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Serum Magnesium and Short-Term Outcomes in Critically Ill Adults: Associations with Mechanical Ventilation, ICU Mortality, and Length of Stay

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ABSTRACT: Serum magnesium disturbances are common in critical illness, but their relationships with clinically important intensive care unit (ICU) outcomes remain inconsistent. This prospective observational cohort study evaluated associations of serum magnesium with mechanical ventilation, ICU mortality, ICU length of stay, and ventilation duration in critically ill adults. Ninety-nine patients admitted to the ICU of Dr. Wahidin Sudirohusodo General Hospital, Makassar, Indonesia, were enrolled and followed throughout their ICU stay. Serum magnesium obtained during the initial ICU assessment was analyzed primarily as a continuous variable. Multivariable logistic regression adjusted for age and APACHE II score was used for mechanical ventilation and ICU mortality, while ICU length of stay was analyzed using negative binomial regression. Median serum magnesium was 1.94 mg/dL (Q1–Q3, 1.65–2.11); 76.8% of patients required mechanical ventilation and 33.3% died in the ICU. Serum magnesium was not independently associated with mechanical ventilation (aOR 1.86, 95% CI 0.52–6.70; $p=0.340$) or ICU mortality (aOR 2.11, 95% CI 0.60–7.36; $p=0.243$). Higher magnesium was associated with longer ICU stay (IRR 1.60, 95% CI 1.06–2.41; $p=0.025$), although the overall model was not significant ($p=0.123$). Magnesium also correlated positively with ventilation duration among ventilated patients ($\rho=0.361$; $p=0.001$). Serum magnesium may therefore reflect aspects of critical illness course rather than independently predict mechanical ventilation or ICU death.

1. INTRODUCTION

Magnesium is the second most abundant intracellular cation and an essential cofactor in numerous enzymatic processes involved in energy metabolism, protein synthesis, membrane stability, neuromuscular signaling, cardiovascular function, and immune regulation [1,2]. Critically ill patients are particularly susceptible to disturbances in magnesium homeostasis because of renal dysfunction, gastrointestinal losses, medication exposure, and metabolic alterations. Although ionized magnesium represents the biologically active fraction, total serum magnesium remains the measurement most commonly used in routine clinical practice [3].

Clinical associations between magnesium disturbances and ICU outcomes are heterogeneous and appear to depend on both the direction and timing of the abnormality. Laupland et al. (2020) found that admission hypo- or hypermagnesemia was not independently associated with mortality after adjustment, whereas ICU-acquired hypermagnesemia was [4]. Similarly, hospital-acquired hypermagnesemia and mixed dysmagnesemia were associated with higher in-hospital mortality in a MIMIC-III cohort [5]. Hypermagnesemia was also associated with ICU mortality among patients with acute respiratory failure [6].

Hypomagnesemia has meanwhile been associated with greater mechanical ventilation requirements and longer ICU stay [7], while a prospective multidisciplinary ICU study reported higher mortality and greater need for mechanical ventilation but no significant association with ICU stay or ventilation duration [8]. Recent sepsis cohorts have further linked higher admission magnesium and specific magnesium patterns with mortality [9,10]. Randomized evidence does not resolve these observational findings, as evidence for magnesium supplementation in general ICU populations remains sparse and of very low certainty [11]. This study evaluated the associations of serum magnesium with mechanical ventilation, ICU mortality, and ICU length of stay in critically ill adults, with ventilation duration examined among mechanically ventilated patients.

2. MATERIALS AND METHODS

2.1 Study design and participants

This prospective observational cohort study was conducted in the intensive care unit (ICU) of Dr. Wahidin Sudirohusodo General Hospital, Makassar, Indonesia, from April to May 2026. A total-sampling approach was used, whereby all patients admitted to the ICU during the predefined study period were screened for eligibility. Patients who fulfilled the eligibility criteria and provided written informed consent were enrolled and followed until ICU discharge or death.

Patients were eligible if they were aged ≥ 18 years, remained in the ICU for >24 hours, were not receiving hormonal therapy, and were not pregnant or breastfeeding. Exclusion criteria were ICU admission within the preceding 3 months, end-stage chronic kidney disease, intravenous magnesium supplementation before ICU admission, terminal multiorgan failure with an expected survival of <24 hours, and severe neuromuscular disease or spinal cord injury that could independently affect ventilatory requirements. The final analytic cohort comprised 99 patients with available baseline serum magnesium measurements and complete data for the primary clinical outcomes.

2.2 Clinical and laboratory assessment

Demographic and clinical information was collected during the initial ICU assessment using a structured data collection form. Recorded variables included age, sex, primary diagnostic category, documented comorbidities, and use of medications potentially affecting serum magnesium concentrations. Illness severity was characterized using the Acute Physiology and Chronic Health Evaluation II (APACHE II) and Sequential Organ Failure Assessment (SOFA) scores. APACHE II was calculated according to the standard scoring framework using physiological and clinical data obtained during the first 24 hours of ICU care, together with age and chronic health status.

Laboratory measurements were obtained as part of routine initial ICU laboratory assessment and included white blood cell count, differential leukocyte count, serum albumin, C-reactive protein (CRP), and total serum magnesium. A single total serum magnesium measurement obtained at ICU admission was used as the baseline exposure and was reported in mg/dL. Serum magnesium was measured in the hospital laboratory using a fully automated photometric method.

Patients who had received intravenous magnesium supplementation before ICU admission were excluded to minimize treatment-related alteration of baseline serum magnesium. The study did not mandate or withhold magnesium replacement after the baseline measurement; subsequent treatment decisions were made by the treating ICU team according to clinical indications. Magnesium treatment administered after baseline assessment did not alter the serum magnesium value used as the exposure in the present analysis.

Serum magnesium was analyzed primarily as a continuous variable. Total lymphocyte count (TLC) was calculated as $\text{WBC (cells}/\mu\text{L)} \times \text{lymphocyte percentage} / 100$. The neutrophil-to-lymphocyte ratio (NLR) was calculated as $\text{neutrophil percentage} / \text{lymphocyte percentage}$. The Prognostic Nutritional Index (PNI) was calculated as $10 \times \text{serum albumin (g/dL)} + 0.005 \times \text{TLC (cells}/\mu\text{L)}$.

2.3 Study outcomes

The principal clinical outcomes were mechanical ventilation during the ICU stay, ICU mortality, and ICU length of stay. Mechanical ventilation was defined as the requirement for invasive mechanical ventilation through endotracheal intubation during ICU treatment. ICU mortality was defined as death occurring during the ICU stay. ICU length of stay was calculated from ICU admission to ICU discharge or death and expressed in days.

Among patients who required mechanical ventilation, the duration of mechanical ventilation was additionally evaluated as an exploratory outcome and expressed in days.

2.4 Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics for Mac, version 30.0 (IBM Corp., Armonk, NY, USA). Data were checked for completeness, consistency, and implausible values before analysis. Normality of continuous variables was assessed using the Shapiro–Wilk test. Normally distributed continuous variables are presented as mean $\pm$ standard deviation, whereas non-normally distributed continuous variables are presented as median with first and third quartiles (Q1–Q3). Categorical variables are presented as frequency and percentage.

Serum magnesium was not normally distributed and was therefore compared between patients who did and did not receive mechanical ventilation and between ICU survivors and non-survivors using the Mann–Whitney U test. Associations of serum magnesium with ICU length of stay and, among mechanically ventilated patients, duration of mechanical ventilation were assessed using Spearman rank correlation.

Univariable binary logistic regression was used to estimate the unadjusted associations of serum magnesium with mechanical ventilation and ICU mortality. Multivariable binary logistic regression was subsequently used to estimate adjusted associations after controlling for age and APACHE II score. Age was included to account for differences in outcome risk related to patient age, whereas APACHE II was included as a clinically established measure of baseline illness severity and a potential confounder of the relationship between serum magnesium and ICU outcomes. A parsimonious adjustment strategy was used because of the sample size and number of outcome events, and covariates were selected on clinical grounds rather than solely according to univariable statistical significance. Results are reported as odds ratios (ORs) or adjusted odds ratios (aORs) with 95% confidence intervals (CIs).

Because ICU length of stay was a positive, markedly right-skewed count outcome with overdispersion, its adjusted association with serum magnesium was evaluated using negative binomial regression with a log link. Serum magnesium, age, and APACHE II score were entered simultaneously into the model. Results are reported as incidence rate ratios (IRRs) with 95% CIs.

Each participant contributed one observation to the analysis. Calibration of the binary logistic regression models was assessed using the Hosmer–Lemeshow goodness-of-fit test. Adequacy of the negative binomial model was evaluated using goodness-of-fit statistics and the overall likelihood-ratio test.

Complete data for serum magnesium, age, APACHE II score, mechanical ventilation, ICU mortality, and ICU length of stay were available for all 99 participants included in the primary analyses. CRP was available for 90 participants and was used descriptively; the remaining 9 CRP values were retained as missing. Missing values were not imputed. All statistical tests were two-sided, and $p < 0.05$ was considered statistically significant.

3. RESULTS AND DISCUSSION

3.1 Study population characteristics

A total of 99 critically ill adults were included in the analysis. The median age was 53 years (Q1–Q3, 40–61), with a nearly balanced sex distribution (50.5% female). Malignancy was the most common diagnostic category (40.4%), followed by head trauma (25.3%), neurologic disorders (13.1%), and musculoskeletal disorders (11.1%). Nineteen patients (19.2%) had at least one documented comorbidity, and 40 (40.4%) received medications potentially affecting serum magnesium levels.

The median APACHE II and SOFA scores were 11 (7–15) and 5 (3–8), respectively. Median serum magnesium was 1.94 mg/dL (1.65–2.11), while mean serum albumin and PNI were 3.06 ± 0.60 g/dL and 34.50 ± 6.88 , respectively. CRP measurements were available for 90 patients, with a median concentration of 114.05 mg/L (42.88–244.95). Mechanical ventilation was required

in 76 patients (76.8%); among these patients, the median ventilation duration was 6 days (4–10). Median ICU length of stay was 6 days (4–10), and 33 patients (33.3%) died during the ICU stay.

Table 1. Clinical and laboratory characteristics of critically ill adults

Characteristic	Overall (n=99)
Demographic and clinical characteristics	
Age, years	53 (40–61)
Sex, n (%)	
Female	50 (50.5)
Male	49 (49.5)
Diagnostic category, n (%)	
Malignancy	40 (40.4)
Head trauma	25 (25.3)
Neurologic	13 (13.1)
Musculoskeletal	11 (11.1)
Other	10 (10.1)
At least one comorbidity, n (%)	19 (19.2)
APACHE II score	11 (7–15)
SOFA score	5 (3–8)
Potential magnesium-altering medication use, n (%)	40 (40.4)
Laboratory characteristics	
WBC, cells/ μ L	14,940 (10,510–18,800)
Lymphocytes, %	4.9 (3.3–8.4)
Neutrophils, %	90.4 (86.1–92.6)
TLC, cells/ μ L	650.0 (459.4–1,029.8)
NLR	18.71 (10.30–27.70)
Serum albumin, g/dL	3.06 $\pm$ 0.60
PNI	34.50 $\pm$ 6.88
CRP, mg/L ^a	114.05 (42.88–244.95)
Serum magnesium, mg/dL	1.94 (1.65–2.11)
Clinical outcomes	
Mechanical ventilation, n (%)	76 (76.8)
Mechanical ventilation duration, days ^b	6 (4–10)
ICU length of stay, days	6 (4–10)
ICU mortality, n (%)	33 (33.3)

Notes: Data are presented as median (Q1–Q3), mean $\pm$ SD, or n (%), as appropriate. Continuous variables were classified according to the Shapiro–Wilk normality test; normally distributed variables are presented as mean $\pm$ SD and non-normally distributed variables as median (Q1–Q3). ^aCRP was available for 90 patients. ^bMechanical ventilation duration was calculated among the 76 patients who received mechanical ventilation.

Abbreviations: APACHE II, Acute Physiology and Chronic Health Evaluation II; SOFA, Sequential Organ Failure Assessment; WBC, white blood cell count; TLC, total lymphocyte count; NLR, neutrophil-to-lymphocyte ratio; PNI, Prognostic Nutritional Index; CRP, C-reactive protein; ICU, intensive care unit.

3.2 Unadjusted associations between serum magnesium and ICU outcomes

Serum magnesium concentrations were numerically higher among patients requiring mechanical ventilation than among those who did not, with median values of 1.97 (1.66–2.15) and 1.88 (1.65–2.03) mg/dL, respectively; however, the difference was not statistically significant (Mann–Whitney $p=0.190$). Consistently, serum magnesium was not significantly associated with the odds of mechanical ventilation in univariable logistic regression (OR 1.85 per 1-mg/dL increase, 95% CI 0.56–6.17; $p=0.315$).

Patients who died in the ICU also had a numerically higher median serum magnesium concentration than survivors [2.03 (1.63–2.43) vs 1.89 (1.67–2.05) mg/dL], although the between-group difference did not reach statistical significance ($p=0.077$). The corresponding unadjusted association with ICU mortality was also not significant (OR 2.10, 95% CI 0.67–6.55; $p=0.200$).

In contrast, serum magnesium was positively correlated with ICU length of stay (Spearman's $\rho=0.251$, $p=0.012$). Among the 76 mechanically ventilated patients, serum magnesium was also positively correlated with ventilation duration ($\rho=0.361$, $p=0.001$).

Table 2. Unadjusted associations between serum magnesium and ICU outcomes

ICU outcome	Serum magnesium, mg/dL	Unadjusted association	95% CI	<i>p</i> -value
Mechanical ventilation				
No (n=23)	1.88 (1.65–2.03)	Reference	—	
Yes (n=76)	1.97 (1.66–2.15)	OR 1.85 ^a	0.56–6.17	0.315
ICU mortality				
Survived (n=66)	1.89 (1.67–2.05)	Reference	—	
Died (n=33)	2.03 (1.63–2.43)	OR 2.10 ^a	0.67–6.55	0.200
ICU length of stay, days (n=99)	—	$\rho=0.251^b$	—	0.012
Mechanical ventilation duration, days (n=76)	—	$\rho=0.361^b$	—	0.001

Notes: Serum magnesium concentrations for binary outcomes are presented as median (Q1–Q3). ^aORs were estimated using univariable binary logistic regression and represent the change in odds associated with a 1-mg/dL increase in serum magnesium. The Mann–Whitney U test showed no significant difference in magnesium concentrations between patients with and without mechanical ventilation ($p=0.190$) or between ICU survivors and non-survivors ($p=0.077$). ^bSpearman rank correlation coefficient. Analysis of mechanical ventilation duration was restricted to patients who received mechanical ventilation (n=76).

Abbreviations: CI, confidence interval; ICU, intensive care unit; OR, odds ratio; Q1, first quartile; Q3, third quartile; ρ , Spearman rank correlation coefficient.

3.3 Adjusted associations between serum magnesium and ICU outcomes

After adjustment for age and APACHE II score, serum magnesium was not significantly associated with mechanical ventilation (aOR 1.86, 95% CI 0.52–6.70; $p=0.340$) or ICU mortality (aOR 2.11, 95% CI 0.60–7.36; $p=0.243$). In contrast, higher serum magnesium was associated with longer ICU length of stay in the adjusted negative binomial model (IRR 1.60, 95% CI 1.06–2.41; $p=0.025$). The latter finding should be interpreted cautiously because the overall likelihood-ratio test for the ICU length-of-stay model was not statistically significant ($p=0.123$).

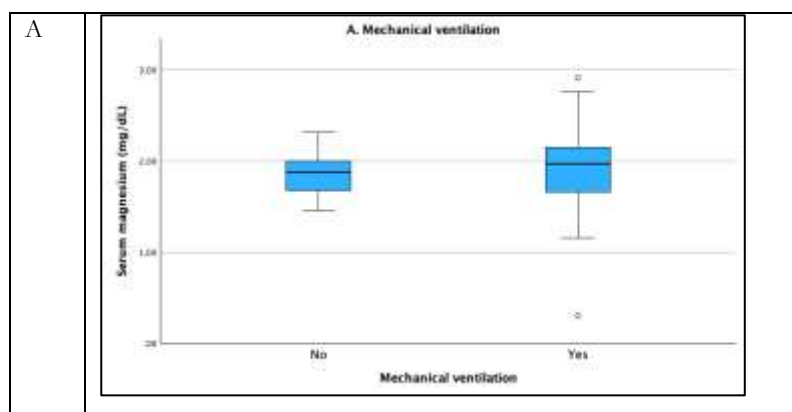
Table 3. Adjusted associations with mechanical ventilation, ICU mortality, and ICU length of stay

Outcome / predictor	Adjusted effect	95% CI	<i>p</i> -value
Mechanical ventilation^a			
Serum magnesium, per 1 mg/dL	aOR 1.86	0.52–6.70	0.340
Age, per year	aOR 0.96	0.92–1.00	0.028
APACHE II, per point	aOR 1.15	1.02–1.30	0.020
ICU mortality^b			
Serum magnesium, per 1 mg/dL	aOR 2.11	0.60–7.36	0.243
Age, per year	aOR 0.96	0.93–1.00	0.032
APACHE II, per point	aOR 1.24	1.11–1.38	<0.001
ICU length of stay^c			
Serum magnesium, per 1 mg/dL	IRR 1.60	1.06–2.41	0.025
Age, per year	IRR 1.00	0.99–1.01	0.793
APACHE II, per point	IRR 1.02	0.98–1.05	0.372

Notes: All models included serum magnesium, age, and APACHE II score simultaneously. ^aMechanical ventilation was analyzed using binary logistic regression; overall model $p=0.024$ and Hosmer–Lemeshow $p=0.865$. ^bICU mortality was analyzed using binary logistic regression; overall model $p<0.001$ and Hosmer–Lemeshow $p=0.936$. ^cICU length of stay was analyzed using negative binomial regression with a log link. The overall likelihood-ratio test was $\chi^2=5.772$, $df=3$, $p=0.123$. The IRR represents the multiplicative change in expected ICU length of stay associated with a one-unit increase in the predictor.

Abbreviations: APACHE II, Acute Physiology and Chronic Health Evaluation II; aOR, adjusted odds ratio; CI, confidence interval; ICU, intensive care unit; IRR, incidence rate ratio.

Figure 1 illustrates the distribution of serum magnesium according to mechanical ventilation status and ICU mortality. Serum magnesium concentrations showed substantial overlap between outcome groups, although median concentrations were numerically higher in mechanically ventilated patients than in non-ventilated patients [1.97 (1.66–2.15) vs 1.88 (1.65–2.03) mg/dL] and in patients who died compared with ICU survivors [2.03 (1.63–2.43) vs 1.89 (1.67–2.05) mg/dL]. Neither between-group difference was statistically significant ($p=0.190$ and $p=0.077$, respectively).



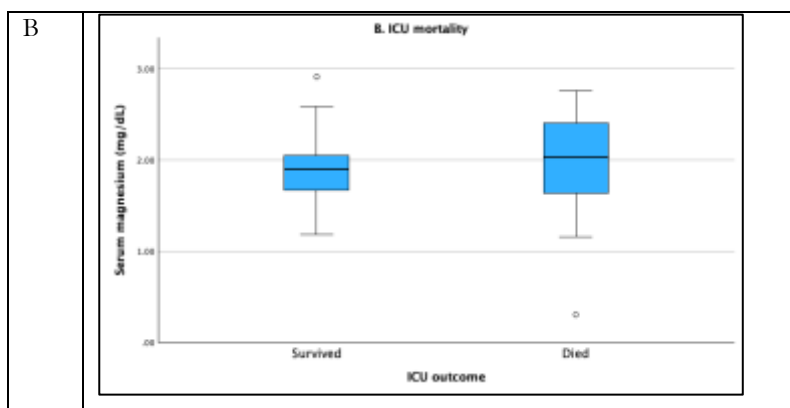


Figure 1. Distribution of serum magnesium according to major ICU outcomes.

(A) Serum magnesium concentrations according to mechanical ventilation status. **(B)** Serum magnesium concentrations according to ICU mortality. Boxes represent the interquartile range, horizontal lines indicate the median, and whiskers represent the distribution beyond the quartiles; outlying observations are retained.

3.4 Discussion

In this prospective cohort of critically ill adults, serum magnesium was not independently associated with the requirement for mechanical ventilation or ICU mortality after adjustment for age and APACHE II score. In contrast, the magnesium coefficient was positively associated with ICU length of stay in the adjusted negative binomial model, although the overall model likelihood-ratio test was not statistically significant. Among mechanically ventilated patients, higher magnesium also correlated with longer ventilation duration. These findings indicate that the prognostic relevance of a single serum magnesium measurement may differ across ICU outcomes and should not be interpreted as a uniform marker of adverse prognosis.

The absence of an independent association with mechanical ventilation contrasts with studies centered on hypomagnesemia. Zeineldin et al. (2022) reported a greater requirement for mechanical ventilation among hypomagnesemic ICU patients [7], while Gonuguntla et al. (2023) found mechanical ventilation to be more frequent in hypomagnesemic than hypermagnesemic patients [8]. In patients with sepsis, Patil and Aslam (2023) similarly reported substantially greater ventilator requirement in the hypomagnesemia group [12]. These studies primarily evaluated categorical magnesium abnormalities, whereas the present analysis examined magnesium continuously and adjusted for illness severity. In our cohort, APACHE II remained associated with mechanical ventilation while magnesium did not, suggesting that baseline illness severity may account for more of the variation in ventilatory requirement than a single magnesium concentration.

A similar pattern emerged for ICU mortality. Although non-survivors had a numerically higher median magnesium concentration, magnesium was not independently associated with mortality after adjustment. This finding is consistent with Laupland et al. (2020), who found that admission hypo- and hypermagnesemia were no longer associated with mortality after adjustment, although ICU-acquired hypermagnesemia carried additional risk [4]. More recently, Cai et al. (2026) reported no independent association between magnesium measured within 24 hours of ICU admission and ICU mortality in a 208-hospital analysis [13]. Other populations, however, have shown different patterns. Ribeiro et al. (2022) found that both admission hypo- and hypermagnesemia were associated with higher adjusted mortality [14], while Wang et al. (2022) observed a U-shaped pattern in unadjusted analysis of traumatic brain injury, with higher initial magnesium remaining positively associated with mortality after adjustment [15]. Mekkodathil et al. (2023) likewise identified hypermagnesemia as an independent mortality predictor in traumatic brain injury, although the hypermagnesemic subgroup was small [16]. Higher magnesium has also been associated with mortality in large sepsis cohorts [10]. Collectively, these data suggest that the relationship between magnesium and mortality may be population-specific and potentially nonlinear.

The positive association with ICU length of stay warrants a cautious interpretation. The adjusted IRR was 1.60 per 1-mg/dL increase in magnesium, but the global likelihood-ratio test for the model was not significant. Previous studies have more commonly associated hypomagnesemia with prolonged ICU stay. Zeineldin et al. (2022) observed longer ICU stays among hypomagnesemic patients [7], and Laddhad et al. (2023) reported a similar association in a prospective ICU cohort [17]. By

contrast, Gonuguntla et al. (2023) found no significant relationship between magnesium categories and ICU length of stay [8]. The direction observed in our study therefore should be regarded as a cohort-specific signal requiring confirmation rather than evidence that higher magnesium directly prolongs ICU stay.

Several physiological factors may contribute to these apparently divergent associations. Magnesium concentrations are influenced by gastrointestinal absorption and losses, renal filtration and reabsorption, medications, and shifts between extracellular and intracellular compartments [18]. In hospitalized adults, hypermagnesemia occurred more frequently alongside chronic kidney disease, higher creatinine, and lower estimated glomerular filtration rate, although these associations were not independently confirmed in multivariable analysis [19]. Serial changes may also provide information not captured by a single measurement: ICU-acquired magnesium abnormalities were prognostically relevant in Laupland et al. [4], while different magnesium trajectories were associated with different mortality patterns in sepsis [9]. Consequently, serum magnesium may partly reflect evolving renal and systemic physiology rather than a direct causal pathway.

The positive correlation with ventilation duration in our ventilated subgroup should also remain exploratory. Patil and Aslam (2023) reported longer ventilation duration among septic patients with hypomagnesemia [12], whereas Laddhad et al. (2023) found no significant association with ventilation duration [17]. Differences in patient populations, magnesium thresholds, renal function, illness severity, and analytical approach may contribute to these inconsistencies. Furthermore, total serum magnesium does not necessarily correspond closely to the biologically active ionized fraction in critically ill patients [3].

The present findings should not be interpreted as evidence that altering serum magnesium would modify ICU outcomes. A systematic review found very low-certainty evidence regarding magnesium supplementation and patient-important outcomes in critically ill adults [11]. Although a propensity score-matched sepsis study found magnesium sulfate use to be associated with lower 28-day, ICU, and in-hospital mortality, the observational design precludes causal inference and prospective confirmation remains necessary [20].

Strengths of this study include its prospective design, assessment of magnesium early during ICU care, prospective ascertainment of clinically relevant outcomes, and adjustment for APACHE II severity. Limitations include the single-center setting and modest sample size, which reduced precision for binary outcomes. Magnesium was represented by a single total serum measurement rather than serial or ionized measurements. The heterogeneous ICU case mix and incomplete adjustment for renal function and evolving organ dysfunction leave potential residual confounding. Ventilation duration was analyzed only among patients receiving mechanical ventilation, and the ICU length-of-stay association requires particular caution because the overall adjusted model was not statistically significant. These considerations support interpreting serum magnesium as a potentially informative component of the clinical profile of critical illness rather than as an isolated predictor of mechanical ventilation or ICU death.

4. CONCLUSION

Serum magnesium was not independently associated with mechanical ventilation or ICU mortality after adjustment for age and APACHE II score. Higher magnesium was associated with longer ICU stay and correlated with longer ventilation duration among mechanically ventilated patients, although the ICU length-of-stay finding should be interpreted cautiously. These findings suggest that serum magnesium may reflect aspects of critical illness trajectory rather than serve as a stand-alone predictor of major ICU outcomes.

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AUTHOR CONTRIBUTIONS

HYL: Conceptualization, Investigation, Data Curation, Formal Analysis, Visualization, and Writing – Original Draft.

AA: Conceptualization, Methodology, Supervision, Validation, and Writing – Review & Editing.

AB: Conceptualization, Methodology, Supervision, Validation, and Writing – Review & Editing.

NAD: Methodology, Supervision, Validation, and Writing – Review & Editing.

AYS: Methodology, Supervision, Validation, and Writing – Review & Editing.

AF: Methodology, Supervision, Validation, and Writing – Review & Editing.

All authors critically reviewed the manuscript, approved the final version, and agreed to be accountable for the accuracy and integrity of the work.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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ETHICS STATEMENT

The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Health Research Ethics Committee of the Faculty of Medicine, Hasanuddin University (Approval No. 327/UN4.6.4.5.31/PP36/2026; Protocol No. UH26020259). All participants received information regarding the study procedures and provided written informed consent before enrollment. Participation was voluntary, and participant confidentiality was maintained throughout the study.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to applicable ethical and institutional restrictions.

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