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Application of Multimodal Sensing Technology in Smart Monitoring and Nursing Process Reengineering in the NICU

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Abstract

To explore the application effectiveness of an intelligent monitoring system based on multimodal sensing technology (flexible sensors, smart central processing platform, mobile medical smart terminals) in the neonatal intensive care unit (NICU) and evaluate its impact on nursing workflow restructuring, a prospective randomized controlled study was conducted. A total of 120 preterm infants admitted to the NICU of a Level-A Tertiary Hospital (the highest level in China) from January to December 2024 were randomly assigned to an observation group (n=60) and a control group (n=60). The control group received conventional wired monitoring and routine care, while the observation group utilized a multimodal intelligent monitoring system comprising flexible sensors, a smart central processing platform, a medical mobile smart terminal (PDA), and environmental sensors. The study compared the following outcomes between groups: timely identification rate and effective alarm rate of clinical events (e.g., respiratory or cardiac abnormalities), nurse response time, daily nursing documentation time, nurse activity trajectory analysis for work efficiency, and nurse workload (assessed using the NASA-TLX scale). The results showed that the observation group’s timely clinical event recognition rate and effective alarm rate were both significantly higher than the control group's ($P < 0.001$). Both of the observation group's response time to alarm events and average daily nursing documentation time for nurses were significantly shorter than those in the control group ($P < 0.001$). The number of trips nurses made to the nursing station for documentation decreased significantly in the observation group compared to the control group, markedly improving work efficiency. Besides, the observation group's NASA-TLX scores were superior to the control group across all dimensions ($P < 0.05$). Conclusions can be drawn as the multimodal intelligent monitoring system accurately monitors neonatal vital signs, significantly enhances the timely identification rate and effective alarm rate of clinical events in the NICU, markedly reduces nurse response time, and substantially shortens the time nurses spend on documentation. It reconfigures the NICU's efficient nursing workflow centered on patient care and early warning, thereby improving nursing quality and ensuring patient safety, demonstrating significant clinical application value.

Keywords: multimodal sensing; neonatal monitoring; intelligent monitoring platform; nursing workflow; workload

1. Introduction & Literature Review

Vital signs of premature and critically ill newborns admitted to the Neonatal Intensive Care Unit (NICU) are critically important. Parameters such as heart rate, respiration, and blood oxygen saturation fluctuate rapidly. Traditional monitoring device connection methods suffer from monitoring blind spots, high false alarm rates, and frequent skin damage related to electrode adhesion (Hadaya & Nosarti, 2020). Furthermore, with separate devices operating independently, nurses must spend additional time transcribing data. Frequent data recording also consumes significant time that should be allocated to direct care and clinical observation, resulting in increased workload (Shaw et al., 2021). Therefore, integrating diverse monitoring technologies to comprehensively evaluate multiple parameters provides a mechanism-driven management framework for unstable neonatal conditions. Simultaneously, this approach is crucial for developing pathophysiology-based medical recommendations and strategies to address potential risks (Elsayed & Abdul Wahab, 2022).

In recent years, advancements in 5G/6G communications and AI technologies have amplified the role of multimodal sensing technology in environmental perception and vital sign monitoring (Lei Minghui, 2025). Its rapid development offers novel clinical pathways to address the aforementioned challenges. This approach integrates data from multiple technologies—such as bio-radar, cameras, temperature sensors, and pressure sensors—to enable non-contact, continuous, and comprehensive monitoring of patients' vital signs (Kwak et al., 2021). In NICU settings, it enables transcutaneous monitoring of blood oxygen trends without frequent blood draws while simultaneously tracking environmental temperature/humidity, noise levels, infant positioning, and activity status (Liang et al., 2019). Flexible electronics technology significantly enhances the safety and comfort of neonatal health monitoring through miniaturization, wireless connectivity, and biocompatible materials (Zhou et al., 2024). Smart central processing platforms with nursing whiteboards enhance information integration efficiency through visual interfaces, reduce nursing error risks, and increase nurses' direct patient care time (Huang & Li, 2024). Medical mobile intelligent terminals (PDAs) significantly improve nursing efficiency and safety through digital, real-time process optimization while enhancing patient experience, providing effective solutions for nursing management in high-risk environments (Zhao Xin, 2024). Mobile nursing systems are pivotal to realizing a “patient-centered” healthcare model (Lin Yuan Lei, 2020).

However, technological innovations lose much of their efficacy without deep clinical integration. This study aims to apply a multi-technology integrated smart monitoring system in the NICU and quantitatively evaluate its impact on enhancing medical quality and safety while optimizing nursing efficiency. This provides practical evidence for building a new generation of intelligent, human-centered NICUs.

2. General Information

This study employed a prospective randomized controlled design with a total of 120 newborns admitted to the NICU of a tertiary hospital between January and December 2024 enrolled. Inclusion criteria: (1) Gestational age 28–36 weeks; (2) Age at admission <7 days. Exclusion criteria: (1) Severe congenital malformations or chromosomal disorders; (2) Immediate surgical intervention required; (3) Skin conditions precluding any form of monitoring. A random number table was used to assign patients to an observation group and a control group, each comprising 100 cases. Baseline characteristics including gender, gestational age, birth weight, and Apgar scores showed no statistically significant differences between groups ($P > 0.05$), ensuring comparability.

3. Methodology

3.1 Control Group

Received routine NICU monitoring and care. Conventional monitors were used for standard vital sign monitoring, including heart rate (HR), respiratory rate (RR), and oxygen saturation (SpO_2). Electrodes and sensors were applied according to standard protocols. Nurses manually observed and recorded vital signs in the hospital information system (HIS).

3.2 Observation Group

In addition to routine care in the control group, the multimodal intelligent monitoring system was applied. The system's core components included: flexible sensors, a smart central processing platform, and medical mobile smart terminals. The core components and working principles of the system are as follows:

Flexible Sensors: Employing near-infrared light sources and high-resolution CMOS sensors, which utilize imaging photoplethysmography principles to track limb movements and extract vital signs such as pulse wave parameters and blood oxygen saturation (Verkruysse et al., 2008).

Embedded Environmental Sensors: Continuously monitor temperature, humidity, and environmental noise levels (measured in decibels) within the incubator.

Central Processing System and Dashboard: Integrates the aforementioned multi-source heterogeneous data using data fusion algorithms. Further employs algorithms for data fusion and automatic identification of abnormal events (e.g., apnea, bradycardia, desaturation) with risk alerts (Buisson et al., 2022). Alert information is pushed in real-time to the central display at the nursing station and mobile nursing terminals (PDAs).

3.3 The Architecture Diagram of the Multimodal Intelligent Monitoring System is Shown Below in Figure 1:

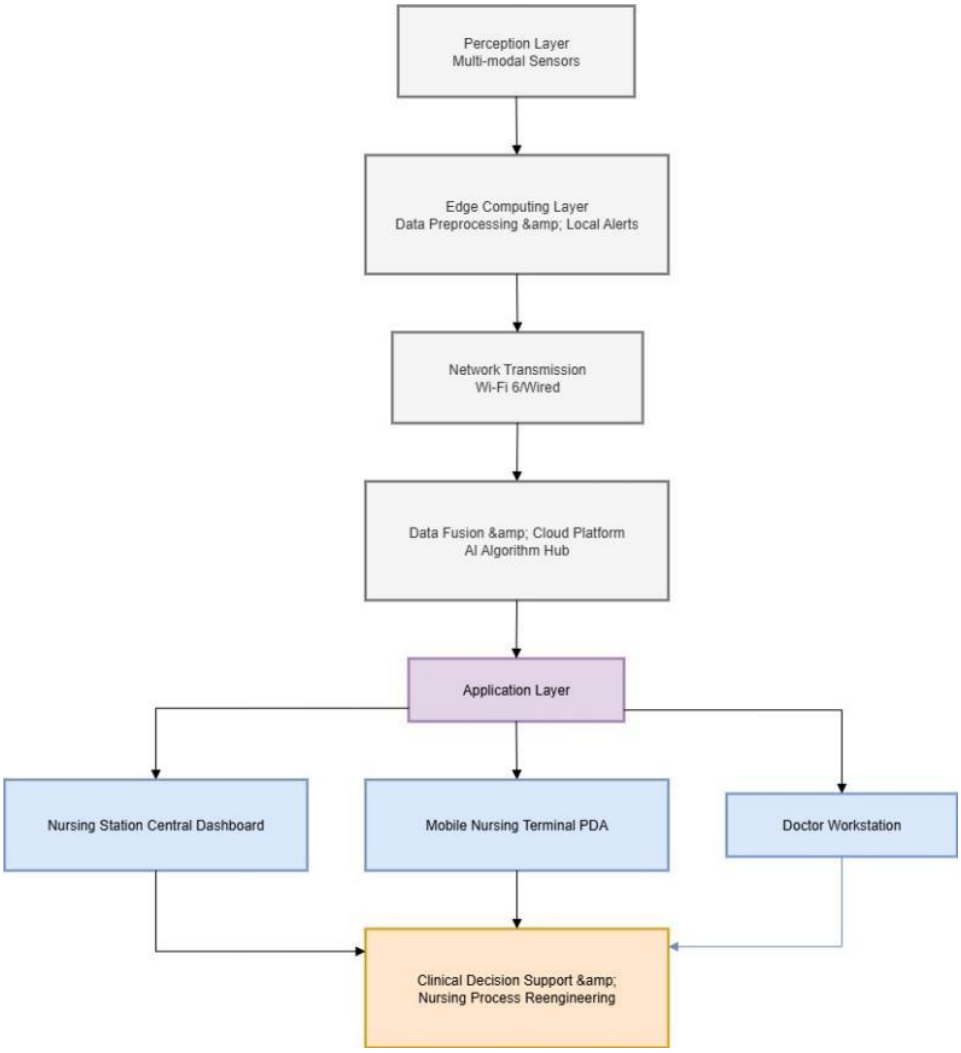

Figure 1. The Architecture Diagram of the Multimodal Intelligent Monitoring System

4. Evaluation Metrics

4.1 Monitoring Effectiveness Metrics

Timely Identification Rate of Clinical Events: The ratio of the system's automatically identified events (e.g., apnea >20 seconds, bradycardia with HR <100 bpm lasting >10 seconds) to the total occurrence rate.

Effective Alarm Rate: (True Alarms / Total Alarms) × 100%.

Nurse Response Time: Time (in seconds) from system alarm activation to nurse arrival at the patient's bedside and initiation of intervention.

4.2 Nursing Process Metrics

Nursing Documentation Time: Total time (minutes) spent daily by nurses entering vital signs data, calculated from backend system logs.

Nurse Activity Trajectory Analysis: Randomly select 20 nurses via the monitoring system to record their daily walking paths and distances within the ward, analyzing changes in work efficiency.

Nurse Workload: Assessed using the Chinese version of the NASA Task Load Index (NASA-TLX) (Liang Liling et al., 2019), which evaluates subjective workload across six dimensions: mental demands, physical demands, time demands, performance, effort, and frustration.

5. Statistical Methods

Data analysis was performed using SPSS 26.0 software. Quantitative data are expressed as mean ± standard deviation (x ± s), with intergroup comparisons conducted using Independent samples t-tests. Qualitative data are presented as percentages (%), with intergroup comparisons performed using Chi-square (χ^2) tests. Differences were considered statistically significant at $P < 0.05$.

6. Results

6.1 Comparing the Timely Identification Rate, Effective Alarm Rate, and Response Time Between the Two Groups

The observation group significantly outperformed the control group in timely clinical event identification, effective alarm rate, and nurse response time ($P < 0.001$).

Table 1. Comparison of Clinical Event Occurrence Frequency, Timely Identification Rate (%), Effective Alarm Rate (%), and Response Time (seconds) Between the Two Groups

Group	Number of Cases	Number of Clinical Events	Timely Detection Rate (%)	Effective Alarm Rate (%)	Response Time (seconds)
Control group	60	202	98.5	91.5	15.3±4.2
Observation group	60	189	85.2	68.3	45.8±12.6
t/χ^2			χ^2=25.731	χ^2=87.442	t=-18.594
P			<0.001	<0.001	<0.001

6.2 Comparing the Average Daily Nursing Documentation Time And Daily Walking Distance Between the Two Groups of Nurses

The observation group nurses spent significantly less time on daily nursing documentation and walked significantly fewer kilometers per day than the control group ($P < 0.05$).

Table 2. Comparison of Average Daily Documentation Time and Daily Walking Distance Between the Two Groups of Nurses

Group	Daily Document Processing Time (min)	Average Daily Walking Distance (km)
Control group（n=60）	98.7 ± 22.1	4.7 ± 1.1
Observation group（n=60）	45.6 ± 10.3	3.1 ± 0.8
t	-16.832	-7.112
P	<0.001	<0.001

6.3 Comparison of Nurse Activity Trajectories Between Two Groups

The intelligent system reduces the number of trips nurses make to the nursing station for documentation, concentrating their activities within direct patient care areas and enhancing work efficiency.

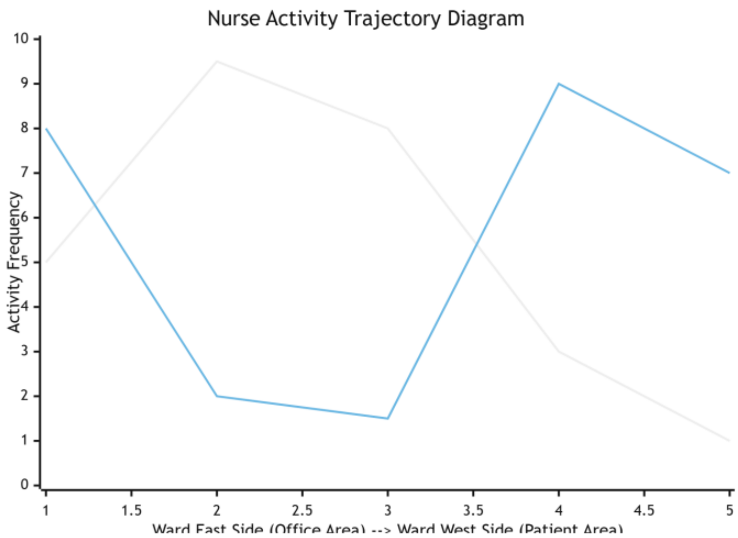

Figure 2. Comparison of Nurse Activity Trajectories Between Two Groups

Note: Dashed line (control group): Frequent switching between the nurses' station (documentation) and patient bedsides (alarm handling), with overlapping and repetitive paths. Solid line (observation group): Activity hotspots more concentrated around patient bedsides, with more efficient and planned pathways.

6.4 Comparison of NASA-TLX Task Load Scores Between the Two Groups of Nurses

As shown in Table 3, the observation group nurses scored significantly lower than the control group across all six dimensions, with the most pronounced differences observed in Mental Demand, Temporal Demand, and Frustration ($P < 0.001$).

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Table 3. Comparison of NASA-TLX Task Load Scores Between Nursing Groups (Points)

Evaluation Dimensions	Observation Group	Control Group	*t*	*P*
Mental Demand	38.5 ± 8.2	72.3 ± 10.5	-14.12	<0.001
Physical Demand	45.2 ± 9.1	45.2 ± 9.1	-5.21	<0.001
Temporal Demand	35.8 ± 7.5	68.9 ± 12.1	-13.08	<0.001
Effort	42.1 ± 8.8	55.4 ± 9.7	-5.72	<0.001
Performance	75.6 ± 6.9	60.2 ± 8.4	7.89	<0.001
Frustration	28.4 ± 6.7	65.7 ± 11.8	-15.93	<0.001
Total Score	265.6 ± 25.3	381.1 ± 35.7	-14.95	<0.001

Note: The NASA-TLX scale scores range from 0 to 100 for each dimension. Higher scores indicate greater workload or more negative feelings in that dimension; however, the “Performance” dimension is an exception, where higher scores reflect nurses' perception of better task completion.

6.5 Roadmap for the Reconstruction Framework of Nursing Processes in the NICU Based on Multimodal Intelligent Monitoring Technology

Through the closed-loop process of “monitoring-alerting-intervention”, the intelligent workflow significantly reduces the proportion of non-technical tasks performed by nurses while increasing the proportion of clinical decision-making.

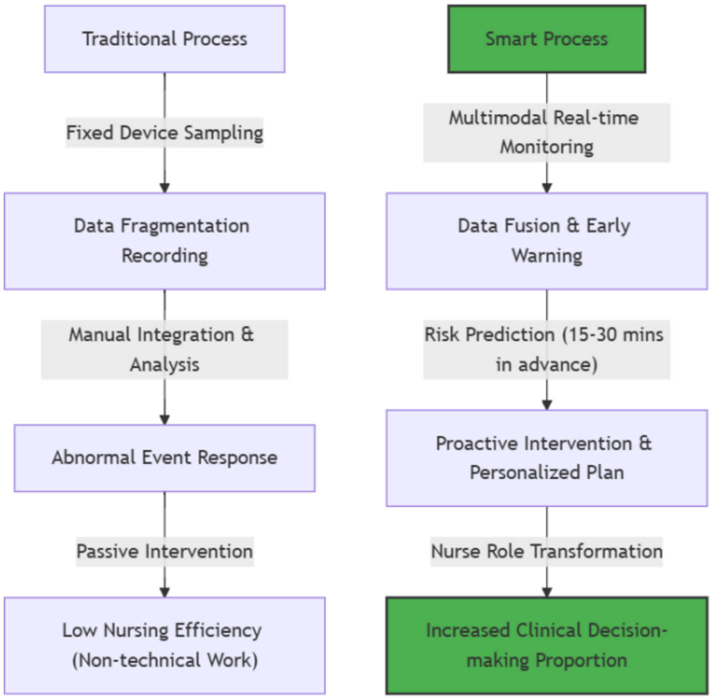

Figure 3. Roadmap for the Reconstruction Framework of NICU Nursing Processes

7. Discussion

The findings of this study indicate that, at the data quality level, the multimodal intelligent monitoring system achieves rigorous surveillance of vital signs in NICU patients through its continuous, multi-parameter monitoring capabilities. Its high event detection rate (98.5%) stems from the algorithm's cross-validation of multi-source information, laying a data foundation for precision medicine while effectively avoiding the time-consuming nature and false alarms/missed alerts associated with traditional monitors (Dong et al., 2021). The shorter response time (15.3 seconds) enables earlier clinical intervention, potentially exerting a significant direct impact on neonatal outcomes and thereby improving patient prognosis (Smith et al., 2021). In addition, at the nursing workflow level, this study quantified the intelligent system's restructuring effect on nursing processes. By automatically performing data collection, recording, and preliminary analysis, the system completely liberates nurses from burdensome, repetitive documentation tasks (saving approximately 1.5 hours daily). This allows nurses to dedicate more time and expertise to high-value humanistic care, participate in case discussions and clinical decision-making, implement developmental supportive care, collaborate with families, and engage in deeper clinical reasoning. This truly facilitates a role transition from “data recorder” to “clinical decision-maker” (Lemieux-Bourque, 2020). What is more, the return to nursing's core value, the evolution of the nursing role, and technology-enabled nursing—optimizing healthcare resource allocation and streamlining processes—can significantly enhance treatment efficiency (Pepito & Locsin, 2019).

8. Summary and Limitations

This study is limited by its single-center design and lack of long-term cost-benefit assessment. Future research should explore its impact on long-term patient outcomes, develop AI-based predictive models for early warning of severe complications, investigate home monitoring for high-risk infants' post-discharge, and conduct multicenter clinical validation to further establish its widespread application in NICUs.

The multimodal intelligent monitoring system represents a pivotal advancement toward intelligent, digital, and human-centered care in NICUs. It signifies not merely a technological innovation but a profound restructuring of nursing workflows and processes. By providing non-invasive, continuous, and highly accurate monitoring data, it significantly enhances patient safety. More critically, it optimizes nursing workflow and human resource allocation, redirecting nurses' time and expertise toward high-value clinical care practices. This ultimately achieves synergistic improvements in nursing quality, patient outcomes, and healthcare provider satisfaction, demonstrating broad clinical application and promotional value. Therefore, it lays a solid foundation for building the next generation of intelligent NICUs.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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