Biomarkers as Predictors of Mortality in Ventilator-Associated Pneumonia and Sepsis: A Comprehensive Analysis

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KEYWORDS

Sepsis, Ventilator-Associated Pneumonia, Biomarkers, Procalcitonin, SOFA Score, Mortality Prediction.

ABSTRACT

Two serious medical conditions named sepsis and ventilator associated pneumonia affect mechanically ventilated patients through high rates of both severe illness and death. This retrospective cohort study evaluated sepsis and VAP predictive biomarkers through the assessment of procalcitonin (PCT), C-reactive protein (CRP) and mean platelet volume (MPV) together with neutrophil to lymphocyte count ratio (NLCR) combined with Sequential Organ Failure Assessment (SOFA) score. The study investigated both the microbial distribution of Gram negative and Gram-positive agents combined with VAP the sepsis cases. The study enrolled 119 sepsis patients with 63 (52.94%) cases of VAP among them while 56 patients (47.05%) had no VAP development. The study investigated pathogen frequency and biomarker quantities through microbiological analysis and employed SOFA scoring on days 0 and 3. The results demonstrated that the SOFA score delivered the best forecasting performance (AUC = 0.860, $p < 0.001$) regarding VAP occurrence and 28-day mortality (OR = 1.536, $p < 0.001$) while PCT, CRP, MPV, and NLCR proved inadequate to predict VAP occurrence or mortality. The primary microbial agents in VAP associated sepsis were Gram negative germs including Pseudomonas aeruginosa, Escherichia coli and Acinetobacter baumannii while Gram positive pathogens included Staphylococcus aureus and Enterococcus species. Research data indicates that the SOFA score plays an essential role in assessing patient risk while also supporting specific antimicrobial drug selection based on detected microbial agents. Finally, this study demonstrates the importance of SOFA score in prediction of VAP and mortality in sepsis patients, whereas traditional biomarkers were not useful. The role of pathogens in VAP-associated sepsis is highlighted by their contribution to microbiological analysis. However, clinical scoring systems and microbial data can be integrated into routine practice to more effectively improve outcomes in sepsis and VAP ICU critically ill patients.

INTRODUCTION

Sepsis stands as a serious international health concern due to its severe morbidity and death rates that worsens notably in people using mechanical ventilation (Ibarz et al., 2024; Kumar et al., 2024). Body-armored infections produce a complicated reaction that triggers widespread organ inflammation which can lead to multiple organ dysfunction and failure (Liu et al., 2024; Srivastava & Singh, 2024). Recent research by Iba et al. (2023) together with Ruiz-Rodriguez et al. (2022) introduced Survival Sepsis Campaign (SSC) i.e Sepsis-3 guidelines that use clinical predictive measures to identify organ failure as an indicator of disease severity. Sepsis represents organ dysfunction that results from an irrelevant host response to systemic infection according to Jacobi (2022) and Cao et al. (2023). The diagnostic criteria for sepsis with hypotension require vasopressor treatment for maintaining mean arterial pressure above 145 mm Hg and fluid resuscitation to reduce lactate levels below 2 mmol/L (Macdonald, 2022; Vella et al., 2024). The current version of Sepsis-3 no longer includes Sepsis continuum and Systemic inflammatory response syndrome (SIRS) because these diagnoses did not achieve clinical effectiveness (Papathanakos et al., 2023; Gopalan, 2022). The occurrence of ventilator associated pneumonia (VAP) among these patients leads to prolonged illness duration and hospital stays while making the condition worse (Klompas et al., 2022; Livesey et al., 2024). After an endotracheal tube insertion and the start of ventilation via a mechanical device, this occurs between 48 to 72 hours (from the time of insertion and start of ventilation) (Ramirez et al., 2024; Fleet, 2023). Although sepsis and VAP carry substantial risks to patients, the prognosis for these patients remains poor despite the advances in intensive care (Alnimr, 2023; Samadani et al., 2023). Due to the necessity for early identification of high-risk individuals, de Souza et al. (2024) suggest that improving clinical outcomes and reducing mortality rates is a priority.

Early and accurate identification of sepsis together with its complications e.g. VAP is important to implement timely interventions intended to prevent severe outcomes (Samadani et al., 2023; AHAC, 2024). Still, the challenge of clinical diagnosis is due to overlapping symptoms, and the lack of rapid, definitive test (Chambliss et al., 2024). This is where biomarkers have come to play a huge role in the disease progression, crucial for clinical decisions, and even useful for doctors to inspect how grave an infection is (He et al., 2024). In sepsis an VAP context, procalcitonin (PCT), C-reactive protein (CRP), mean platelet volume (MPV) and neutrophil to lymphocyte count ratio (NLCR) have been explored as biomarkers. These markers are reflective of the body's inflammatory and immune response and their level can change from disease severity to prognosis. Creactive protein and procalcitonin are well known incremental inflammatory markers to measure the extent of infection and systemic inflammation (Rahali et al., 2024). For instance, the levels of PCT are strongly related to bacterial infections and can be used as a predictor for progression and mortality from sepsis (Zhu et al., 2024). CRP is another acute phase reactant that is also used to monitor the clinical course of infections (Levinson & Wasserman, 2022), 'crp is similar... MPV, as a measure of platelet activation, is also of interest in critical illness as it is linked to systemic inflammation (Leung & Middleton, 2024). A ratio derived from the white blood cell differential, namely the NLCR, has exhibited potential as a simple and economical marker to predict outcomes in sepsis and other infections (Regassa et al., 2024). Individual biomarkers have been investigated in sepsis; however, their ability to predict mortality after combining with clinical scoring systems is still under investigation (D'Onofrio et al., 2022; Póvoa et al., 2023).

The Sequential Organ Failure Assessment (SOFA) score is a well-established clinical measure used to asses organ function in critically ill patients and is a central aspect of sepsis risk stratification. Sequential organ dysfuntion assessment (SOFA) score:

This is a scoring system containing the return and performance six organ systems in the body.

- Central Nervous System- Glasgow Coma Scale.
- Liver: Serum Bilirubin levels (mg/dl).
- Renal System: Serum Creatinine mg/dl OR Urine Output.
- Cardiovascular System Hypotension – Systolic Blood Pressure <90mmHg.
- Coagulation System: Low Platelet Count < 150,000 /cumm.

Score each category and assign a score. The likelihood of mortality will be higher with higher SOFA Score.

Interest is growing in the potential of biomarker based assessments to provide more precise predictions, and in particular whether they would be better, or at least as good, than the SOFA score. Despite the usefulness of biomarkers like PCT, CRP, MPV and NLCR, information provided by these biomarkers about mortality, in particular in patients with sepsis and VAP, remains uncertain. The significance of such a knowledge gap highlights the value of assessing these biomarkers in combination in clinical settings.

The microbiological nature of VAP-associated sepsis requires understanding to build better treatment approaches. The microbiological agents commonly linked to ventilator-associated pneumonia include Pseudomonas aeruginosa together with Escherichia coli and Klebsiella pneumoniae and Acinetobacter baumannii which demonstrate multidrug resistance leading to increased therapy challenges. The burden of VAP associated sepsis contains Gram positive organisms including Staphylococcus aureus in its methicillin sensitive and methicillin resistant variations as well as Enterococcus species. Knowledge about the exact microbial origin of VAP serves as a fundamental requirement for designing proper antibiotic therapy and enhancing clinical end results.

It is important to understand the prognostic potential of biomarkers and microbiological spectrum in predicting mortality in sepsis and VAP patients. Through the systematic analysis of biomarker and microbial levels from available patient pairs compared to clinical outcomes, this study aims to contribute valuable information that can facilitate early risk detection and prompt intervention, and ultimately lead to better patient care. However, the potential of a full analysis of these biomarkers and microbe data may offer a better understanding of their predictive mortality potential in predicting sepsis and VAP in critically ill patients and may lead to better community clinical decision making regarding sepsis and VAP management.

METHODOLOGY

Study Design and Population

To evaluate the predictive value of biomarkers, this study was designed as a retrospective cohort analysis of biomarkers in ventilator associated pneumonia (VAP) and sepsis. At a total of 119 patients diagnosed as stringent sepsis, of which 63 (52.94%) did and 56 (47.05%) did not develop VAP. Data related to patient demographics, clinical characteristics, and biomarker levels were collected and their predictive utility in sepsis and VAP was determined. Furthermore, the microbiological profile of Gram negative and Gram positive microorganisms favoring VAP in sepsis patients was studied.

Inclusion and Exclusion Criteria

Patients included in the study had Sepsis-3 sepsis, with or without VAP, and had complete biomarker data on Day 3 and at baseline. Inclusion criteria included patients who provided blood

for testing of biomarkers and those less severely immunosuppressed. Exclusion criteria included patients with missing or clear biomarkers or those with other infections that may confound biomarker analysis.

Data Collection and Biomarker Measurement

Data collection included demographic information from patients combined with clinical scores together with biomarker measurement results. This research examined the biomarkers Procalcitonin (PCT), C reactive protein (CRP), mean platelet volume (MPV), neutrophil to lymphocyte count ratio (NLCR) and Sequential Organ Failure Assessment (SOFA) score. The study evaluated biomarker level trends alongside predictive capacities both on Day 0 admission and Day 3 following admission.

The study evaluated the Gram negative and Gram positive microorganisms affecting VAP development in sepsis through microbiological data collection. The collected microbiological samples revealed the presence of Pseudomonas aeruginosa, Escherichia coli, Klebsiella pneumoniae, and Acinetobacter baumannii as well as Enterobacter species however Staphylococcus aureus was identified multiple times. The Gram positive bacteria consisted of two strains of methicillin-sensitive and methicillin-resistant Staphylococcus aureus in combination with Streptococcus pneumoniae and Enterococcus species. Researchers evaluated these microbiological profiles to understand their spread rates and their impact on patient health outcomes.

Statistical Analysis

Multiple statistical approaches were applied to produce a solid interpretation of the study results. The researchers performed Mann Whitney U testing on continuous variables and chi square testing on categorical variables for VAP and non VAP comparison of baseline characteristics. We analyzed biomarker-VAP connection in sepsis patients using univariate and multivariate logistic regression methods which yielded odds ratio (OR) and 95% confidence intervals (CI) data. ROC curve analysis showed the predictive capability of each biomarker toward sepsis diagnosis as well as VAP diagnosis. The assessment relied on AUC measurements where results above 0.8 indicated an excellent interpretation while results between 0.7–0.8 indicated good performance and moderate results stood at 0.6–0.7 and results below 0.6 reflected poor interpretation. Univariate and multivariate logistic regression revealed the linkage of 28-day mortality with biomarker levels through mortality risk evaluation. Visual comparisons of biomarker levels between surviving and non-surviving patients appear in these scatter plot plots which helped explain the data findings.

The microbiological data were analyzed to generate prevalence of Gram negative and Gram-positive organisms in VAP associated sepsis. Microorganisms were summarized using descriptive statistics and their association with clinical outcomes was explored using logistic regression models. This analysis enabled inferences of the microbial etiology of VAP in sepsis patients and hopefully aids in developing future treatment strategies.

RESULTS

Study Population and Baseline Characteristics

The research included 119 patients with 63 participants (52.94%) having VAP and 56 participants (47.05%) showing no signs of VAP. The research report presented the entire population's demographic and clinical information through Table 1. Baseline VAP sepsis patients showed significant differences in their PCT levels as well as MPV results and NLCR ratios and SOFA scores compared to non-VAP sepsis patients. Both patient groups showed marginal PCT variations after Day 3.

Table 1: Whole Population Characteristics and Differences Between VAP and Non-VAP Patients

Variable	Total	VAP Patients (n=63, 52.94%)	Non-VAP Patients (n=56, 47.05%)	P-value
Age	43 (34 – 62)	49 (34 – 62)	43 (30.25 – 64)	0.519
Gender				
- Male	57	26	31	0.125
- Female	62	37	25	
Markers at Baseline				
- PCT	5.53 (0.73 – 28.87)	27.25 (8.79 – 76.09)	1.50 (0.38 – 3.59)	<0.001
- CRP	45 (23.78 – 87)	45.98 (29.00 – 88.09)	44.50 (23.00 – 81.99)	0.323
- MPV	9 (8 – 11)	10.00 (8.90 – 12.00)	8.14 (8.00 – 9.15)	<0.001
- NLCR	9 (7 – 15)	12.00 (8.50 – 18.00)	7.00 (6.00 – 8.95)	<0.001
- SOFA				<0.001
Markers at Day 3				
- PCT	3.40 (0.20 – 22.98)	2.09 (0.17 – 6.78)	10.50 (0.51 – 50.38)	0.011
- CRP	56 (32 – 110)	54.87 (34 – 112)	59.44 (19.14 – 108)	0.664
- MPV	9 (8.09 – 11)	8.90 (8 – 10.20)	9 (8.54 – 12.06)	0.074
- NLCR	10.45 (8 – 14.90)	10 (6.50 – 13.40)	11.20 (8 – 15)	0.234

The research evaluated VAP occurrence risk factors for sepsis patients by conducting univariate followed by multivariate logistic regression analysis on baseline biomarker measurements. The study revealed that the SOFA score demonstrated a statistically significant connection with VAP development based on univariate and multivariate results with respective odds ratios of 1.016 (95% CI: 0.969, 1.066) and 1.671 (95% CI: 1.392, 2.006). Analysis through area under the curve (AUC) showed minimal statistical significance for PCT, CRP, MPV and NLCR along with low findings. The SOFA score achieved outstanding prediction success for VAP development in sepsis patients through its AUC value of 0.860 ($p < 0.001$).

Table 2: Univariate and Multivariate Associations of Baseline PCT, CRP, MPV, NLCR, and SOFA Score with VAP in Sepsis

Variable	Univariate OR (95% CI)	P-value	Multivariate OR (95% CI)	P-value
Age			0.996 (0.978, 1.013)	0.632
Gender	1.118 (0.544, 2.299)	0.762	1.606 (0.597, 4.321)	0.348
PCT	0.998 (0.986, 1.009)	0.671	1.005 (0.990, 1.020)	0.512
CRP	1.001 (0.996, 1.006)	0.667	1.001 (0.994, 1.007)	0.869
MPV	1.020 (0.951, 1.093)	0.584	1.021 (0.965, 1.081)	0.469
NLCR	1.016 (0.969, 1.066)	0.510	1.014 (0.953, 1.078)	0.663
SOFA	1.016 (0.969, 1.066)	<0.001	1.671 (1.392, 2.006)	<0.001

Receiver Operating Characteristic (ROC) Curve Analysis

The ROC curve analysis was conducted to evaluate the predictive accuracy of various biomarkers and the SOFA score for sepsis and VAP. The AUC values for PCT, CRP, MPV, and NLCR were

low, indicating poor predictive ability. In contrast, the SOFA score demonstrated excellent predictive accuracy, with an AUC of 0.860 ($p < 0.001$). This is illustrated in Figure 1.

Figure 1: ROC Curve Analysis for Biomarkers and SOFA Score

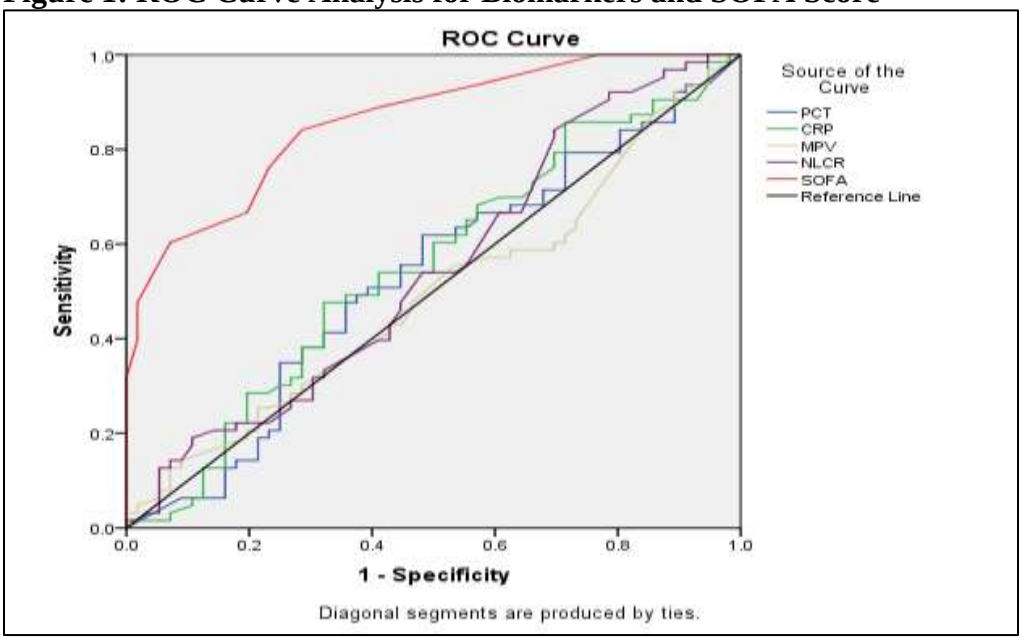


Figure 1 illustrates the predictive accuracy of PCT, CRP, MPV, NLCR, and the SOFA score for sepsis and VAP. The SOFA score (AUC = 0.860, $p < 0.001$) showed excellent predictive ability, while the other biomarkers had low AUC values.

Table 3: AUC Values for Biomarkers and SOFA Score

Variable	AUC	P-value	Asymptotic 95% Confidence Interval
PCT	0.529	0.582	0.424 – 0.635
CRP	0.552	0.327	0.448 – 0.657
MPV	0.494	0.913	0.390 – 0.599
NLCR	0.544	0.405	0.439 – 0.649
SOFA	0.860	0.000	0.796 – 0.924

Risk Factors for 28-Day Mortality

A 28-day mortality risk analysis through baseline SOFA score evaluation found the predictive strength at 1.492 (OR 95% CI: 1.288 – 1.728 $p < 0.001$). Gender and the SOFA score manifested statistically significant correlations with 28-day mortality based on multivariate analysis through their respective odds ratios of 0.306 (95% CI: 0.107 – 0.874, $p = 0.027$) and 1.536 (95% CI: 1.311 – 1.801, $p < 0.001$).

Table 4: Univariate and Multivariate Analysis of 28-Day Mortality

Variable	Univariate OR (95% CI)	P-value	Multivariate OR (95% CI)	P-value
Age	0.988 (0.990, 1.007)	0.736	0.998 (0.986, 1.010)	0.766
Gender	2.369 (1.081, 5.193)	0.031	0.306 (0.107, 0.874)	0.027
PCT	0.999 (0.987, 1.011)	0.863	1.008 (0.991, 1.024)	0.354
CRP	0.999 (0.994, 1.005)	0.810	0.999 (0.992, 1.006)	0.777
MPV	0.988 (0.945, 1.034)	0.607	1.001 (0.955, 1.049)	0.957
NLCR	0.993 (0.994, 1.044)	0.771	0.987 (0.917, 1.063)	0.733
SOFA	1.492 (1.288, 1.728)	<0.001	1.536 (1.311, 1.801)	<0.001

Scatter Plots of Biomarkers and SOFA Score in Survivors vs. Non-Survivors
Scatter plots were generated to visualize the differences in biomarker levels and SOFA scores between survivors and non-survivors of sepsis-related VAP. The scatter plots for PCT, CRP, and NLCR (Figures 2, 3, and 4) revealed no significant differences between survivors and non-survivors, indicating their limited predictive value for mortality. In contrast, the scatter plot for the SOFA score (Figure 5) demonstrated that non-survivors had significantly higher SOFA scores compared to survivors, highlighting its utility in mortality risk assessment.

Figure 2: Scatter Plot of PCT Levels in Survivors vs. Non-Survivors

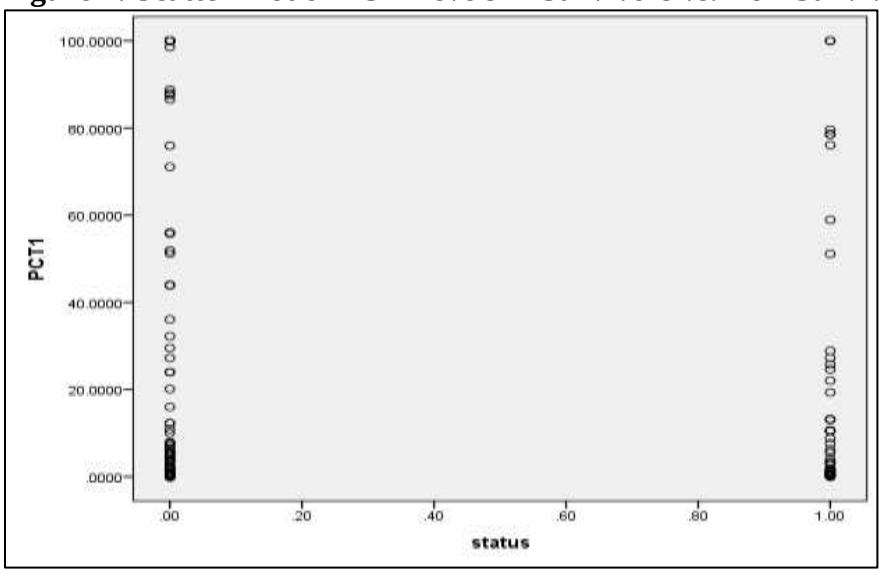


Figure 2 shows that PCT levels did not significantly differ between survivors and non-survivors of sepsis-related VAP, indicating its limited predictive value for mortality.

Figure 3: Scatter Plot of CRP Levels in Survivors vs. Non-Survivors

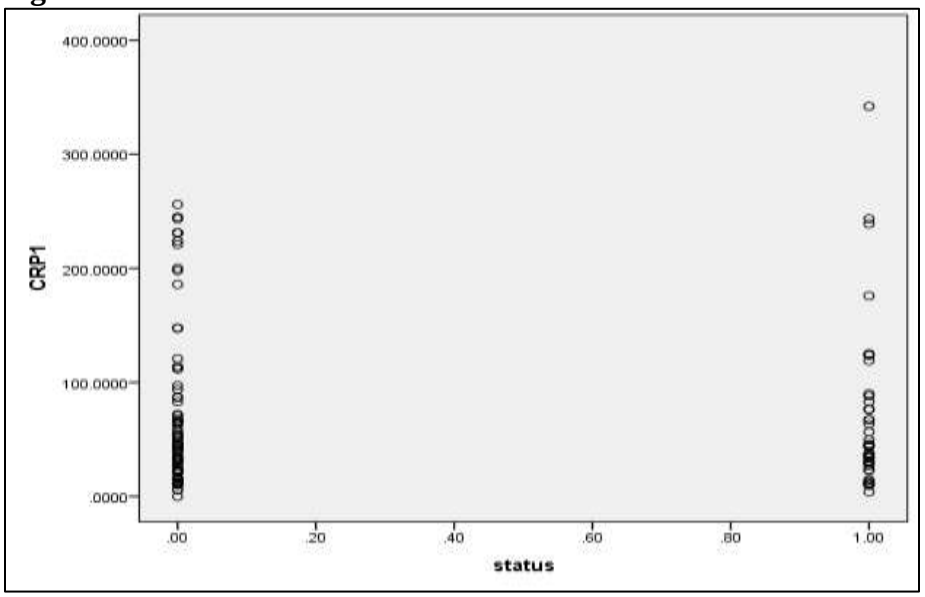


Figure 3 demonstrates that CRP levels were similar in both survivors and non-survivors, further supporting its limited role in predicting mortality.

Figure 4: Scatter Plot of NLCR in Survivors vs. Non-Survivors

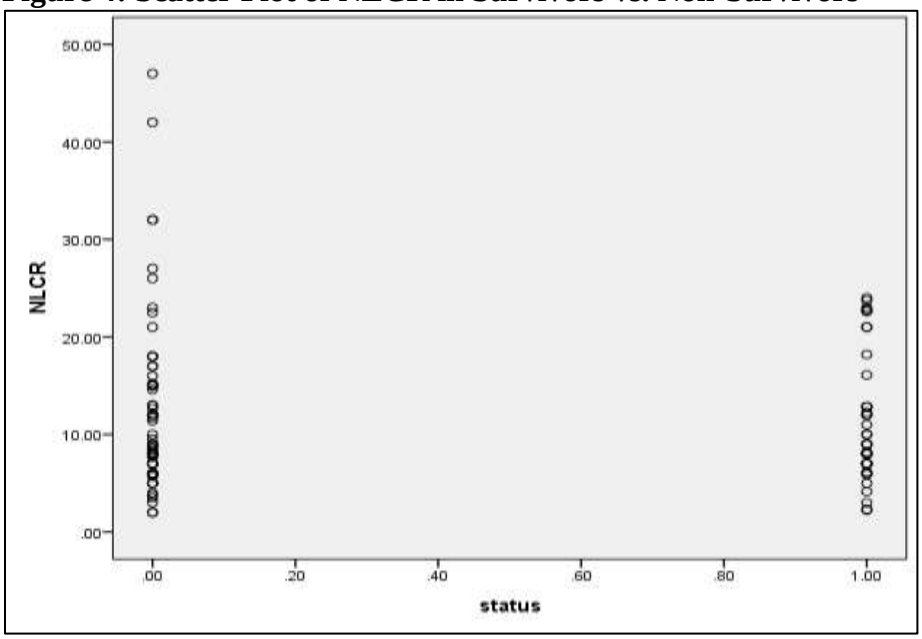


Figure 4 reveals that NLCR levels were comparable in both survivors and non-survivors, reinforcing its non-significant role in mortality prediction.

Figure 5: Scatter Plot of SOFA Scores in Survivors vs. Non-Survivors

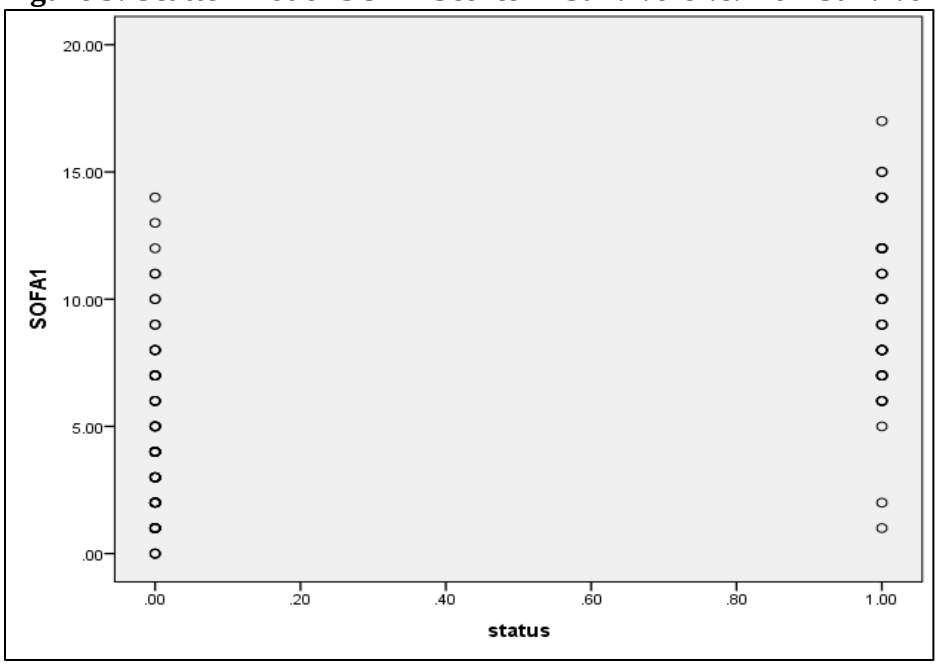
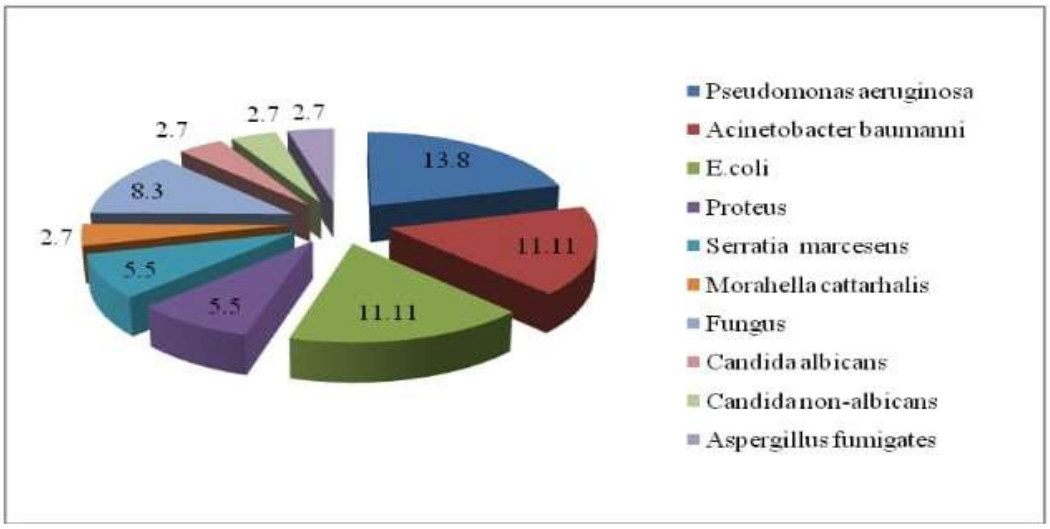


Figure 5 clearly depicts that non-survivors had significantly higher SOFA scores compared to survivors, emphasizing its importance in mortality risk assessment.

In conclusion, the SOFA score emerged as a key predictor of both VAP occurrence and 28-day mortality in sepsis patients, while traditional biomarkers such as PCT, CRP, MPV, and NLCR exhibited limited predictive potential. These findings underscore the importance of integrating

clinical scoring systems, such as the SOFA score, into the risk assessment and management of sepsis-related complications.

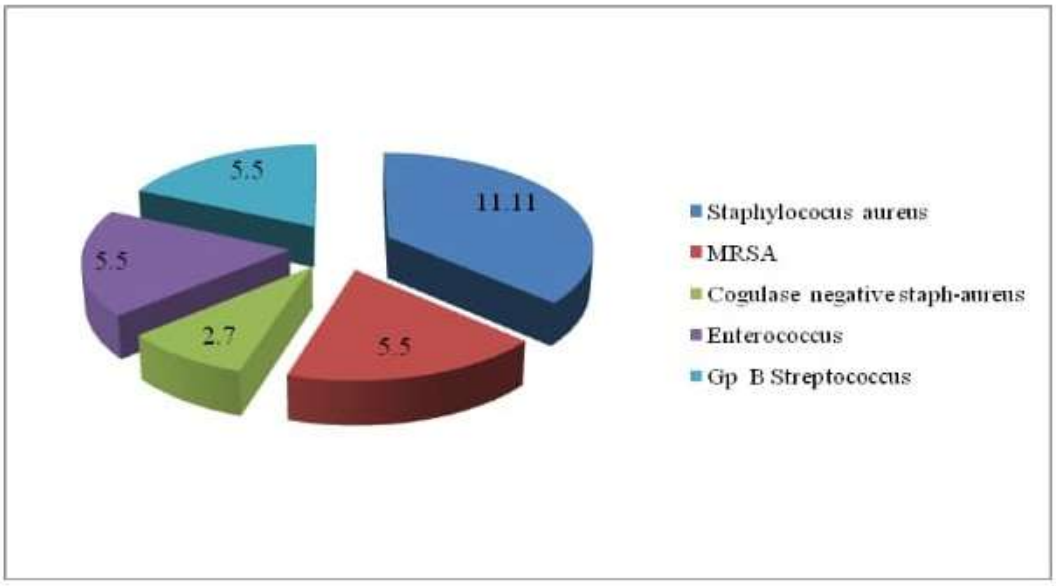
Figure 6: Microbiological Spectrum of Gram-Negative Organisms in VAP-Associated Sepsis



DISTRIBUTION OF GRAM NEGATIVE ORGANISMS IN CULTURE POSITIVE SEPSIS CASES (N=11)

Figure 6 illustrates the prevalence of Gram-negative organisms, including Pseudomonas aeruginosa, Escherichia coli, Klebsiella pneumoniae, Acinetobacter baumannii, and Enterobacter species, in VAP-associated sepsis.

Figure 7: Microbiological Spectrum of Gram-Positive Organisms in VAP-Associated Sepsis



DISTRIBUTION OF GRAM POSITIVE ORGANISMS IN CULTURE POSITIVE SEPSIS CASES (N=11)

Figure 7 shows the distribution of Gram-positive organisms, such as Staphylococcus aureus (both

methicillin-sensitive and methicillin-resistant strains), Streptococcus pneumoniae, and Enterococcus species, in VAP-associated sepsis.

DISCUSSION

The purpose of this study was to determine the usefulness of biomarkers and SOFA score for the prediction of VAP and sepsis, and to assess the microbiologic spectrum of Gram negative and Gram positive organisms in VAP associated sepsis. Findings indicate importance of SOFA score to predict both incidence of VAP and 28 days mortality, whereas traditional biomarkers such as procalcitonin (PCT), C-reactive protein (CRP), mean platelet volume (MPV), and neutrophil-to-lymphocyte count ratio (NLCR) had little added predictive value. The microbiological analysis also contributed to understanding the level of Gram negative and Gram-positive organisms present in VAP associated sepsis, which is significant in terms of treatment approach.

In sepsis patients, the SOFA score was the best predictor of VAP with excellent predictive accuracy (AUC = 0.860, $p < 0.001$). This supports previous findings that clinical scoring systems have utility in identifying patients at risk for developing VAP. In critically ill patients, the SOFA score, that evaluations organ dysfunction, is highly important as it correlates with the severity of illness and predicts complications such as VAP. Conversely, PCT, CRP, MPV, and NLCR, standard biomarkers, did not perform well in predicting the early detection of VAP in sepsis patients, perhaps exhibiting insufficient sensitivity or specificity for such an early detection. This implies the importance of incorporating clinical scoring systems like the SOFA score into routine clinical practice for estimating the risk of sepsis associated complications.

Higher SOFA score assessments in sepsis cases function as pivotal factors in identifying patients at risk of death during a 28-day period. Studies previously confirmed that the SOFA score serves as a useful prognostic indicator in intensive care unit patients. The multivariate analysis confirmed that gender combined with the SOFA score acted as independent factors which increased the risk of death during the 28-day period thus highlighting the significance of personalized sepsis treatment. The predictive capabilities of the SOFA score were found to be better than PCT, CRP and MPV and NLCR according to this study's results. The entire analysis illustrates that biomarkers can help doctors obtain richer mortality risk data beyond clinical scores at their disposal.

Healthcare practitioners diagnosed VAP-associated sepsis with *Pseudomonas aeruginosa*, *Escherichia coli*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, and *Enterobacter* species through microbiological assessments. The study results match international observations showing Gram-negative pathogens cause most hospital-acquired infections for intensive care unit patients receiving mechanical ventilation. Strengthened antimicrobial stewardship programs become essential because infection agents such as Acinetobacter baumannii and Pseudomonas aeruginosa appear frequently in multidrug resistant forms. Laboratory tests revealed Staphylococcus aureus (methicillin sensitive and methicillin resistant strains) and Streptococcus pneumoniae along with Enterococcus species as additional gram-positive bacterial isolates but at reduced frequencies. Hospital presence of Methicillin resistant Staphylococcus aureus (MRSA) proves that rapid microorganism detection and precise antibiotic treatment decisions lead to enhanced therapeutic outcomes.

This research faces limitations because of its retrospective data collection approach combined with a limited number of subjects which affects the generalization of study results. The findings from this research apply only to a singular clinical setting since the study was conducted in one facility which limits their implications for healthcare settings with different patient demographics and infection management protocols. Additional prospective studies with large sample sizes need to

validate these research findings as well as determine how emerging biomarkers contribute to sepsis and VAP investigation.

This study concludes with the observation that the SOFA score was a useful predictor for VAP occurrence and 28 day mortality in sepsis patients and traditional biomarkers were not predictive. The microbiological findings serve to consolidate the spectrum of pathogens implicated in VAP associated to sepsis and suggest the necessity of an appropriate antimicrobial therapy and infection control measures. These results emphasize that clinical scoring systems should become a part of routine practice forassessment and management of sepsis related complications to improve patients outcomes.

CONCLUSION

We show that Sequential Organ Failure Assessment (SOFA) score is superior to traditional biomarkers (procalcitonin (PCT), C-reactive protein (CRP), mean platelet volume (MPV) and neutrophil to lymphocyte count ratio (NLCR) to predict ventilator associated pneumonia (VAP) and to 28-day mortality in sepsis patients and have identified the SOFA score as an important resilience biomarker in sepsis patients. Although the VAP biomarkers added supplemental information, for both VAP and mortality their accuracy at predicting was limited, reaffirming that clinical scoring systems for risk stratification and decisions remain important. Through this assessment, the SOFA score proved to be a reliable tool for identifying high-risk patients such that timely interventions could be instituted to improve outcomes in critically ill individuals.

Furthermore, the microbiological analysis demonstrated figures of VAP associated sepsis with predominance of Gram-negative organisms, namely Pseudomonas aeruginosa, Escherichia coli and Acinetobacter baumannii as well as Gram positive pathogens, such as Staphylococcus aureus and Enterococcus species. These findings emphasize a critical point, that multidrug-resistant infections are a growing challenge, and prompt the need for individually tailored antimicrobial therapy and rigorous infection control measures in intensive care settings.

The results of this study advocate for incorporation of the SOFA score and microbial data into routine clinical practice to improve management of sepsis and VAP. Enhancing risk assessment and determining precise antimicrobial appropriate for critically ill patients can be accomplished by combining clinical scoring systems with targeted antimicrobial strategies. These findings pave the way to a more comprehensive approach to tackling sepsis related complications, which is vital for better patient outcomes.

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