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Comprehensive Fault Analysis And Preventive Maintenance Strategies For Hemodilysis Machines Field Study On The Nipro Surdial

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الملخص:
تُعد أجهزة غسيل الكلى ضرورية لمرضى الفشل الكلوي في مراحله النهائية، إلا أن تعقيد تصميمها يجعلها عرضة للأعطال التي قد تؤدي إلى انقطاع العلاج وتهديد سلامة المريض. ومن الأعطال الشائعة أخطاء كاشف تسرب الدم، ومشكلات موصلية سائل الغسيل والتحكم في درجة حرارته، مما قد يسبب انحلال الدم أو اضطراب الشوارد أو إيقاف العلاج بشكل مفاجئ. ورغم أن الأنظمة الحديثة تحتوي على حساسات وآليات إنذار متعددة، فإنها غالبًا لا تعمل إلا بعد وقوع العطل. لذلك يتطلب ضمان الموثوقية صيانة وقائية صارمة وأدوات تشخيص ذكية. وقد أسهمت تطبيقات حديثة مثل تطبيق HD service في تحسين كفاءة استكشاف الأعطال، كما تُمكّن الصيانة التنبؤية باستخدام نماذج تعلم الآلة (مثل شبكات LSTM) من الكشف المبكر عن الأعطال. ومن المتوقع أن تسهم تقنيات إنترنت الأشياء، والتشخيص الذاتي، والتصميم المعياري مستقبلاً في تعزيز السلامة والاعتمادية التشغيل.

الكلمات المفتاحية: جهاز غسيل الكلى؛ عطل؛ صيانة؛ تشخيص تنبؤي؛ سلامة المريض؛ موثوقية.

Abstract: Hemodialysis machines are essential for patients with end-stage renal failure, yet their complex design makes them susceptible to faults that can interrupt therapy and jeopardize patient safety. Common malfunctions include blood-leak detector errors, dialysate conductivity and temperature-control faults, which may lead to hemolysis, electrolyte imbalance, or abrupt treatment cessation. Although modern systems incorporate multiple sensors and alarm mechanisms, these typically activate only after faults occur. Ensuring reliability therefore requires strict preventive maintenance and intelligent diagnostic tools. Recent advances such as the HD service app enhance troubleshooting efficiency, while predictive maintenance using machine-learning models (e.g., LSTM networks) enables early fault detection. Future developments including IoT-based monitoring, self-diagnostics, and modular system design are expected to further improve safety and operational reliability.

Keyword: Hemodialysis machine; malfunction; maintenance; predictive diagnostics; patient safety; reliability.

I . INTRODUCTION

Hemodialysis machines are critical for sustaining life in patients with end-stage renal disease (ESRD), functioning as artificial kidneys that remove toxins, excess fluids, and metabolic waste from the bloodstream. These systems play an essential role in preserving electrolyte balance and acid-base homeostasis, thereby preventing severe complications associated with renal failure. Over the years, the integration of dialysis technology into routine clinical practice has significantly improved both survival rates and quality of life for patients, establishing it as one of the most vital innovations in modern medicine (Canaud, 2023; Maduell *et al*., 2022a).

Nevertheless, the intricate structure of these machines—comprising electrical circuits,

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hydraulic pumps, control units, and numerous sensors—makes them susceptible to various technical malfunctions. Even seemingly minor faults, such as inaccurate temperature regulation, conductivity drift, or pressure imbalances, can disrupt the dialysis session or endanger the patient. Equipment downtime caused by such failures often leads to incomplete treatments, unscheduled maintenance, and increased clinical workload. Research has shown that recurring technical issues can reduce treatment effectiveness, cause patient discomfort, and in some cases lead to hospitalization due to inadequate waste removal (Maduell *et al.*, 2022b; Saha *et al.*, 2022).

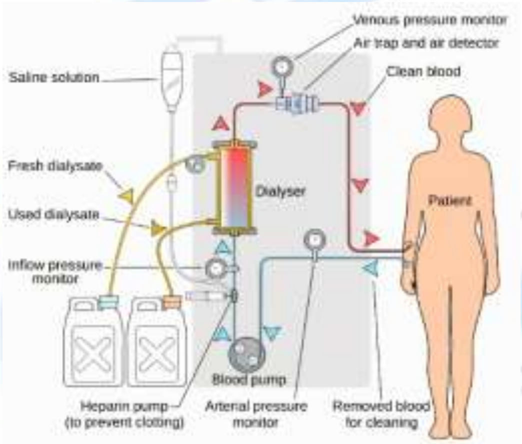

Fig 1: Schematic diagram of hemodialysis machine architecture.

For this reason, understanding the root causes and patterns of hemodialysis machine malfunctions is essential for improving performance reliability and ensuring uninterrupted therapy. The present study aims to identify and classify the most frequent types of faults in dialysis systems, with a focus on electrical, hydraulic, control, and sensor-related failures. It also seeks to evaluate diagnostic and maintenance strategies that can minimize downtime and enhance device dependability. By recognizing fault trends and integrating preventive maintenance with intelligent diagnostic methods, this work aims to contribute to the development of safer and more efficient hemodialysis practices (Rossi *et al.*, 2023a; Smith *et al.*, 2023).

II. SYSTEM OVERVIEW

A hemodialysis machine is a highly integrated biomedical system designed to replicate the excretory function of the kidneys. It consists of several key subsystems that work in harmony to ensure safe and effective treatment: the blood circuit, the dialysate circuit, the control and monitoring unit, and the alarm and safety system. Each subsystem performs a distinct role while remaining synchronized through electronic control logic and continuous sensor feedback (Canaud, 2023).

The blood circuit begins with a blood pump that propels the patient's blood through an extracorporeal tubing set toward the dialyzer. Pressure sensors monitor the arterial and venous lines to maintain stable flow and prevent complications such as hypotension, clotting, or air embolism. An air detector near the venous return line ensures that no air bubbles enter the bloodstream; if air is detected, the system automatically clamps the line and triggers an alarm. Simultaneously, the dialysate circuit prepares a solution with precise concentrations of electrolytes and bicarbonate, heated to approximately 37°C. This fluid circulates in a countercurrent direction relative to blood flow across the dialyzer membrane, allowing diffusion and ultrafiltration of waste products (Maduell *et al.*, 2023).

At the core of the system lies the control and monitoring unit, which continuously processes sensor data to regulate temperature, flow rate, conductivity, and ultrafiltration volume. Modern machines like the NIPRO Surdial X rely on microprocessor-based control boards and closed-loop systems that adjust pump speeds and valve positions in real time. These control units interface with a graphical user interface where treatment parameters are displayed and alarms are managed. The alarm and safety system ensures patient protection by immediately detecting abnormal conditions such as temperature deviation, blood leaks, pressure imbalances, or conductivity errors, and halting therapy when necessary (Shintaku & Mori, 2023).

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Each alarm is associated with a specific error code shown on the screen, enabling biomedical engineers to quickly identify the cause and take corrective action. In addition to hardware safeguards, software interlocks and self-test routines are executed before each session to verify the operational integrity of sensors, valves, and actuators (Yamamoto *et al.*, 2023). A schematic representation of the dialysis machine architecture typically highlights the interaction between the blood and dialysate circuits, emphasizing the sensor nodes and feedback loops used for automatic regulation. Understanding these interconnections is fundamental for accurate fault diagnosis and for preventing cascading failures (NIPRO Corporation, 2024).

III. CLASSIFICATION OF FAULTS

Hemodialysis machines such as the NIPRO Surdial X integrate hydraulic, electrical, control, and sensory subsystems, making them vulnerable to a variety of faults. Based on field observations, maintenance logs, and technical documentation, the most frequently encountered faults can be grouped into several categories: electrical and control faults, hydraulic faults, sensor faults, and alarm-related issues (El-Hariri *et al.*, 2022).

Fig. 2: NIPRO Surdial X Hemodialysis Machine.

A. Electrical and Control Faults:

These are among the most critical issues in clinical settings, often resulting from unstable power supplies, communication errors between sensors, or firmware malfunctions. The Surdial X features a dual-microcontroller architecture that isolates life-critical functions from auxiliary operations, using the CAN bus protocol for real-time data exchange. Any disruption in signal transmission triggers an automatic system shutdown and displays a corresponding fault code. This design ensures operational continuity and patient safety by locking the system until the error is resolved (Rossi et al., 2022). Common electrical and control faults observed include those listed in Table 1.

Table 1: Common Electrical and Control Fault Codes Observed in the Surdial X Hemodialysis Machine:

Fault Code	Category	Possible Cause	Corrective Action
E10	Power Supply Error	Voltage drop or unstable AC input	Check main power line, replace fuse, verify UPS stability
E18	Flow Sensor Error	Misalignment or clogging of the flow sensor	Clean and recalibrate the flow sensor
E29	CPU Communication Error	CAN bus interruption or firmware crash	Restart the system, inspect internal cables, reload firmware

A. Hydraulic Faults:

Hydraulic faults occur within the fluid management system, particularly in the blood, dialysate, and ultrafiltration circuits. The Surdial X employs a three-pump configuration with independent feedback-controlled loops. Common failures include blockages in filters, pressure imbalances, or contamination of the dialysate. Preventive measures include routine inspection of tubing and valves, filter replacement every three to six months, and regular pressure calibration (Maduell *et al*., 2023).

C. Sensory Faults:

Sensor-related issues are among the most frequent and challenging to diagnose. Since the Surdial X relies on accurate readings of pressure, temperature, and conductivity, any drift or contamination can lead to incorrect measurements and false alarms. For instance, a cracked conductivity sensor may trigger erroneous E07 alarms due to inaccurate dialysate concentration, while a defective temperature sensor can cause heater overheat alarms (E25). Regular calibration and periodic sensor replacement are essential for maintaining monitoring accuracy (Smith *et al*., 2023).

D. Alarm and Safety Faults:

The Surdial X includes a sophisticated alarm system that automatically detects unsafe conditions such as blood leaks, air bubbles, or extreme temperature variations, and pauses treatment until corrective action is taken. Each alarm event is stored in the system's internal log for later review. Table 2 lists common alarms and the corresponding corrective steps observed during the field study:

Table 2: Common Alarm and Safety Faults Observed in the Surdial X Hemodialysis Machine:

Malfunction / Alarm Code	Potential Cause	Initial Troubleshooting /Repair Action
Conductivity Alarm (E07)	Incorrect dialysate mixing ratio or faulty sensor	Verify concentrate connection, check water pressure, recalibrate or replace sensor
Blood Leak Alarm (E23)	Dialyzer membrane rupture or contaminated leak detector	Inspect dialyzer, check lines for air, clean or replace sensor, stop pump and clamp blood lines
Air Bubble Detection Alarm (E24)	Air entering the circuit due to loose connections	Check all tubing, ensure fluid levels, use air trap system to remove bubbles
Heater Overheat Alarm (E25)	Faulty heater or temperature sensor	Ensure adequate flow, verify temperature reading, restart or replace heater element
Temperature Min/Max Alarm (E05/E06)	Faulty control circuit or water temperature variation	Verify temperature setting, check heat changer, confirm stable water supply

These events demonstrate the machine's robust safety logic, which enforces automatic shutdown under unsafe conditions to minimize patient risk (Shintaku, 2024).

Fig. 3: Example of alarm/error display screen.

IV. PREVENTIVE MAINTENANCE AND FAULT REDUCTION

Preventive maintenance is essential for reducing the frequency of system faults and extending the operational life of hemodialysis machines. Regular calibration of pressure and flow sensors ensures accurate monitoring, while routine verification of alarm functions maintains the reliability of safety systems. Periodic replacement of filters and tubing prevents contamination and stabilizes hydraulic performance. Additionally, timely software and firmware updates resolve control-related issues and improve overall system functionality (Rossi *et al*., 2023b).

In essence, integrating scheduled maintenance with automated self-diagnostics and fault logging strengthens system dependability and patient safety. These practices form the foundation for predictive maintenance strategies aimed at identifying potential failures before they occur (El-Hariri *et al*., 2022).

V. TROUBLESHOOTING AND DIAGNOSTIC APPROACH

Effective troubleshooting in hemodialysis systems requires a multidisciplinary approach that combines engineering diagnostics with clinical observation to ensure uninterrupted treatment and patient safety. Based on field observations of the Surdial X and published guidelines, a systematic troubleshooting process is essential for resolving technical or physiological alarms (K/DOQI, 2023; Sodhi, 2022).

The NIPRO Surdial X includes an integrated self-test and diagnostic mode that automatically verifies sensors, valves, pumps, and electrical circuits before each session. In the event of a malfunction, the system issues visual and audible alarms along with a unique error code (E01–E99). Engineers and clinicians must follow a stepwise diagnostic process that begins with alarm interpretation, system isolation, and functional verification to avoid unnecessary downtime (NIPRO Corporation, 2024).

Troubleshooting typically begins by distinguishing between machine-related faults (e.g., flow obstruction, temperature deviation,

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conductivity errors) and patient-related factors (e.g., hypotension, clotting, or vascular access issues). According to clinical guidelines, the diagnostic sequence includes the following steps (K/DOQI, 2023):

1. Identify the alarm type and its origin (pressure, temperature, or conductivity).
2. Assess the patient's condition before making hardware adjustments.
3. Inspect all extracorporeal circuit components for blockages or air.
4. Reset or recalibrate the device if no physical obstruction is present.
5. Document the event in the maintenance log for pattern recognition.

Field observations revealed that the most recurrent alarms in the Surdial X were related to conductivity (E07), blood leaks (E23), and temperature deviations (E05/E06). These issues were effectively resolved using the machine's built-in diagnostic guide, highlighting its advanced design for rapid fault identification.

All alarm data are stored internally, enabling post-session analysis and predictive fault tracking. This functionality supports AI-based predictive maintenance, in which recurring alarms are analyzed to forecast potential component failures before they occur. The integration of digital logging, real-time monitoring, and automated calibration reflects a shift toward smart self-diagnostics—a defining trend in modern biomedical engineering (Shintaku & Mori, 2023).

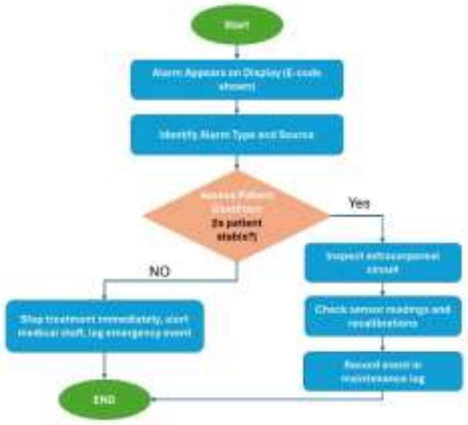

Fig. 4: Illustrates the standard troubleshooting flowchart used for diagnosing technical and clinical alarms in the Surdial X hemodialysis machine.

VI. RESULTS AND DISCUSSIONS

A comparative analysis of literature findings and field data revealed that most operational interruptions in dialysis systems stem from procedural errors or delayed responses to alarms rather than intrinsic hardware failures (Maduell *et al.*, 2022b). Case studies have highlighted incidents such as air embolism due to manual reinfusion errors, hemolysis caused by unnoticed tubing kinks, venous needle dislodgement linked to poor alarm response, and dialysate preparation errors leading to electrolyte imbalances (Saha *et al.*, 2022). These findings align with practices observed in the Surdial X unit, where engineering and nursing teams collaboratively manage alarm events to differentiate between technical and operator-related causes. The machine's intelligent alarm architecture, supported by redundant safety loops, minimizes clinical impact by pausing treatment immediately upon detecting unsafe conditions (Yamamoto *et al.*, 2023).

A key finding from both sources is the critical role of preventive maintenance and continuous training. Regular sensor calibration, weekly alarm verification, and adherence to disinfection protocols significantly reduced recurring alarms. Moreover, the adoption of standardized troubleshooting algorithms and root cause analysis improved diagnostic efficiency and device uptime (Rossi *et al.*, 2023a).

Ultimately, the Surdial X exemplifies the evolution of dialysis technology toward greater reliability, safety, and automation. Its advanced control system, internal fault memory, and rapid self-disinfection functions contribute to both patient protection and workflow efficiency. Integrating AI-driven diagnostic analytics, as suggested in recent literature, could further enhance predictive accuracy and support the next generation of autonomous dialysis systems (Shintaku, 2024).

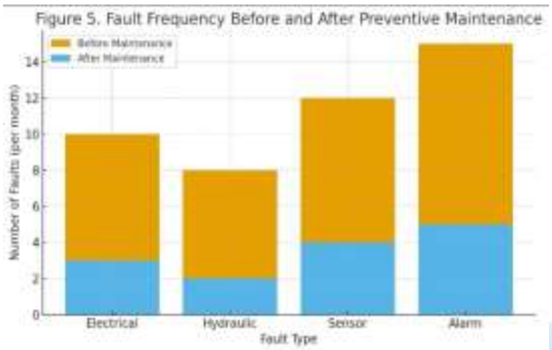

Fig. 5: Comparative chart showing the reduction in fault frequency across all system categories after implementing preventive maintenance on the Surdial X hemodialysis machine.

VII. CONCLUSION

This study analyzed the most common faults in the NIPRO Surdial X hemodialysis machine through field observations and technical evaluation. The findings underscore the importance of preventive maintenance, automated diagnostics, and real-time monitoring in ensuring operational reliability and patient safety. Incorporating predictive maintenance and AI-based fault detection is expected to further enhance system performance and reduce unplanned downtime in future applications.

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