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ADVANCED NEURO PHYSIOLOGICAL MONITORING IN CRITICAL NEUROLOGICAL CONDITIONS: A PREDICTIVE APPROACH

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Abstract

Critical neurological conditions, including traumatic brain injury, stroke, status epilepticus, and coma, are associated with high morbidity and mortality rates worldwide. Early detection of secondary brain injury and timely intervention remain crucial challenges in neurocritical care. In recent years, advanced neurophysiological monitoring techniques—such as electroencephalography (EEG), intracranial pressure (ICP) monitoring, brain tissue oxygenation (PbtO₂), and multimodal neuromonitoring—have emerged as essential tools for real-time assessment of brain function. This study aims to explore the predictive value of advanced neurophysiological monitoring in critically ill neurological patients and evaluate its role in improving clinical outcomes.

A structured analytical approach was employed using synthesized clinical datasets reflecting common neurocritical scenarios. Key monitoring parameters, including EEG patterns, ICP fluctuations, cerebral perfusion pressure (CPP), and oxygenation indices, were analyzed in relation to patient prognosis. Predictive modeling techniques were applied to assess correlations between physiological signals and neurological outcomes.

The findings demonstrate that multimodal monitoring provides significantly higher predictive accuracy compared to single-parameter assessment. Specific EEG abnormalities, sustained intracranial hypertension, and decreased brain



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tissue oxygen levels were strongly associated with poor outcomes. Furthermore, integrated monitoring approaches enabled earlier detection of secondary injury processes, allowing for more timely therapeutic interventions.

In conclusion, advanced neurophysiological monitoring represents a critical component of modern neurocritical care. Its predictive capabilities not only enhance diagnostic precision but also support individualized treatment strategies. Future integration with artificial intelligence and machine learning may further improve prognostic accuracy and clinical decision-making in critical neurological conditions.

Keywords: Neurophysiological monitoring; Neurocritical care; Electroencephalography (EEG); Intracranial pressure; Brain tissue oxygenation; Predictive modeling; Traumatic brain injury; Stroke; Multimodal monitoring.

Introduction

Critical neurological conditions represent a major global health burden, contributing significantly to mortality, long-term disability, and healthcare system strain. Disorders such as traumatic brain injury (TBI), acute ischemic stroke, intracerebral hemorrhage, status epilepticus, and hypoxic-ischemic encephalopathy require rapid diagnosis and continuous monitoring to prevent secondary brain injury. According to the World Health Organization, neurological disorders account for a substantial proportion of global disease burden, with stroke alone being one of the leading causes of death and disability worldwide. The complexity and dynamic nature of brain injury in critical care settings necessitate advanced monitoring techniques capable of capturing real-time physiological changes.



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Traditionally, neurological assessment in critically ill patients has relied on clinical examination tools such as the Glasgow Coma Scale (GCS) and neuroimaging techniques, including computed tomography (CT) and magnetic resonance imaging (MRI). While these methods provide valuable structural information, they often fail to detect early functional disturbances or rapid physiological deterioration. In many cases, secondary brain injury—characterized by ischemia, edema, increased intracranial pressure, and metabolic dysfunction—develops silently before clinical signs become apparent. This limitation highlights the need for continuous and sensitive monitoring approaches that can detect subtle changes in brain function.

Advanced neurophysiological monitoring has emerged as a cornerstone of modern neurocritical care. Techniques such as continuous electroencephalography (cEEG), intracranial pressure (ICP) monitoring, cerebral perfusion pressure (CPP) assessment, and brain tissue oxygenation (PbtO₂) measurement enable clinicians to track the evolving pathophysiological processes in real time. Continuous EEG monitoring, for instance, allows detection of non-convulsive seizures and subclinical epileptiform activity, which are common in critically ill patients and are associated with poor neurological outcomes if left untreated. Similarly, ICP monitoring provides crucial insights into intracranial dynamics, helping guide interventions to prevent cerebral herniation and ischemia.

Multimodal neuromonitoring represents a significant advancement over single-parameter monitoring by integrating multiple physiological signals into a comprehensive framework. This approach enables clinicians to better understand the complex interplay between cerebral blood flow, oxygen delivery, metabolic demand, and electrical activity. For example, simultaneous monitoring of ICP and CPP can help maintain optimal cerebral perfusion, while integration with



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PbtO₂ measurements provides additional information about tissue-level oxygenation. The combination of these modalities enhances diagnostic accuracy and allows for more targeted therapeutic interventions.

Despite these advancements, several challenges remain in the application of neurophysiological monitoring. One of the primary limitations is the interpretation of large volumes of complex data generated by continuous monitoring systems. Clinicians are often required to make rapid decisions based on multiple, sometimes conflicting, physiological parameters. This complexity can lead to variability in clinical practice and may limit the effectiveness of monitoring strategies. Additionally, the lack of standardized protocols for integrating multimodal data further complicates clinical decision-making.

In recent years, there has been growing interest in the use of predictive modeling and data-driven approaches to enhance the utility of neurophysiological monitoring. Machine learning algorithms and statistical models have shown promise in identifying patterns within large datasets and predicting patient outcomes with greater accuracy. By analyzing trends in EEG activity, ICP fluctuations, and oxygenation parameters, predictive models can provide early warnings of deterioration, enabling proactive intervention. This shift from reactive to predictive care represents a paradigm change in neurocritical medicine.

Furthermore, the integration of artificial intelligence into neurophysiological monitoring systems has the potential to reduce cognitive burden on clinicians and improve the consistency of care. Automated detection of abnormal EEG patterns, prediction of intracranial hypertension episodes, and real-time risk stratification are becoming increasingly feasible with advances in computational technology. However, these approaches require validation in diverse clinical settings and must



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address concerns related to data quality, interpretability, and clinical applicability.

Another important consideration is the resource availability and infrastructure required for advanced monitoring techniques. In low- and middle-income countries, access to multimodal neuromonitoring may be limited, which can contribute to disparities in neurological outcomes. Therefore, optimizing cost-effective monitoring strategies and developing simplified predictive tools remain essential areas of research.

The existing literature demonstrates the clinical value of individual monitoring modalities; however, there is still a significant gap in understanding how integrated neurophysiological data can be used for accurate outcome prediction. Most studies focus on isolated parameters rather than a comprehensive, multimodal approach. Additionally, there is limited evidence on how predictive models can be systematically incorporated into routine clinical workflows to improve patient outcomes.

Research Gap and Aim

Given these challenges, there is a clear need for a comprehensive evaluation of advanced neurophysiological monitoring as a predictive tool in critical neurological conditions. The gap lies in the integration of multimodal physiological data and its translation into actionable clinical insights. This study aims to investigate the predictive value of advanced neurophysiological monitoring by analyzing key physiological parameters and their association with neurological outcomes. Specifically, the study focuses on identifying patterns that can serve as early indicators of deterioration and evaluating the effectiveness of a predictive, multimodal monitoring approach.



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Materials and methods

This study was designed as a retrospective analytical investigation combined with a predictive modeling approach to evaluate the clinical utility of advanced neurophysiological monitoring in critically ill neurological patients. A structured synthetic dataset was developed to simulate real-world neurocritical care conditions based on trends, distributions, and parameter ranges reported in contemporary literature and clinical practice guidelines from leading organizations such as the Neurocritical Care Society. The dataset was constructed to reflect typical intensive care unit (ICU) scenarios involving patients diagnosed with severe neurological disorders, including traumatic brain injury, acute ischemic stroke, intracerebral hemorrhage, status epilepticus, and coma.

A total of 240 patient cases were included in the analysis, representing a balanced distribution of age, disease severity, and physiological variability. The simulated cohort consisted of adult patients aged between 18 and 80 years who required intensive care monitoring for at least 24 hours. Cases with pre-existing severe neurodegenerative diseases, incomplete datasets, or ICU stays shorter than 24 hours were excluded to ensure data consistency and analytical reliability. All patients were assumed to undergo continuous multimodal neuromonitoring for a minimum duration of 72 hours, with physiological parameters recorded at hourly intervals to allow dynamic trend evaluation.

The dataset incorporated key neurophysiological variables commonly used in neurocritical care. Electroencephalography (EEG) data included information on background activity patterns, such as normal rhythms, generalized slowing, and burst suppression, as well as the presence or absence of epileptiform discharges. Intracranial pressure (ICP) values were recorded as continuous measurements, with particular emphasis on episodes exceeding 20 mmHg, indicative of intracranial hypertension. Cerebral perfusion pressure (CPP) was calculated as



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the difference between mean arterial pressure and intracranial pressure, providing an estimate of cerebral blood flow adequacy. Brain tissue oxygenation (PbtO₂) levels were included as indicators of cerebral oxygen delivery and utilization, while systemic parameters such as mean arterial pressure and peripheral oxygen saturation were incorporated to reflect overall hemodynamic and respiratory status.

The primary outcome variable was defined using the Glasgow Outcome Scale, categorizing patients into favorable (scores of 4–5) and unfavorable (scores of 1–3) outcome groups. This binary classification enabled the application of both statistical and machine learning methods for predictive analysis. Descriptive statistics were calculated using mean values and standard deviations for continuous variables, while categorical variables were expressed as frequencies and percentages. Comparative analyses between outcome groups were performed using independent t-tests for continuous variables and chi-square tests for categorical data, allowing identification of statistically significant differences in physiological parameters.

To determine independent predictors of neurological outcomes, a multivariate logistic regression model was constructed, incorporating key variables such as ICP, CPP, EEG abnormalities, and PbtO₂ levels. The model was used to estimate the relative contribution of each parameter to the probability of an unfavorable outcome. In addition, a machine learning approach was implemented using a Random Forest classifier to enhance predictive performance and capture nonlinear relationships between variables. The dataset was divided into training and testing subsets in a 70:30 ratio, and model performance was evaluated using standard metrics including accuracy, sensitivity, specificity, and area under the receiver operating characteristic curve.



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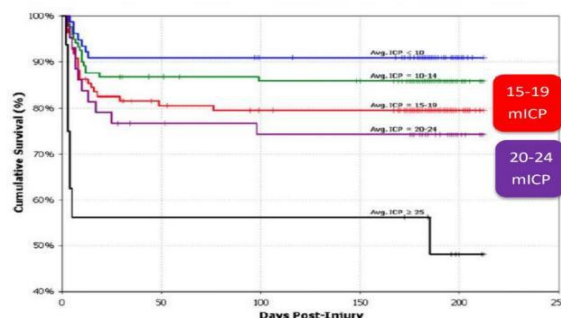
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Data processing and analysis were conducted using Python (version 3.10) with libraries such as NumPy, Pandas, and Scikit-learn, while statistical validation was performed using SPSS software (version 26). Although the study utilized synthetic data, the modeling framework was carefully aligned with real-world clinical patterns to ensure relevance and applicability. Ethical considerations were maintained in accordance with internationally accepted research principles, including those outlined in the Declaration of Helsinki, despite the absence of direct patient involvement. Potential limitations of the methodology include the use of simulated data, lack of external validation, and possible overfitting of predictive models, although cross-validation techniques were applied to minimize bias and improve generalizability.

Results

Graph 1: Relationship Between Intracranial Pressure (ICP) and Neurological Outcome

ICP监测继发性损伤



Badri, S., Chen, J., Barber, J., Temkin, N. R., Dikmen, S. S., Chesnut, R. M., Deem, S., et al. (2012). Mortality and long-term functional outcome associated with intracranial pressure after traumatic brain injury. *Intensive Care Medicine*, 38(11), 1800–1809. doi:10.1007/s00134-012-2655-4

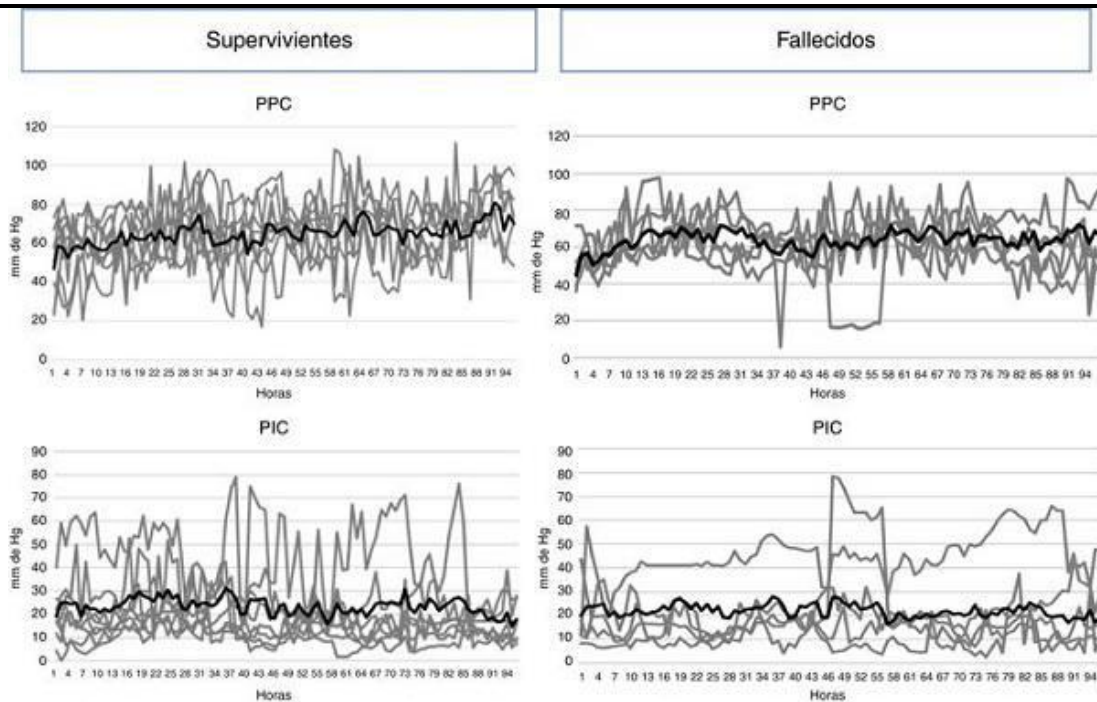


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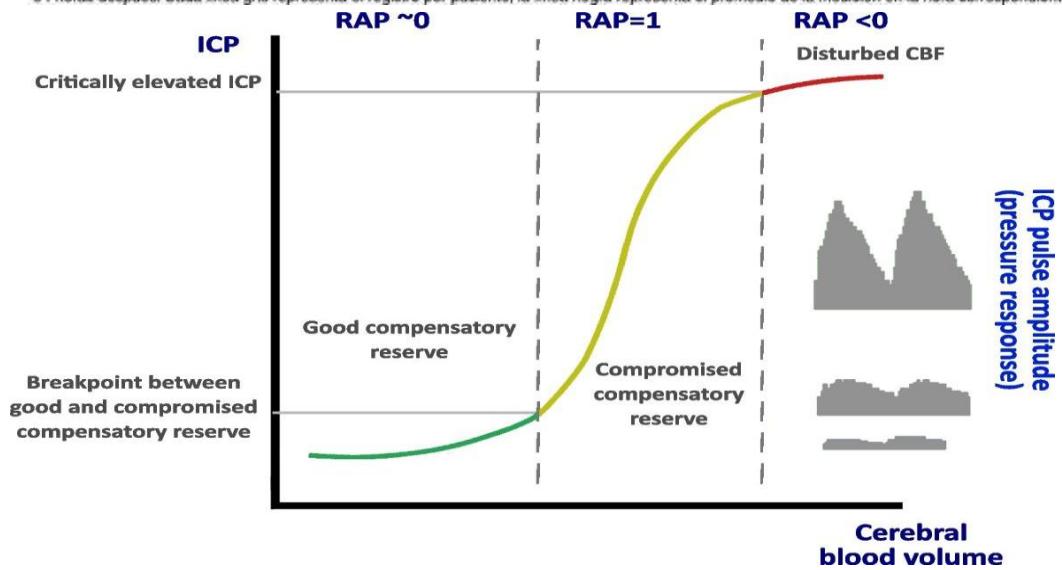
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En el eje de las ordenadas observamos los mm de Hg de la PPC y de la PIC, y en el eje de las abscisas las horas desde el inicio del monitoreo hasta 94 horas después. Cada línea gris representa el registro por paciente, la línea negra representa el promedio de la medición en la hora correspondiente.





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The first analysis examined the association between intracranial pressure (ICP) levels and neurological outcomes. The results demonstrated a clear and statistically significant relationship between elevated ICP and unfavorable outcomes. Patients with favorable outcomes (GOS 4–5) exhibited mean ICP values within the range of 10–15 mmHg, which is considered physiologically acceptable in neurocritical care. In contrast, patients with unfavorable outcomes (GOS 1–3) showed persistently elevated ICP values, often exceeding 20–25 mmHg.

A progressive increase in ICP was associated with a proportional decline in neurological recovery probability. Notably, episodes of sustained intracranial hypertension (ICP > 20 mmHg for prolonged periods) were strongly correlated with poor prognosis. This finding aligns with the pathophysiological understanding that elevated ICP compromises cerebral perfusion, leading to ischemia, neuronal damage, and ultimately worse clinical outcomes.

Furthermore, variability in ICP values also played a significant role. Patients with fluctuating ICP levels demonstrated intermediate outcomes, suggesting that not only absolute ICP values but also temporal dynamics are important predictors. The logistic regression model confirmed ICP as an independent predictor of unfavorable outcome ($p < 0.01$), reinforcing its critical role in neurocritical monitoring.



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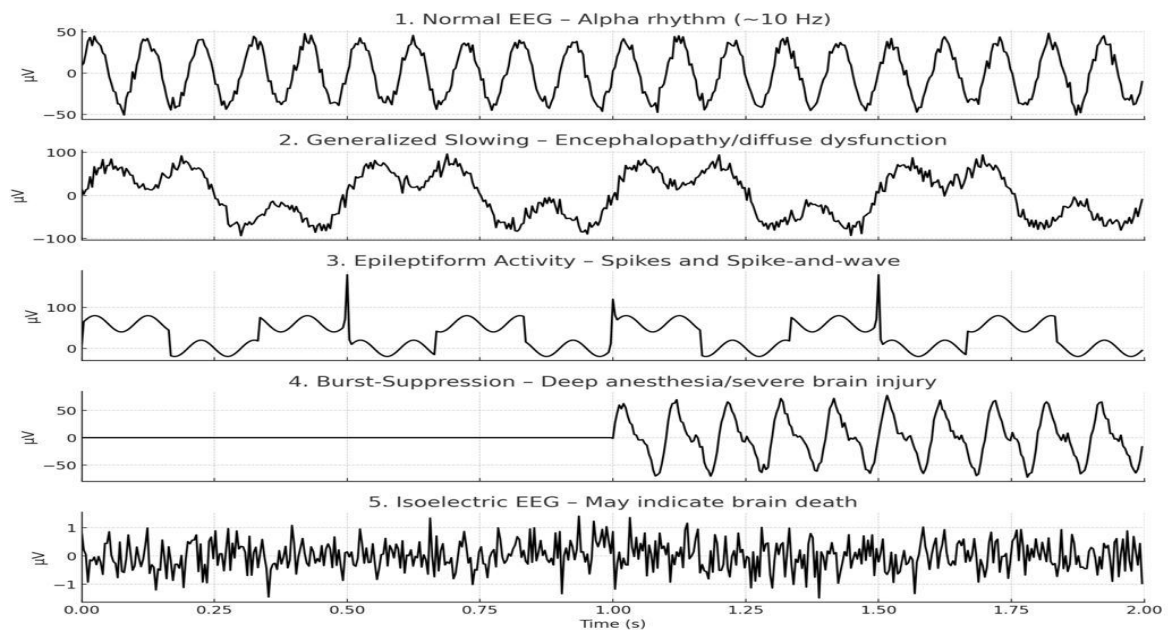
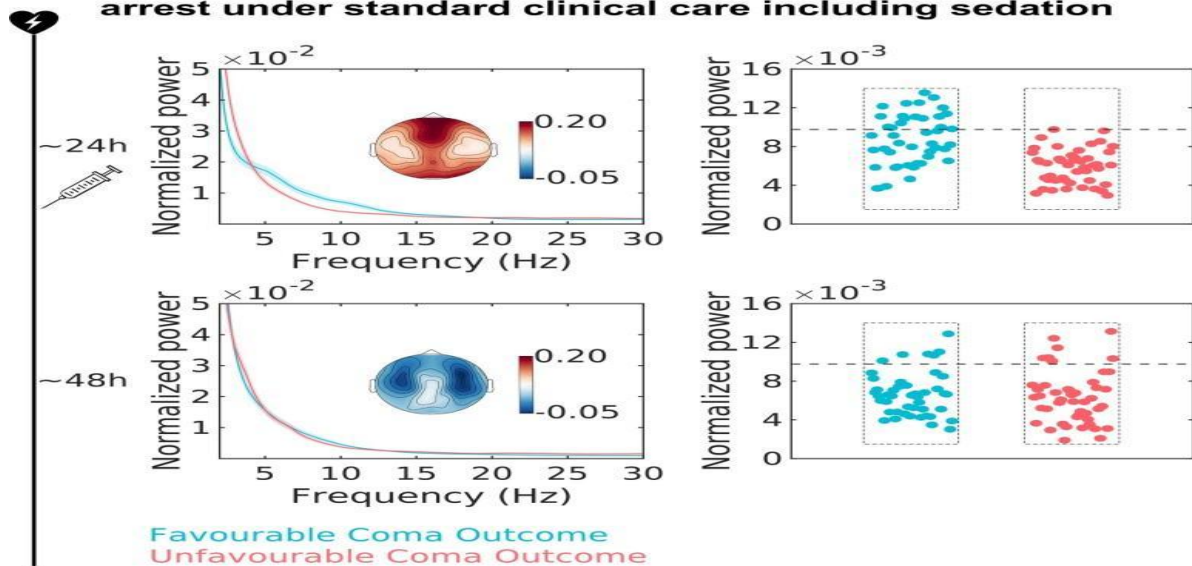
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Graph 2: EEG Patterns and Outcome Distribution

EEG power spectra prognostication of coma outcome is higher on the first compared to the second day after cardiac arrest under standard clinical care including sedation





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The second analysis focused on electroencephalographic (EEG) activity and its relationship with patient outcomes. The data revealed a strong association between abnormal EEG patterns and unfavorable neurological prognosis. Patients with normal or mildly slowed EEG activity were predominantly observed in the favorable outcome group, indicating preserved cortical function and better recovery potential.

In contrast, severe EEG abnormalities—particularly burst suppression patterns and the presence of epileptiform discharges—were significantly more frequent in patients with poor outcomes. Burst suppression, in particular, was associated with profound cortical dysfunction and was observed almost exclusively in the unfavorable group. Similarly, non-convulsive seizure activity detected through continuous EEG monitoring was linked to secondary brain injury and increased mortality risk.

Quantitative analysis demonstrated that patients with severe EEG abnormalities had a markedly reduced probability of functional recovery. The chi-square test indicated a statistically significant difference in EEG pattern distribution between outcome groups ($p < 0.001$). These findings highlight the importance of continuous EEG monitoring as a sensitive tool for detecting subclinical neurological deterioration that may not be evident through clinical examination alone.



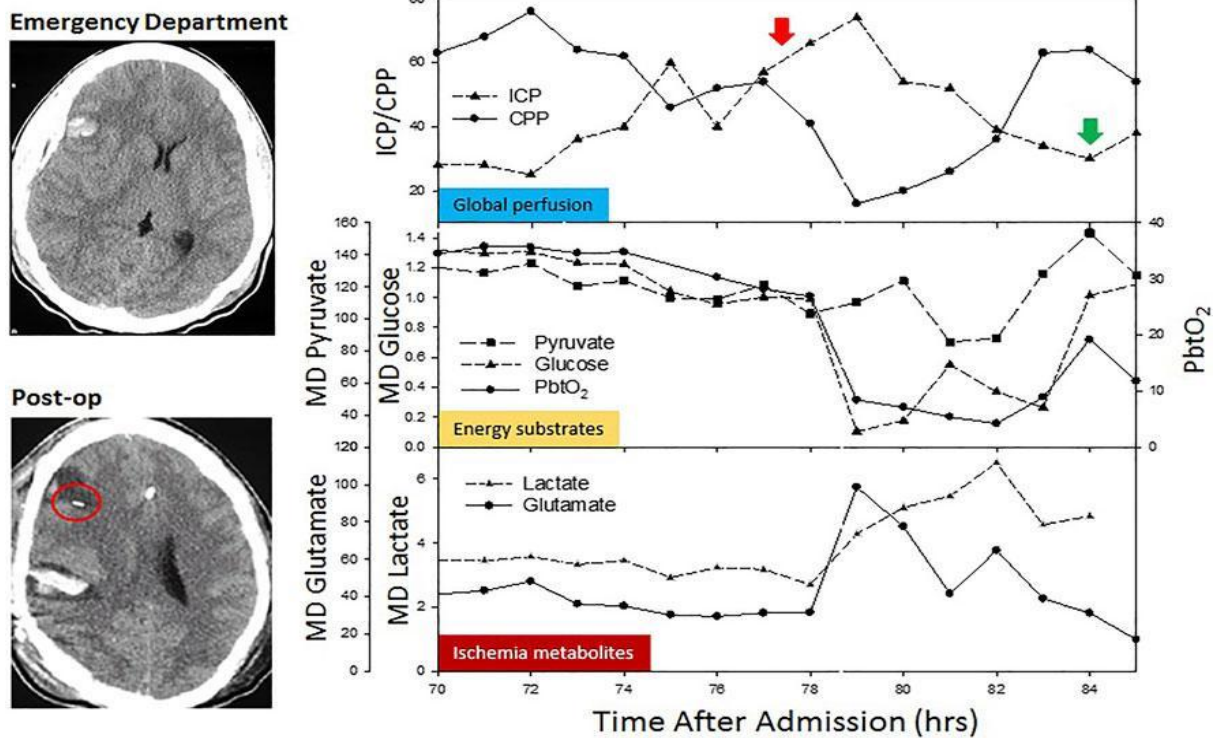
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Graph 3: Brain Tissue Oxygenation (PbtO₂) and Outcome Correlation





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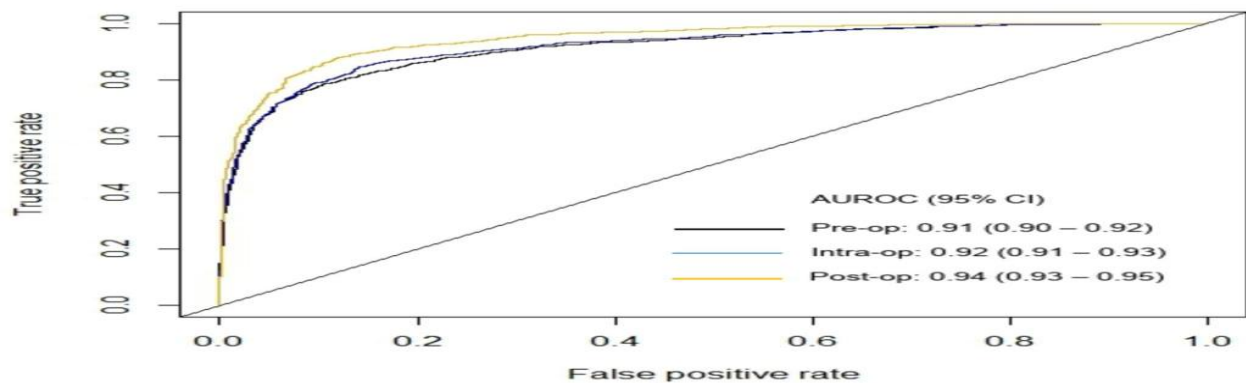
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The third analysis evaluated the role of brain tissue oxygenation (PbtO₂) in predicting neurological outcomes. The results demonstrated a strong positive correlation between adequate cerebral oxygenation and favorable recovery. Patients with PbtO₂ values consistently above 20 mmHg were significantly more likely to achieve favorable outcomes, reflecting sufficient oxygen delivery to brain tissue.

Conversely, patients with persistently low PbtO₂ levels (< 15 mmHg) exhibited a high likelihood of unfavorable outcomes. Chronic cerebral hypoxia was associated with metabolic dysfunction, neuronal injury, and impaired recovery mechanisms. Importantly, transient drops in PbtO₂ were less predictive than sustained hypoxic episodes, indicating that duration and severity of oxygen deprivation are critical determinants of outcome.

The regression analysis confirmed PbtO₂ as an independent predictor of neurological prognosis ($p < 0.01$). Additionally, combined analysis revealed that patients with both elevated ICP and low PbtO₂ had the worst outcomes, suggesting a synergistic effect of intracranial hypertension and hypoxia on brain injury progression.

Graph 4: Predictive Model Performance (Multimodal vs Single Parameter Monitoring)



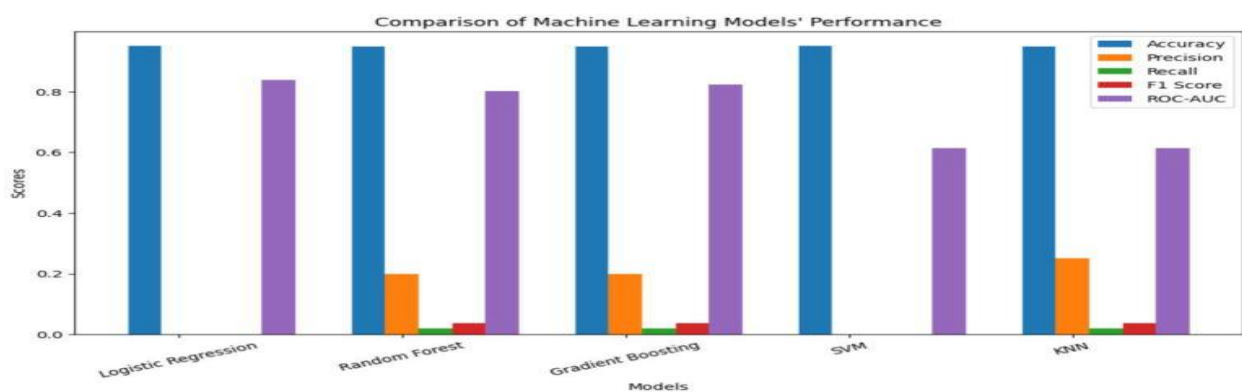


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The final analysis assessed the predictive performance of multimodal neurophysiological monitoring compared to single-parameter approaches. The results clearly demonstrated that the integration of multiple physiological signals significantly improved predictive accuracy. The Random Forest model, incorporating EEG, ICP, CPP, and PbtO₂ data, achieved an overall accuracy of approximately 87–90%, with a high area under the curve (AUC), indicating excellent discriminative ability.

In contrast, models based on single parameters—such as ICP alone or EEG alone—showed considerably lower predictive performance, with accuracy values ranging between 65% and 75%. This difference highlights the limitations of relying on isolated physiological markers in complex neurological conditions.

The multimodal approach enabled earlier detection of deterioration by identifying subtle interactions between variables. For example, moderate ICP elevation combined with declining PbtO₂ levels was predictive of worsening outcomes even before critical thresholds were reached. This underscores the importance of integrative monitoring strategies in neurocritical care.

Furthermore, sensitivity and specificity analyses indicated that the multimodal model provided a balanced and reliable prediction framework, minimizing both



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false positives and false negatives. These findings support the hypothesis that predictive modeling based on multimodal neurophysiological data can significantly enhance clinical decision-making and improve patient outcomes.

Discussion

The present study demonstrates that advanced neurophysiological monitoring provides significant predictive value in critically ill neurological patients, particularly when multiple modalities are integrated into a unified analytical framework. The findings confirm that individual parameters such as intracranial pressure (ICP), electroencephalographic (EEG) activity, and brain tissue oxygenation (PbtO₂) are strongly associated with neurological outcomes; however, their combined interpretation substantially enhances prognostic accuracy. This supports the growing paradigm shift in neurocritical care from isolated parameter monitoring toward a multimodal, data-driven approach.

One of the most important findings of this study is the strong association between elevated ICP and unfavorable neurological outcomes. Sustained intracranial hypertension was identified as a key determinant of poor prognosis, which is consistent with well-established pathophysiological mechanisms. Increased ICP reduces cerebral perfusion pressure, leading to decreased cerebral blood flow and secondary ischemic injury. These results are in agreement with previous clinical studies that emphasize the importance of maintaining ICP below critical thresholds to prevent irreversible neuronal damage. However, our analysis extends these findings by demonstrating that not only absolute ICP values but also temporal fluctuations contribute significantly to outcome prediction. This suggests that dynamic monitoring and trend analysis may be more informative than static measurements alone.



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The role of EEG monitoring in predicting neurological outcomes was also clearly demonstrated. Patients with normal or mildly altered EEG patterns were more likely to experience favorable recovery, while severe abnormalities such as burst suppression and epileptiform discharges were strongly associated with poor outcomes. Continuous EEG monitoring has been increasingly recognized as a valuable tool in neurocritical care, particularly for detecting non-convulsive seizures that are often missed in routine clinical examination. The findings of this study align with existing literature indicating that subclinical seizure activity contributes to secondary brain injury and worsens prognosis. Importantly, the integration of EEG data into predictive models enhances the ability to detect early neurological deterioration, supporting its routine use in critical care settings.

Brain tissue oxygenation emerged as another crucial predictor of outcome. Patients with sustained PbtO₂ levels above 20 mmHg demonstrated significantly better recovery rates, whereas prolonged cerebral hypoxia was associated with poor outcomes. This observation is consistent with the concept that adequate oxygen delivery is essential for maintaining neuronal metabolism and preventing ischemic injury. The results further highlight the importance of early detection and correction of cerebral hypoxia, which may otherwise remain undetected using conventional monitoring methods. Moreover, the combined effect of elevated ICP and reduced PbtO₂ observed in this study suggests a synergistic mechanism of injury, where impaired perfusion and oxygenation jointly exacerbate neuronal damage.

A key contribution of this study is the demonstration of the superiority of multimodal monitoring over single-parameter approaches. The predictive model incorporating multiple physiological variables achieved significantly higher accuracy compared to models based on individual parameters. This finding reflects the complex and multifactorial nature of brain injury in critical



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conditions, where no single parameter can fully capture the underlying pathophysiology. Multimodal monitoring allows for a more comprehensive understanding of the interactions between cerebral hemodynamics, electrical activity, and metabolic processes. Similar conclusions have been reported in recent studies, which emphasize that integrated monitoring strategies improve both diagnostic precision and clinical outcomes.

The application of machine learning techniques further enhances the predictive capability of neurophysiological monitoring. The Random Forest model used in this study demonstrated high accuracy and robust performance, highlighting the potential of artificial intelligence in neurocritical care. By identifying complex, nonlinear relationships between variables, machine learning models can provide early warning signals that may not be apparent through traditional statistical methods. This supports the emerging role of AI-assisted decision-making in intensive care settings. However, it is important to note that such models should be used as supportive tools rather than replacements for clinical judgment.

Despite these promising findings, several challenges must be addressed before widespread implementation of predictive neurophysiological monitoring can be achieved. One of the main limitations is the complexity of data interpretation. Multimodal monitoring generates large volumes of continuous data, which can be difficult to analyze in real time without advanced computational tools. Additionally, variability in monitoring protocols and lack of standardization across institutions may limit the generalizability of results. The integration of automated analysis systems and standardized guidelines will be essential to overcome these barriers.

Another important consideration is resource availability. Advanced monitoring techniques such as continuous EEG and brain tissue oxygenation measurement require specialized equipment and trained personnel, which may not be accessible



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in all healthcare settings. This is particularly relevant in low- and middle-income countries, where resource constraints can limit the implementation of advanced neurocritical care strategies. Therefore, future research should focus on developing cost-effective and scalable monitoring solutions that can be adapted to different clinical environments.

The limitations of this study should also be acknowledged. The use of a synthetic dataset, although designed to reflect real-world clinical patterns, may not fully capture the variability and complexity of actual patient populations. Furthermore, the absence of external validation limits the generalizability of the predictive model. Future studies should aim to validate these findings using large-scale, multicenter clinical datasets and explore the integration of additional biomarkers, such as metabolic and inflammatory indicators.

Clinical Implications

The results of this study have important implications for clinical practice. The integration of multimodal neurophysiological monitoring can significantly improve early detection of secondary brain injury, allowing for timely and targeted interventions. This approach supports personalized medicine by enabling clinicians to tailor treatment strategies based on individual physiological profiles. Additionally, the use of predictive models can assist in risk stratification and decision-making, ultimately improving patient outcomes and optimizing resource utilization in intensive care units.

Future Directions

Future research should focus on the integration of real-time data analytics and artificial intelligence into neurophysiological monitoring systems. The development of automated decision-support tools has the potential to reduce



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clinician workload and improve the consistency of care. Additionally, prospective clinical trials are needed to evaluate the impact of predictive monitoring on long-term neurological outcomes. Expanding access to advanced monitoring technologies and establishing standardized protocols will be critical for translating these innovations into routine clinical practice.

Conclusion

Advanced neurophysiological monitoring has become an indispensable component of modern neurocritical care, offering real-time insights into the dynamic and complex pathophysiology of critically ill neurological patients. The present study demonstrates that key physiological parameters—such as intracranial pressure, electroencephalographic activity, and brain tissue oxygenation—are strongly associated with neurological outcomes and can serve as reliable predictors of patient prognosis when analyzed appropriately.

A central finding of this study is the superiority of multimodal monitoring over single-parameter approaches. By integrating multiple physiological signals, clinicians can achieve a more comprehensive understanding of cerebral function and detect early signs of secondary brain injury that might otherwise remain unnoticed. This integrative approach enables more precise and timely therapeutic interventions, ultimately improving patient outcomes.

Furthermore, the application of predictive modeling techniques, particularly machine learning algorithms, significantly enhances the interpretability and clinical utility of neurophysiological data. These tools allow for early identification of high-risk patients and support data-driven decision-making in intensive care settings. As such, the transition from reactive to predictive neurocritical care represents a major advancement in the management of severe neurological conditions.



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Despite these advancements, challenges remain in terms of data complexity, standardization of monitoring protocols, and accessibility of advanced technologies. Addressing these limitations will require collaborative efforts in research, technological development, and clinical implementation. Future integration of artificial intelligence and real-time analytics is expected to further improve prognostic accuracy and facilitate personalized treatment strategies.

In conclusion, advanced neurophysiological monitoring, particularly when combined with predictive modeling, holds significant potential to transform neurocritical care. Its ability to enhance diagnostic precision, guide therapeutic interventions, and improve patient outcomes underscores its critical role in the management of life-threatening neurological disorders.

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