

Hydrocortisone, Vitamin C, and Thiamine for the Treatment of Severe Sepsis and Septic Shock



A Retrospective Before-After Study



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BACKGROUND: The global burden of sepsis is estimated as 15 to 19 million cases annually, with a mortality rate approaching 60% in low-income countries.

METHODS: In this retrospective before-after clinical study, we compared the outcome and clinical course of consecutive septic patients treated with intravenous vitamin C, hydrocortisone, and thiamine during a 7-month period (treatment group) with a control group treated in our ICU during the preceding 7 months. The primary outcome was hospital survival. A propensity score was generated to adjust the primary outcome.

RESULTS: There were 47 patients in both treatment and control groups, with no significant differences in baseline characteristics between the two groups. The hospital mortality was 8.5% (4 of 47) in the treatment group compared with 40.4% (19 of 47) in the control group ($P < .001$). The propensity adjusted odds of mortality in the patients treated with the vitamin C protocol was 0.13 (95% CI, 0.04-0.48; $P = .002$). The Sepsis-Related Organ Failure Assessment score decreased in all patients in the treatment group, with none developing progressive organ failure. All patients in the treatment group were weaned off vasopressors, a mean of 18.3 ± 9.8 h after starting treatment with the vitamin C protocol. The mean duration of vasopressor use was 54.9 ± 28.4 h in the control group ($P < .001$).

CONCLUSIONS: Our results suggest that the early use of intravenous vitamin C, together with corticosteroids and thiamine, are effective in preventing progressive organ dysfunction, including acute kidney injury, and in reducing the mortality of patients with severe sepsis and septic shock. Additional studies are required to confirm these preliminary findings.

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KEY WORDS: corticosteroid; hydrocortisone; septic shock; thiamine; vitamin C

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ABBREVIATIONS: AKI = acute kidney injury; APACHE = Acute Physiology and Chronic Health Evaluation; D5W = dextrose 5% in water; EHR = electronic health record; LOS = length of stay; PCT = procalcitonin; SOFA = Sepsis-Related Organ Failure Assessment; SVCT2 = sodium-vitamin C transporter-2

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The global burden of sepsis is substantial with an estimated 15 to 19 million cases per year; the vast majority of these cases occur in low-income countries.¹ With more timely diagnosis and improvement in supportive care the 28-day mortality from sepsis in high-income countries has declined to about 25%; however, the mortality rate from septic shock remains as high as 50%.²⁻⁵ Moreover, the mortality from sepsis and septic shock in low-income countries is approximately 60%.⁶⁻⁸ In addition to short-term mortality, septic patients suffer from numerous short- and long-term complications, with reduced quality of life and an increased risk of death up to 5 years following the acute event.⁹⁻¹¹ Over the last 3 decades, more than 100 phase 2 and phase 3 clinical trials have been performed testing various novel pharmacologic agents and therapeutic interventions in an attempt to improve the outcome of patients with severe sepsis and septic shock; all of these efforts ultimately failed to produce a novel pharmacologic agent that improved the outcome of sepsis.¹² New therapeutic approaches to sepsis are desperately required. To impact the global burden of sepsis these interventions should be effective, inexpensive, safe, and readily available. We were confronted with three patients with fulminant sepsis who were almost certainly destined to die from overwhelming septic shock. On the basis of experimental

and emerging clinical data, we decided to administer intravenous vitamin C to these patients as a life-saving measure.¹³⁻¹⁷ “Moderate-dose” hydrocortisone was added for its theoretical synergistic benefit. All three of these patients made a dramatic recovery and were discharged from the ICU within days with no residual organ dysfunction. On the basis of this experience and the reported safety and potential benefit of this therapeutic intervention, the combination of intravenous vitamin C and corticosteroid became routinely used as adjunctive therapy for the treatment of severe sepsis and septic shock in our ICU. Patients with sepsis predictably have very low serum vitamin C levels, which can only be corrected with intravenous vitamin C at a dose of more than 3 g/d.^{16,18,19} On the basis of published clinical data, vitamin C pharmacokinetic modeling, as well as the package insert, we decided to administer 6 g of vitamin C per day, divided in four equal doses.^{16,18-23} This dosage is devoid of any reported complications or side effects. Doses as high as 100 to 150 g have been safely administered to patients with burns and malignancy.^{17,24,25} Hydrocortisone was dosed according to the consensus guidelines of the American College of Critical Care Medicine.²⁶ Intravenous thiamine (vitamin B₁) was added to the vitamin C protocol (see the Discussion section for rationale).²⁷

Methods

This study was an electronic health record (EHR)-based retrospective before-after clinical study.²⁸ The study was approved by our institutional review board (#16-08-WC-0179) and the Sentara Health System Office of Research (16-08-SRC-88) (see study protocol e-Appendix 1). This study was conducted at Sentara Norfolk General Hospital, a tertiary care referral hospital affiliated with Eastern Virginia Medical School and the only tertiary care facility in the Hampton Roads area, serving a population of approximately 1.8 million people. Between January 2016 and July 2016, consecutive patients admitted to the Eastern Virginia Medical School Critical Care Medicine service in the general ICU at Sentara Norfolk General Hospital with a primary diagnosis of severe sepsis or septic shock and a procalcitonin (PCT) level ≥ 2 ng/mL were treated with intravenous hydrocortisone, vitamin C, and thiamine (vitamin C protocol) within 24 h of ICU admission (treatment group). PCT is routinely measured in our hospital as a screening tool for sepsis and to monitor the evolution of the disease.²⁹⁻³² PCT is measured in our laboratory using the VIDAS B·R·A·H·M·S PCT assay, a one-step immunoassay sandwich method with final fluorescence detection (bioMérieux); the lower limit of PCT detection was 0.05 ng/mL. Septic patients with a PCT level < 2 ng/mL within the first 24 h of ICU admission were not treated with the vitamin C protocol. We used a threshold PCT level of 2 ng/mL to increase the certainty that the patients had severe sepsis and were at risk of developing sepsis-related organ dysfunction.³²⁻³⁴ Patients < 18 years of age, pregnant patients, and patients with limitations of care were not treated with

the vitamin C protocol. The control group consisted of a similar number of consecutive patients admitted to our ICU between June 2015 and December 2015, using the same inclusion and exclusion criteria as the treatment group. During the control period, patients with sepsis did not receive intravenous vitamin C or thiamine. The diagnoses of severe sepsis and septic shock were based on the 1992 American College of Chest Physicians/Society of Critical Care Medicine Consensus Conference definitions.³⁵

We queried our EHRs (Epic Systems) to identify patients who met the inclusion criteria for the treatment and control groups. The patients' clinical and demographic data, including age, sex, admitting diagnosis, comorbidities, requirement for mechanical ventilation, use of vasopressors (and hourly dosages), daily urine output (for the first 4 days), fluid balance after 24 and 72 h, length of ICU stay (LOS), and laboratory data, were abstracted from the EHR. Patients were considered immunocompromised if they were taking more than 10 mg of prednisone-equivalent per day for at least 2 weeks, were receiving cytotoxic therapy, or were diagnosed with acquired immunodeficiency syndrome. The hourly dosage of vasopressors was recorded as the norepinephrine equivalent dosage.^{36,37} The serum creatinine, WBC, platelet count, total bilirubin, PCT, and lactate levels were recorded daily for the first 4 days. Acute kidney injury (AKI) was defined on the basis of KDIGO (Kidney Disease: Improving Global Outcomes) criteria; namely, an increase in serum creatinine > 0.3 mg/dL or a level > 1.5 times the baseline value.³⁸ If the baseline serum creatinine was not known a value > 1.5 mg/dL was assumed to be indicative of AKI. The patient's admission

APACHE (Acute Physiology and Chronic Health Evaluation) II and APACHE IV scores, including the APACHE IV predicted hospital mortality, were recorded. The APACHE II score (incrementing score of 0 to 71) and APACHE IV score (incrementing score of 0 to 286) are standardized measures of disease severity that are used to predict hospital mortality.^{39,40} The SOFA (Sepsis-Related Organ Failure Assessment) score was calculated daily for 4 days. The SOFA score was designed to sequentially assess the severity of organ dysfunction in patients who were critically ill from sepsis (incrementing score of 0 to 24).⁴¹ The SOFA scores were calculated 24 h after admission to the ICU and daily thereafter.

ICU Treatment Protocol

The overall treatment of patients with sepsis during the control and treatment periods was similar except for the administration of the combination of vitamin C, hydrocortisone, and thiamine during the treatment period.⁴² There were no known significant changes to our ICU protocols, referral patterns, or patient population during the study period. During the control period patients received hydrocortisone (50 mg every 6 h) at the discretion of the attending physician.^{26,42,43} As per standard operating procedure in our ICU, all patients with sepsis and septic shock are started empirically on broad-spectrum antibiotics, which are then deescalated according to microbiologic data and clinical progress⁴⁴; are treated according to a conservative, physiologically based fluid and vasopressor strategy^{45,46}; and are ventilated according to a lung-protective strategy,^{46,47} avoiding hyperoxia⁴⁸ and with the limited use of sedative agents (preferred agent, dexmedetomidine).⁴⁹ Norepinephrine is the vasopressor of first choice and is titrated to a dose of 20 µg/min, targeting a mean arterial pressure > 65 mm Hg. In patients failing to achieve this target, fixed-dose vasopressin was then added at 0.04 units/min followed by phenylephrine or epinephrine.^{42,45} Patients receive enteral nutrition with a whey-based formula (Vital 1.2; Abbott), using an intermittent bolus protocol that is started 24 h after ICU admission; once clinical stability is achieved,^{50,51} they receive deep venous thrombosis prophylaxis with both enoxaparin (or heparin in patients with a calculated creatinine clearance < 30 mL/min) and sequential compression, and we allow permissive hyperglycemia.⁵² Routine stress ulcer prophylaxis is not administered.⁵³ During the treatment period consecutive patients with a primary admitting diagnosis of severe sepsis or septic shock and a PCT level > 2 ng/mL were treated with intravenous vitamin C (1.5 g every 6 h for 4 days or until ICU discharge), hydrocortisone (50 mg every 6 h for 7 days or until ICU discharge followed by a taper over 3 days), as well as intravenous thiamine (200 mg every 12 h for 4 days or until ICU discharge). The vitamin C was administered as an infusion over 30 to 60 min and mixed in a 100-mL solution of either dextrose 5% in water (D5W) or normal saline.

Intravenous thiamine was given as a piggyback in 50 mL of either D5W or normal saline and was administered as a 30-min infusion. We attempted to determine the vitamin C level prior to the first dose of vitamin C. The vitamin C assay was performed at LabCorp by high-pressure liquid chromatography with electrochemical detection. The specimens were collected in a serum separation gel tube, protected from light, and transported on ice. The specimens were frozen prior to transport to the local reference laboratory (LabCorp).

Data Analysis

The first three “pivotal” patients treated with the vitamin cocktail were excluded from analysis. The patients’ deidentified clinical and laboratory data were recorded in an electronic spreadsheet. The primary outcome was hospital survival. Secondary outcomes included duration of vasopressor therapy,⁵⁴ requirement for renal replacement therapy in patients with AKI, ICU LOS, and the change in serum PCT and SOFA score over the first 72 h.^{30,55-58} The procalcitonin clearance was calculated according to the following formula: initial PCT minus PCT at 72 h, divided by the initial PCT multiplied by 100.^{57,59} Summary statistics were used to describe the clinical data and are presented as means ± SD, medians and interquartile range, or percentages as appropriate. χ^2 analysis with Fisher’s exact test (when appropriate) and Student’s *t* test (Mann-Whitney *U* test for nonnormal distributions) were used to compare data between the treatment and control groups, with statistical significance declared for probability values of 0.05 or less. Logistic discriminant analysis was performed on the entire data set to determine the independent predictors of survival. Statistical analysis was performed with NCSS 11 (NCSS Statistical Software) and SPSS Statistics version 24 (IBM).

To adjust for potential baseline differences between the treatment and control groups, SPSS Statistics was used to generate propensity scores for the patients’ likelihood to receive the vitamin C protocol. Factors included in propensity score generation included age, weight, sex, APACHE IV score, need for mechanical ventilation at presentation, use of vasopressor agents at presentation, WBC count at presentation, serum lactate level at presentation, procalcitonin level at presentation, and serum creatinine at presentation (e-Table 1). Binary logistic regression with propensity score adjustment was then performed to assess the odds ratio for mortality by treatment group.⁶⁰ This analysis was then repeated with both age and propensity score adjustments to assess the odds ratio for mortality (e-Table 2). The propensity score distribution for the treatment and control groups is presented in e-Figure 1, while the APACHE IV distribution between the treatment and control groups is presented in e-Figure 2.

Results

There were 47 patients in each group. The baseline characteristics of the two groups are presented in Table 1; there were no significant differences in baseline characteristics between the two groups. Most patients had multiple comorbidities, with only two patients in the treatment group and one in the control group being previously “healthy.” The distribution of infections was similar between the two groups, with the lung being the most common site of infection. Blood cultures were positive in 13 patients (28%) in each group. *Escherichia coli* (n = 6) and gram-positive organisms (n = 3) were

the commonest blood isolates in the treatment group while gram-positive organisms (n = 6) and *E coli* (n = 4) were the commonest isolates in the control group. Correctly timed baseline vitamin C levels were available for 22 patients in the treatment group; the mean level was 14.1 ± 11.8 µM (normal, 40-60 µM), with no patient having a normal level. Twenty-two patients (47%) in each group were treated with vasopressor agents and met the criteria for septic shock. The primary and secondary outcomes are provided in Table 2. The hospital mortality was 8.5% (4 of 47 patients) in the treatment group compared with

TABLE 1] Baseline Characteristics of Treated and Control Patients

Variable	Treated (n = 47)	Control (n = 47)
Age, mean ± SD, y	58.3 ± 14.1	62.2 ± 14.3
Sex, male, No. (%)	27 (57)	23 (49)
Comorbidities, No. (%)		
None	2 (4)	1 (2)
Diabetes	16 (34)	20 (42)
Hypertension	20 (43)	25 (53)
Heart failure	15 (32)	16 (34)
Malignancy	5 (11)	7 (15)
COPD	8 (17)	7 (15)
Cirrhosis	6 (13)	3 (6)
CVA	8 (17)	5 (11)
CRF	7 (15)	8 (17)
Morbid obesity	6 (13)	8 (17)
Immunocompromised ^a	6 (13)	4 (9)
Drug addiction	5 (11)	5 (11)
Primary diagnosis, No. (%)		
Pneumonia	18 (38)	19 (40)
Urosepsis	11 (23)	10 (21)
Primary bacteremia	7 (15)	7 (15)
GI/biliary	6 (13)	6 (13)
Other	5 (11)	5 (11)
Mechanical ventilation, No. (%)	22 (47)	26 (55)
Vasopressors, No. (%)	22 (46)	22 (46)
Acute kidney injury, No. (%)	31 (66)	30 (64)
Positive blood cultures, No. (%)	13 (28)	13 (28)
WBC, ^b mean ± SD, × 10 ⁹	20.6 ± 13.5	17.1 ± 13.4
Lactate, mean ± SD, mM	2.7 ± 1.5	3.1 ± 2.8
Creatinine, ^c mean ± SD, mg/dL	1.9 ± 1.4	1.9 ± 1.1
Procalcitonin, median and IQR, ng/ml	25.8 (5.8-93.4)	15.2 (5.9-39.0)
Day 1 SOFA, mean ± SD	8.3 ± 2.8	8.7 ± 3.7
APACHE II, mean ± SD	22.1 ± 6.3	22.6 ± 5.7
APACHE IV, mean ± SD	79.5 ± 16.4	82.0 ± 27.4
Predicted mortality, mean ± SD	39.7 ± 16.7	41.6 ± 24.2

There were no significant differences in baseline characteristics between groups. APACHE = Acute Physiology and Chronic Health Evaluation; CRF = chronic respiratory failure; CVA = cerebrovascular accident; IQR = interquartile range; SOFA = Sepsis-Related Organ Failure Assessment.

^aHIV infection, neutropenia, post-transplantation, and so on.

^bExcluding neutropenic patients.

^cExcluding patients with chronic renal failure.

40.4% (19 of 47 patients) in the control group ($P < .001$). The predicted and actual mortality for the treatment and control groups is illustrated in [Figure 1](#). Logistic discriminant analysis identified three independent predictors of mortality, namely, treatment with the vitamin C protocol (F value, 17.33; $P < .001$), the APACHE IV score (F value, 13.29; $P < .001$), and

need for mechanical ventilation (F value, 3.75; $P = .05$). The propensity adjusted odds of mortality in patients treated with the vitamin C protocol was 0.13 (95% CI, 0.04-0.48; $P = .002$). None of the patients in the treatment group died of complications related to sepsis. All these patients survived their ICU stay, received “comfort care” on the hospital floor, and died of

TABLE 2] Outcome and Treatment Variables

Variable	Treated (n = 47)	Control (n = 47)
Hospital mortality, No. (%)	4 (8.5)	19 (40.4) ^a
ICU LOS, median and IQR, d	4 (3-5)	4 (4-10)
Duration of vasopressors, mean ± SD, h	18.3 ± 9.8	54.9 ± 28.4 ^a
RRT for AKI, No. (%)	3 of 31 (10%)	11 of 30 (33%) ^b
ΔSOFA, 72 h	4.8 ± 2.4	0.9 ± 2.7 ^a
Procalcitonin clearance, median % and IQR, 72 h	86.4 (80.1-90.8)	33.9 (-62.4 to 64.3) ^a

AKI = acute kidney injury; LOS = length of stay; RRT = renal replacement therapy; ΔSOFA = change in Sepsis-Related Organ Failure Assessment score. See Table 1 legend for expansion of other abbreviations.

^aP < .001.

^bP = .02.

complications of their underlying disease (advanced dementia, severe heart failure, advanced sarcoidosis, and severe COPD).

Twenty-eight patients (59.6%) in the control group were treated with hydrocortisone. Thirty-one patients (66%) in the treatment group met the criteria for AKI compared with 30 (64%) in the control group (not significantly different). Three patients (10%) with AKI in the treatment group required renal replacement therapy compared with 11 (37%) in the control group (P = .02). The 24-h fluid balance was 2.1 ± 3.2 L in the treatment group compared with 1.9 ± 2.7 L in the control group (not significantly different). Similarly, the 72-h fluid balance was 1.9 ± 3.7 L in the treatment group compared with 1.6 ± 3.3 L in the control group. All patients in the treatment group were weaned off vasopressors a mean of 18.3 ± 9.8 h after starting treatment with the vitamin C protocol. The dose of pressors was predictably reduced between 2 and 4 h after

the first infusion of vitamin C. The mean duration of vasopressor use was 54.9 ± 28.4 h in the control group (P < .001); nine patients in the control group received escalating doses of vasopressors and died of refractory septic shock. The mean duration of vasopressor treatment was 61.4 ± 33.8 h in the control patients who died compared with 38.7 ± 6.5 h in those who survived. The time course of the vasopressor dose (in norepinephrine equivalents)^{36,37} in the treatment group, the control patients who died, and the control patients who survived is illustrated in Figure 2. The 72-h ΔSOFA score was 4.8 ± 2.4 in the treatment group compared with 0.9 ± 2.7 in the control group (P < .001). None of the patients in the treatment group developed new organ failure (as reflected by an increase in their SOFA score) requiring an escalation of therapy. The time course of the SOFA score in the treatment group, the control patients who died, and the control patients who survived

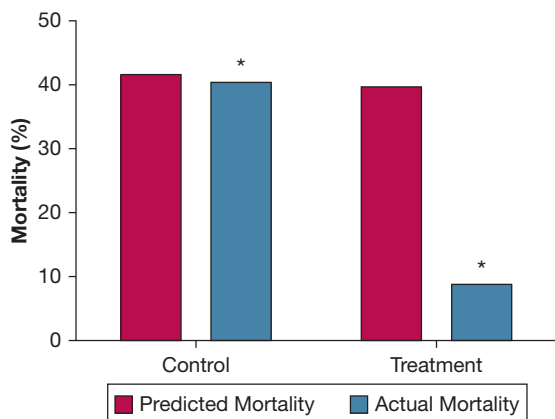


Figure 1 – Predicted and actual mortality in the treatment and control groups. Predicted mortality was derived from APACHE IV scoring system results. *P < .001 for comparison of treatment group vs control group (see text). APACHE = Acute Physiology and Chronic Health Evaluation.

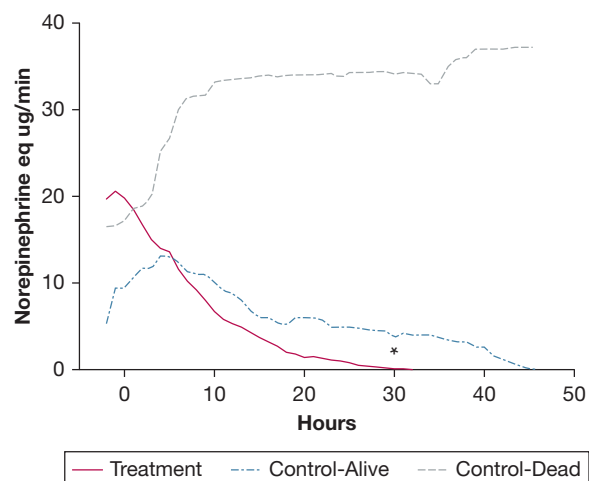


Figure 2 – Time course of vasopressor dose (in norepinephrine equivalents) in the treatment group and in the control group survivors and nonsurvivors. *P < .001 for comparison of treatment group vs control group (see text).

is shown in Figure 3. The median 72-h PCT clearance was 86.4% (80.1%-90.8%) in the treatment group compared with 33.9% (-62.4% to 64.3%) in the control group ($P < .001$); the time course of the PCT over the first 4 days is illustrated in Figure 4. The median ICU LOS was 4 (3-5) days in the treatment group compared with 4 (4-10) days in the control group (not significantly different).

Discussion

In this observational study the combination of intravenous vitamin C, moderate-dose hydrocortisone, and thiamine appeared to have a marked effect on the natural history of patients with severe sepsis and septic shock. No patient in the treatment group developed progressive organ failure, and the four deaths in this group were related to the patients' underlying disease; these patients did not die of sepsis-related complications. Our study evaluated the use of intravenous vitamin C, hydrocortisone, and thiamine in a real-world setting where all eligible patients with sepsis were studied. This is important as less than 20% of eligible patients with severe sepsis and septic shock are commonly included in many of the sepsis trials, limiting the applicability and generalizability of the results.⁶¹ Furthermore, we did not test an expensive, proprietary designer molecule, but rather the combination of three inexpensive and readily available agents with a long safety record and in clinical use since 1949.^{62,63}

The findings of our study are supported by extensive experimental and clinical studies that have demonstrated

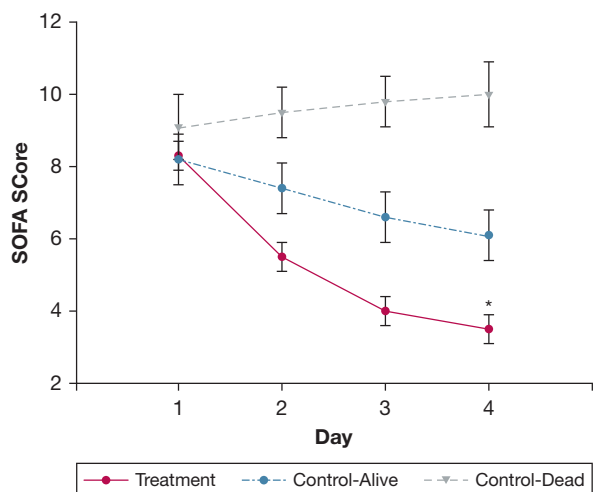


Figure 3 – Time course of the SOFA score over the 4-day treatment period in the treatment group and in the control group survivors and nonsurvivors. * $P < .001$ for comparison of treatment group vs control group (see text). SOFA = Sepsis-Related Organ Failure Assessment.

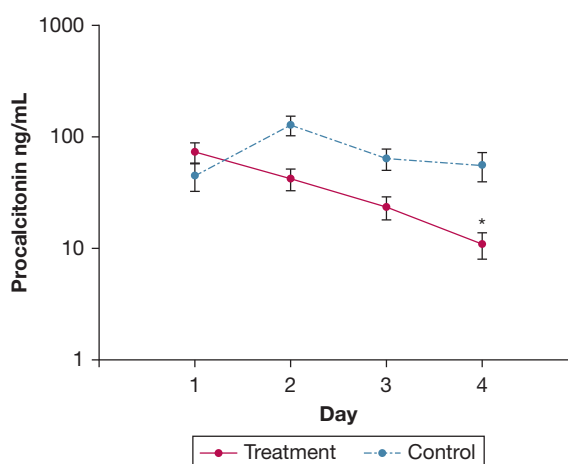


Figure 4 – Time course of the PCT score over the 4-day treatment period in the treatment group and in the control group plotted on a semilog scale. * $P < .001$ for comparison of treatment group vs control group (see text). PCT = procalcitonin.

the safety and potential benefit of moderate-dose hydrocortisone, intravenous vitamin C, and thiamine in critically ill patients.^{16,17,21,26,64} However, ours is the first study to evaluate the combination of intravenous vitamin C, hydrocortisone, and thiamine, a combination we believe synergistically reverses the pathophysiologic changes of sepsis. The outcome data are supported by the time course of the PCT levels and SOFA score as well as the rapid decline in vasopressor requirements in the treatment group as compared with the control group. The time course of PCT in patients with severe sepsis and septic shock has been evaluated in a number of studies.^{31,32,65} These studies have demonstrated a linear fall in PCT, reaching about 30% of the baseline value in 72 h; a fall of greater than 30% over this time has been shown to indicate the appropriate use of antibiotics and is predictive of survival. In the treatment group, the PCT fell exponentially in all patients, reaching a median of 86% of the baseline value at 72 h. In comparison, the PCT remained relatively unchanged in the control group during this time. This observation is supported by the pilot study of Fowler et al,¹⁶ who in a randomized controlled trial evaluated the clinical response to low-dose (50 mg/kg/d) and high-dose vitamin C (200 mg/kg/d) (without corticosteroids) in 24 patients with sepsis. In this study, the fall of the PCT in the first 72 h was approximately 40% in the low-dose group and 80% in the high-dose group whereas it increased in the control group. In our study, the mean time to vasopressor independence after starting the vitamin C protocol was 18 h. The mean duration of vasopressor therapy was 54 h in the control group. In the literature, the mean duration of vasopressor dependency in patients with septic shock is

reported to vary between about 72 and 120 h.^{37,54} In the VANISH (Vasopressin vs Noradrenaline as Initial Therapy in Septic Shock) trial, the median time to shock reversal was 45 h (interquartile range, 23-75 h).⁶⁶ The mean duration of vasopressor dependency in the patients treated with vitamin C in the study by Fowler et al¹⁶ was 86 h. Similarly, in the CORTICUS (Corticosteroid Therapy of Septic Shock) study, the time to vasopressor independence was 79 h.⁵⁴ These data support the contention that vitamin C, hydrocortisone, and thiamine have synergistic effects in reversing vasoplegic shock in patients with sepsis. Shortening the duration of vasopressor treatment and preventing dose escalation likely have numerous beneficial effects, including limiting organ and limb ischemia.⁶⁶⁻⁶⁸ Furthermore, norepinephrine exerts antiinflammatory and bacterial growth-promoting effects, which may potentiate the immunoparesis of sepsis, thereby increasing the susceptibility to secondary infections.⁶⁹

Experimental studies have demonstrated that both vitamin C and hydrocortisone have multiple and overlapping beneficial pathophysiological effects in sepsis. Vitamin C is a potent antioxidant that directly scavenges oxygen free radicals; restores other cellular antioxidants, including tetrahydrobiopterin and α -tocopherol; and is an essential cofactor for iron- and copper-containing enzymes.^{70,71} Both drugs inhibit nuclear factor- κ B activation, down-regulating the production of proinflammatory mediators; increase tight junctions between endothelial and epithelial cells; preserve endothelial function and microcirculatory flow; are required for the synthesis of catecholamines; and increase vasopressor sensitivity.^{13-15,26,70-75} Vitamin C plays a major role in preserving endothelial function and microcirculatory flow.^{70,72} In addition, vitamin C activates the nuclear factor erythroid 2-like 2 (Nrf2)/heme oxygenase (HO)-1 pathway, which plays a critical role in antioxidant defenses and enhances T-cell and macrophage function.⁷⁶⁻⁷⁸ The explanation as to why the combination of intravenous vitamin C, hydrocortisone, and thiamine appeared to have a marked effect on the course of sepsis, as compared with the myriad of designer molecules that have been evaluated in previous sepsis trials, is likely related to the multiple and overlapping effects of all three agents as compared with drugs that target a single molecule or pathway.¹² Furthermore, we believe that vitamin C and corticosteroids act synergistically.⁷⁹ Oxidation of cysteine thiol groups of the glucocorticoid receptor affects ligand and DNA binding, reducing the efficacy of

glucocorticoids.^{80,81} Vitamin C has been demonstrated to reverse these changes and restore glucocorticoid function.⁸² The transport of vitamin C into the cell is mediated by the sodium-vitamin C transporter-2 (SVCT2).⁸³ Proinflammatory cytokines have been demonstrated to decrease expression of SVCT2.⁸⁴ Glucocorticoids, however, have been shown to increase expression of SVCT2.⁸⁵ In an experimental model using cultured human lung vascular endothelial cells exposed to endotoxin we have demonstrated that incubation with the combination of vitamin C and hydrocortisone preserved endothelial integrity as compared with either agent alone, the latter being no more effective than placebo.⁸⁶ This finding is in keeping with clinical studies suggesting that hydrocortisone and vitamin C alone have little impact on the clinical outcome of patients with sepsis.^{16,54} The HYPRESS (Hydrocortisone for Prevention of Septic Shock) study failed to demonstrate an outcome benefit from a hydrocortisone infusion in patients with severe sepsis.⁸⁷

While the dosing strategy for corticosteroids (hydrocortisone) in patients with severe sepsis and septic shock has been well studied,^{26,88} that for vitamin C is more uncertain. Critically ill patients have either low or undetectable vitamin C levels (normal serum levels, 40-60 μ M).^{18,19} Because of the saturable intestinal transporter (sodium-vitamin C transporter-1),^{20,83} oral administration of doses as high as 1,500 mg cannot restore normal serum levels.²⁰ To achieve normal serum vitamin C levels in critically ill patients, a daily dose of more than 3 g is required.^{16,18,21} On the basis of pharmacokinetic data and preliminary dose-response data we believe that a daily dose of 6 g combined with hydrocortisone is optimal. When high dosages of vitamin C are given intravenously, metabolic conversion to oxalate increases.¹⁹ Oxalate is normally excreted by the kidney, and serum levels will increase with renal impairment. In patients with renal impairment receiving megadose vitamin C, supersaturation of serum with oxalate may result in tissue deposition as well as crystallization in the kidney.^{89,90} Worsening renal function is therefore a concern with megadose vitamin C. It is noteworthy that renal function improved in all the patients with AKI. Glyoxylate, a byproduct of intermediary metabolism, is either reduced to oxalate or oxidized to carbon dioxide by the enzyme glyoxylate aminotransferase; thiamine pyrophosphate is a coenzyme required for this reaction.⁹¹ Thiamine deficiency increases the conversion of glyoxylate to oxalate.^{92,93} Thiamine deficiency is common in septic patients and is associated with an increased risk of death.⁶⁴

For these reasons, thiamine was included in our vitamin C protocol.

Our study has several limitations, namely the small sample size, single-center design, and the participation of nonconcurrent control subjects. Furthermore, the treatment and control periods occurred during different seasons. We used propensity score adjustment in an attempt to control for some of these factors. We believe that the data from our study are internally consistent, have a valid mechanistic basis, and are supported by experimental studies. In addition, the safety of hydrocortisone, vitamin C, and thiamine is supported by more than 50 years of clinical experience. Because of the inherent safety of the combination of hydrocortisone, vitamin C, and thiamine we believe that this treatment strategy can be adopted pending the results of further clinical trials. We believe that the results of our study provide sufficient information for the design of an adequately powered, high-quality pragmatic trial to

confirm the findings of our study. Because of the lack of clinical equipoise and the ethics of withholding a potentially lifesaving intervention, we were unable to initiate a randomized controlled trial in our center. Furthermore, while our observational study suggests that a 4-day course of vitamin C is optimal, additional studies are required to determine the ideal dosing strategy, and the contributing role of thiamine requires further exploration.

In conclusion, the results of our study suggest that the early use of intravenous vitamin C, together with moderate-dose hydrocortisone and thiamine, may prove to be effective in preventing progressive organ dysfunction, including acute kidney injury, and reducing the mortality of patients with severe sepsis and septic shock. This inexpensive and readily available intervention has the potential to reduce the global mortality from sepsis. Additional studies are required to confirm our preliminary findings.

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Author contributions: P. M. had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. P. M.: Conception of study, literature review, pharmacologic modeling and interpretation, study design, study execution, data collection, data analysis, data interpretation, writing of study. V. K.: Literature review, study design, data analysis, data interpretation, writing of study. R. R.: Pharmacologic modeling and interpretation, formulation of dosing strategy, study execution, data collection, writing of study. M. H.: Interpretation of data, statistical analysis, writing of study. J. C.: Study design, interpretation of data, writing of study.

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Additional information: The e-Appendix, e-Figures and e-Tables can be found in the Supplemental Materials section of the online article.

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