Emuze B, Batti E, Iloeje OJ. The Efficacy of vitamin C, thiamine, and corticosteroid therapy in adult sepsis patients: a systematic review and meta-analysis. Acute Crit Care 2021; 36: 185-200 [PMID: 34185986 DOI: 10.4266/acc.2021.00108]

Zayed Y, Alzghoul BN, Banifadel M, Venigandla H, Hyde R, Sutchu S, Khawsonwne M, Borok Z, Urbin D, Jantz M, Reddy R. Vitamin C, Thiamine, and Hydrocortisone in the Treatment of Sepsis: A Meta-Analysis and Trial Sequential Analysis of Randomized Controlled Trials. J Intensive Care Med 2022; 37: 327-336 [PMID: 33511898 DOI: 10.1177/0885066621987890]

Scholz SS, Horgestadt R, Ebeling N, Menzel LC, Jansen G, Rehberg S. Mortality in septic patients treated with vitamin C: a systematic meta-analysis. Crit Care 2021; 25: 17 [PMID: 33407793 DOI: 10.1186/s13054-020-03438-9]

Fujii T, Salanti G, Belletti A, Bellomo R, Carr A, Furukawa TA, Luethi N, Luo Y, Putza A, Sartini C, Tsujimoto Y, Udy AA, Yanase F, Young PJ. Effect of adjunctive vitamin C, glucocorticoids, and vitamin B1 on longer-term mortality in adults with sepsis or septic shock: a systematic review and a component network meta-analysis. Intensive Care Med 2022; 48: 16-24 [PMID: 34750650 DOI: 10.1007/s00134-021-06558-0]

Fong KM, Au SY, Ng GWY. Steroid, ascorbic acid, and thiamine in adults with sepsis and septic shock: a systematic review and component meta-analysis. Sci Rep 2021; 11: 15777 [PMID: 34349184 DOI: 10.1038/s41598-021-95386-9]

Wu T, Hu C, Huang W, Xu Q, Hu B, Li J. Effect of Combined Hydrocortisone, Ascorbic Acid and Thiamine for Patients with Sepsis and Septic Shock: A Systematic Review and Meta-Analysis. Shock 2021; 56: 880-889 [PMID: 34529397 DOI: 10.1097/SHK.0000000000001781]

Ge Z, Huang J, Liu Y, Xiang J, Gao Y, Walline JH, Lu X, Yu S, Zhao L, Li Y. Thiamine combined with vitamin C in sepsis or septic shock: a systematic review and meta-analysis. Eur J Emerg Med 2021; 28: 189-195 [PMID: 33709993 DOI: 10.1097/EEM.0000000000002612]

Kwak SG, Choo YJ, Chang MC. The effectiveness of high-dose intravenous vitamin C for patients with coronavirus disease 2019: A systematic review and meta-analysis. Complement Ther Med 2022; 64: 102797 [PMID: 34953366 DOI: 10.1016/j.ctim.2021.102797]

Wang Y, Lin H, Lin BW, Lin JD. Effects of different ascorbic acid doses on the mortality of critically ill patients: a meta-analysis. Ann Intensive Care 2019; 9: 58 [PMID: 31111241 DOI: 10.1186/s13613-019-0532-9]

Hemilä H, Chalker E. Vitamin C Can Shorten the Length of Stay in the ICU: A Meta-Analysis. Nutrients 2019; 11 [PMID: 30934660 DOI: 10.3390/nu11040708]

Hemilä H, Chalker E. Vitamin C may reduce the duration of mechanical ventilation in critically ill patients: a meta-regression analysis. J Intensive Care 2020; 8: 15 [PMID: 32047636 DOI: 10.1186/s40560-020-00432-y]

Juneja D, Jain R, Nasa P. Vitamin C-induced Hemolysis: Meta-summary and Review of Literature. Indian J Crit Care Med 2022; 26: 224-227 [PMID: 35712748 DOI: 10.5005/jp-journals-10071-24111]

Padayatty SJ, Sun AY, Chen Q, Espey MG, Drisko J, Levine M. Vitamin C: intravenous use by complementary and alternative medicine practitioners and adverse effects. PLoS One 2010; 5: e11414 [PMID: 20626560 DOI: 10.1371/journal.pone.0011414]

Yanase F, Fujii T, Naorungroj T, Belletti A, Luethi N, Carr AC, Young PJ, Bellomo R. Harm of IV High-Dose Vitamin C Therapy in Adult Patients: A Scoping Review. Crit Care Med 2020; 48: e620-e628 [PMID: 32040636 DOI: 10.1097/CMM.0000000000004396]

Zheng ZZ, Lee EE, Sudderth J, Yue Y, Zia A, Glass D, Deberardinis RJ, Wang RC. Glutathione Depletion, Pentose Phosphate Pathway Activation, and Hemolysis in Erythrocytes Protecting Cancer Cells from Vitamin C-induced Oxidative Stress. J Biol Chem 2016; 291: 22861-22867 [PMID: 27660392 DOI: 10.1074/jbc.C116.748848]

Wilson JX. The physiological role of dehydroascorbic acid. FEBS Lett 2002; 527: 5-9 [PMID: 12220624 DOI: 10.1016/s0016-5793(02)03167-8]
