AI-Based Smart IV Drip Controller Using IoT for Safe and Adaptive Drug Delivery

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Abstract - Intravenous (IV) therapy is ubiquitous in acute care, yet gravity-driven drip administration remains highly dependent on periodic human observation and manual roller-clamp adjustment. Variations in bag height, venous backpressure, patient movement, and tubing kinks can cause unintended under- or over-infusion between rounds, while documentation and alarm escalation are inconsistent. These factors increase the likelihood of dosing error and place additional cognitive load on nursing staff. This paper presents an AI-based smart IV drip controller with Internet of Things (IoT) connectivity that estimates delivered flow in real time, adaptively actuates the clamp using a low-cost motorized mechanism, and enforces safety guardrails to prevent overdose and detect abnormal conditions such as occlusion or line disconnection. The proposed approach combines lightweight regression control with rule-based safety constraints and human-in-the-loop override. A benchtop-oriented evaluation is described, together with closed-loop simulations demonstrating improved flow-rate tracking and timely anomaly alerts compared with intermittent manual adjustment. The architecture is designed to support edge operation and secure telemetry to clinical dashboards, reducing human error while maintaining clinical accountability.

Keywords - AI in Healthcare, IoT, Smart IV Drip, Patient Safety, Medical Automation

I. INTRODUCTION

Intravenous (IV) therapy enables rapid administration of fluids, electrolytes, blood products, and medications and is routinely used across emergency departments, operating rooms, wards, and intensive care units. While electronic infusion pumps are common for high-risk medications, gravity-driven administration using a drip chamber and roller clamp remains prevalent for maintenance fluids and in resource-constrained settings because it is inexpensive and easy to deploy. However, gravity systems provide limited observability and rely on periodic human inspection and manual clamp adjustment, which can be delayed during high workload.

Manual control is vulnerable to (i) flow drift caused by changing hydrostatic head as the bag empties or is repositioned, (ii) changes in line resistance due to kinks or partial occlusion, and (iii) inadvertent clamp manipulation. These factors can cause unintended under- or over-infusion between rounds. Infusion safety remains a persistent concern: the U.S. Food and Drug Administration (FDA) reported approximately 56,000 infusion pump adverse event reports from 2005-2009, motivating safety initiatives and guidance focused on systematic engineering controls and risk management [1], [2]. Although gravity sets differ from programmable pumps, the same safety principles apply: delivered dose should be observable, bounded by guardrails, and abnormal conditions should be detected early.

This paper proposes an AI-based smart IV drip controller with Internet of Things (IoT) connectivity for safer gravity-based infusion. The core hypothesis is that combining continuous flow sensing, adaptive actuation, and networked supervision can reduce human error and prevent prescription-relative overdose while preserving clinician authority. The main contributions are:
(1) a modular architecture that retrofits onto conventional IV sets using flow sensing and a motorized clamp; (2) a lightweight AI control policy suitable for embedded processors, coupled with a rule-based safety layer and manual override; and (3) an evaluation methodology with representative disturbance and fault scenarios, including overdose risk, occlusion, and disconnection.

II. RELATED WORK AND LITERATURE REVIEW

A variety of solutions have been proposed to improve infusion safety and monitoring. Smart infusion pumps commonly integrate dose error-reduction systems (DERS) and drug libraries that provide decision support and guardrails for programmed doses and rates, and they are increasingly connected via wireless networks for data capture and updates [3]. Safety organizations and regulators have published implementation guidance and safety alerts emphasizing the importance of drug libraries, interoperability, and alarm management to reduce medication administration errors [4], [5]. A recent systematic review reported that smart pump interoperability with electronic health records (EHRs) can reduce certain types of medication administration errors, but real-world impact depends on workflow and compliance [6].

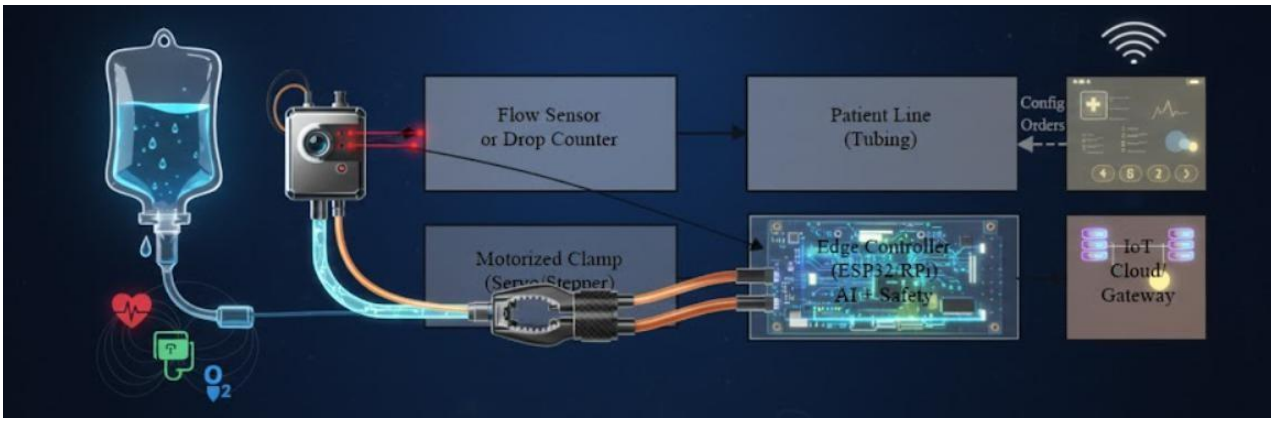
For gravity-driven infusion, prior work has explored sensors such as optical drop counters, bag weight estimation, and in-line flow sensors to provide continuous monitoring and threshold-based alarms. IoT-based healthcare monitoring systems enable remote visualization and escalation, but they introduce security and privacy concerns because networked nodes handle sensitive clinical data and may be targets for adversarial manipulation [7]. In parallel, closed-loop drug delivery systems in other contexts (e.g., chemotherapy) demonstrate the clinical value of feedback control to maintain therapeutic targets despite physiological variability [8].

However, several gaps persist in gravity-infusion research prototypes: (i) many systems are monitoring-only and do not close the loop to maintain a prescribed rate; (ii) safety constraints are often limited to basic thresholds and do not enforce prescription-centric overdose prevention; (iii) detection of occlusion and disconnection may be under-specified and not integrated with clinician workflows; and (iv) lifecycle considerations relevant to medical devices (risk management, software lifecycle, cybersecurity) are not consistently addressed [9]-[11].

III. PROPOSED SYSTEM ARCHITECTURE

Fig. 1 illustrates the proposed architecture. The system mounts on a standard IV pole and interfaces with existing tubing via a motorized clamp mechanism that actuates the roller clamp (or a pinch-valve adapter). A flow-sensing module provides continuous estimates of delivered rate. Optional patient sensing (e.g., heart rate, non-invasive blood pressure, pulse oximetry) can be integrated to contextualize alarms or enable conservative adaptation under clinician-approved rules; however, the primary safety function relies on infusion-side measurements.

An ESP32-class microcontroller performs real-time sensing, edge inference, and motor control. Secure IoT connectivity supports telemetry and alerting to a nursing dashboard. The design separates (i) a control layer that maintains the prescribed rate and (ii) an independent safety layer that enforces hard limits, detects abnormal conditions (occlusion/disconnection), and initiates a fail-safe clamp closure on watchdog timeout or power loss.



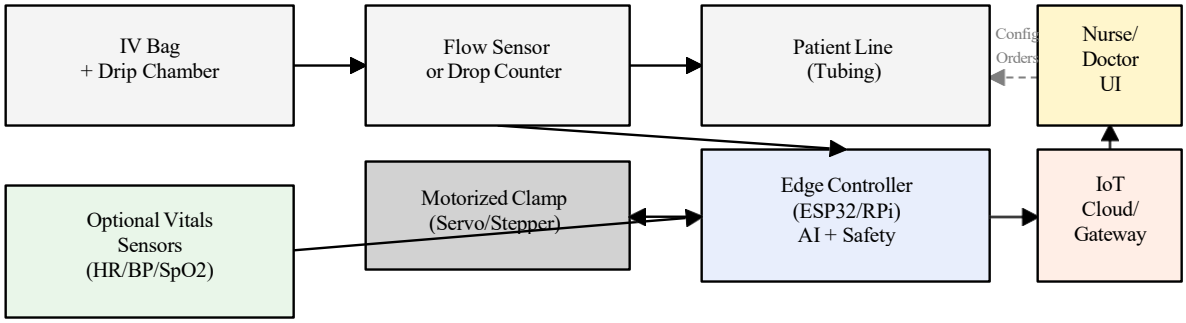


Fig. 1. Block diagram of the AI-enabled smart IV drip controller with IoT connectivity.

Table I. Prototype-Oriented Component Summary

Component	Example Implementation	Purpose / Notes
Flow sensing	Optical drop counter (IR LED + photodiode) or in-line flow sensor	Continuous estimation of delivered rate; requires calibration per tubing set; medical-grade sensing required for clinical deployment.
Actuation	Stepper motor + clamp adapter (roller clamp) or pinch valve module	Adjusts effective line resistance to regulate flow; designed for quick release and manual fallback.
Microcontroller	ESP32 (Wi-Fi/BLE) or Raspberry Pi Pico W	Runs sampling, filtering, AI policy, safety supervisor, and secure telemetry; watchdog enforces safe state.
Local UI	OLED display + buzzer + physical override switch	Displays prescribed and delivered rate; provides bedside alarms; supports clinician override.
IoT connectivity	MQTT over TLS to hospital gateway / cloud	Real-time logging, dashboards, alert routing, and device management; security is mandatory.
Optional patient sensing	Heart rate, non-invasive blood pressure, SpO2 (via validated monitor interface)	Contextualizes alarms and enables conservative, clinician-approved adaptation; not required for primary safety loop.

IV. AI METHODOLOGY

The proposed controller follows a hybrid approach suitable for embedded deployment:

A) Data inputs: delivered flow rate (primary), valve position (motor steps), cumulative infused volume, and optional vitals. Prescription parameters include target rate and allowable bounds derived from a drug library or clinician-entered guardrails.

B) AI model: a lightweight regression model predicts the valve adjustment Δu needed to reduce flow error over the next control interval. Features include current error $e(t)=r\_cmd - r\_meas$, error derivative de/dt, and an integral term to remove bias. Regression coefficients are trained during a calibration routine on the specific clamp/line hardware and can be refined online using bounded recursive least squares.

C) Decision logic: each control cycle filters the flow measurement, computes error features, predicts Δu, and applies saturation constraints (maximum step per cycle and bounds $0 \le u \le 1$). A safety supervisor then enforces: (i) prescription-centric overdose prevention (delivered rate exceeding r_cmd by a margin for a sustained duration), (ii) absolute maximum rate constraints (device-specific), and (iii) anomaly detection for occlusion (persistent under-delivery while the clamp is near fully open) and disconnection (near-zero flow with a non-zero command).

D) Safety constraints and overrides: clinician override is provided via a local physical switch and authenticated dashboard commands. Override forces the device into monitoring-only mode or fully closes the clamp, depending on configuration.

V. IOT IMPLEMENTATION

IoT connectivity is implemented using publish-subscribe messaging (e.g., MQTT) over TLS. The edge device transmits flow rate, valve position, cumulative volume, and alarm state at configurable intervals (e.g., 1-5 s), with event-driven bursts on anomalies. Two processing modes are supported: (i) edge-first, where control and safety decisions are executed locally and the cloud provides supervision and logging; and (ii) cloud-assisted analytics, where longer-horizon trend analysis supports quality improvement.

Alerts are routed to nurses or clinicians through a web dashboard or mobile interface, including bedside audible/visual indicators. To mitigate alarm fatigue, alerts include context (recent trend, corrective actions taken) and a recommended response (check line patency, confirm bag height, verify prescription). Cybersecurity controls include device identity, mutual authentication, encrypted telemetry, and secure firmware update mechanisms consistent with health software security lifecycle guidance [11].

VI. CONTROL ALGORITHM (PSEUDOCODE)

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Algorithm 1: Constrained AI Control for Smart IV Drip
Inputs: r_cmd (prescribed rate), r_min/r_max (guardrails), y_k (flow sensor),
        u_k (valve position), optional vitals v_k
Outputs: u_{k+1} (updated valve position), alarm_state

1:  r_cmd <- clamp(r_cmd, r_min, r_max)
2:  r_hat <- filter(y_k)                            # robust flow estimate
3:  e <- r_cmd - r_hat
4:  de <- (e - e_prev)/Δt;  ie <- sat(ie + eΔt)
5:  Δu <- RegressionModel([e, de, ie, u_k, v_k])    # lightweight regression
6:  Δu <- clamp(Δu, -Δu_max, +Δu_max)
7:  u_tmp <- clamp(u_k + Δu, 0, 1)

8:  if r_hat > r_cmd + δ_over for τ_over seconds then
9:       alarm_state <- OVERDOSE_RISK
10:      u_tmp <- max(0, u_tmp - u_fast_close)      # rapid mitigation
11:  end if

12: if (e > δ_under) and (u_tmp > u_high) for τ_occ seconds then
13:      alarm_state <- OCCLUSION_SUSPECTED
14:  end if

15: if (r_hat < δ_zero) and (r_cmd > r_thr) for τ_disc seconds then
16:      alarm_state <- DISCONNECTION_SUSPECTED
17:      u_tmp <- 0                                 # clamp closed
18:  end if

19: if local_override == TRUE or watchdog_timeout == TRUE then
20:      alarm_state <- MANUAL_MODE
21:      u_tmp <- 0                                 # safe state
22:  end if
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23: apply_motor(u_tmp);  publish_telemetry(r_hat, u_tmp, alarm_state)
24: e_prev <- e
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VII. EXPERIMENTAL SETUP

A benchtop prototype can be constructed using: (i) an in-line flow sensor or optical drop counter at the drip chamber, (ii) a stepper motor with a clamp adapter to actuate the roller clamp, and (iii) an ESP32-class microcontroller for sensing and control. A local display and buzzer provide bedside feedback, while an MQTT broker enables dashboard visualization. For proof-of-concept, low-cost sensors may be used, but clinical translation requires medical-grade components and verification to relevant standards.

Test scenarios include: (a) normal operation with a step change in prescription; (b) overdose risk due to increased head pressure (bag raised); (c) partial occlusion simulated by restricting the line; and (d) disconnection simulated by opening the circuit downstream. Performance metrics include mean absolute flow error (MAE), response time to prescription changes, number of required manual interventions, and time-to-detection for abnormal events.

Table II. Evaluation Scenarios

Scenario	Perturbation / Fault	Expected System Response
Normal tracking	Prescription step (100 to 120 mL/h)	Adaptive clamp actuation to reach setpoint within bounds; no alarms.
Overdose risk	Increased head pressure (bag raised) causing higher flow for same clamp setting	Detect sustained over-delivery vs prescription; rapidly reduce valve opening; issue high-priority alert.
Partial occlusion	Reduced line conductance (kink/obstruction)	Detect persistent under-delivery with clamp near fully open; issue occlusion alert.
Disconnection	Downstream open circuit or sensor indicates near-zero flow	Clamp closed to safe state; issue disconnection alert and prompt bedside check.

VIII. RESULTS AND DISCUSSION

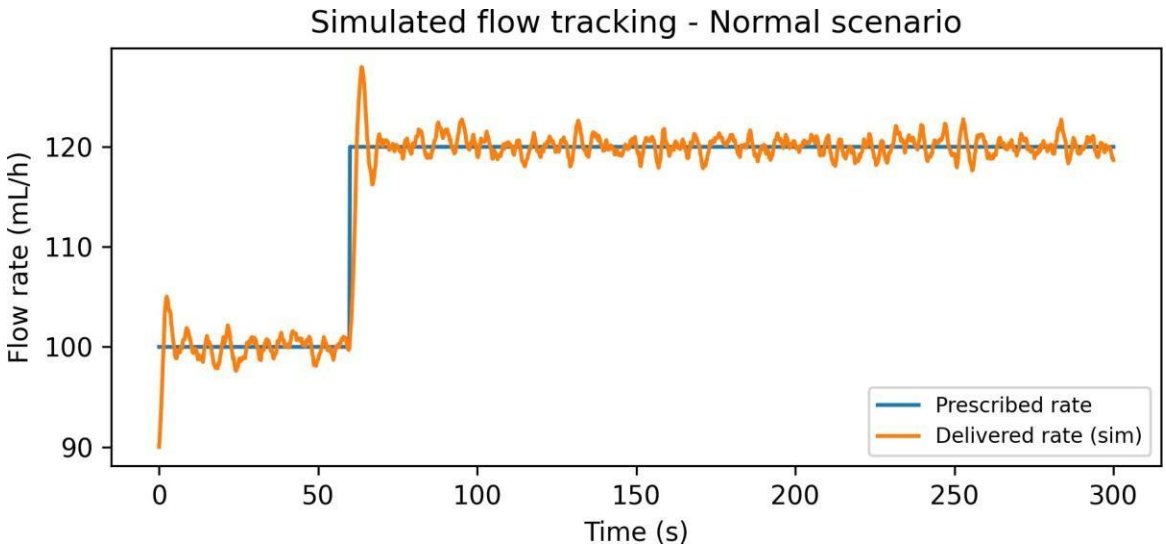

Fig. 2. Simulated flow tracking under normal conditions (step change at 60 s).

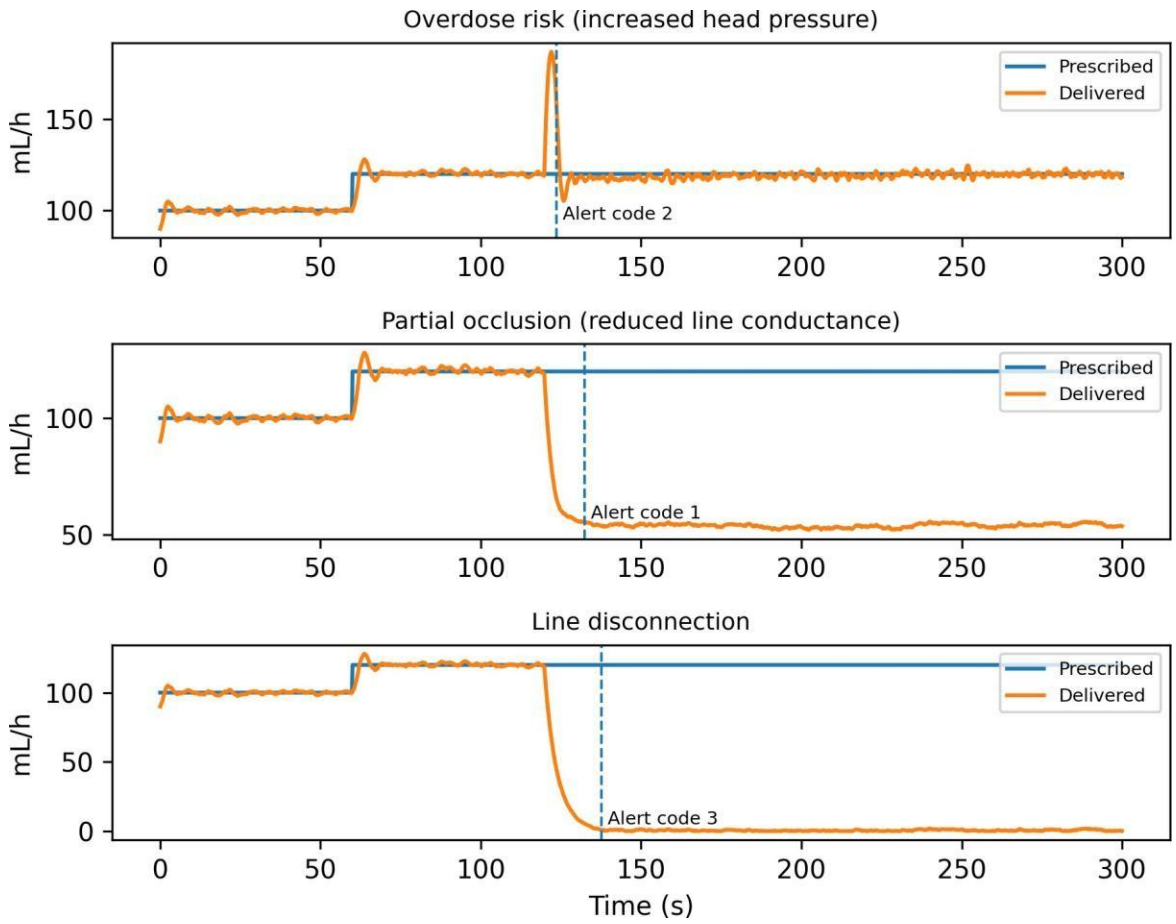

Fig. 3. Simulated adverse scenarios with safety alerts (dashed line indicates first alert).

Closed-loop simulations were conducted using a simplified first-order infusion-line model with sensor noise and scenario-dependent gain changes. Fig. 2 shows tracking under normal conditions with a step change from 100 mL/h to 120 mL/h. Fig. 3 illustrates adverse scenarios: increased head pressure causing transient over-infusion, partial occlusion causing sustained under-delivery, and line disconnection causing near-zero flow. Alerts are triggered by the safety supervisor when deviations persist beyond configurable time thresholds.

Table III summarizes representative simulation metrics. Compared with intermittent manual adjustment modeled as periodic nurse checks with adjustment uncertainty, the proposed controller reduces average flow error and limits peak over-infusion in the overdose scenario by rapidly closing the clamp and issuing an alert. In occlusion and disconnection cases, persistent deviations are detected and escalated within seconds, supporting timely bedside intervention. These results are illustrative and intended to guide prototype design and test planning; clinical performance must be established through standardized benchtop testing and clinical studies.

Table III. Illustrative Simulation Metrics (Manual Intermittent vs Proposed Controller)

Metric	**Normal**	**Overdose risk**	**Partial occlusion**	**Disconnection**
MAE (mL/h) - Manual intermittent	9.57	24.11	47.75	77.58
MAE (mL/h) - Proposed controller	0.87	2.14	42.32	75.69
Peak flow (mL/h) - Manual intermittent	138.85	288.17	116.58	116.58

Peak flow (mL/h) - Proposed controller	127.98	186.69	127.98	127.98
First safety alert time (s)	-	123.60	132.40	137.60

IX. ETHICAL AND SAFETY CONSIDERATIONS

Infusion automation is safety-critical and must remain clinician-directed. The proposed system is designed as human-in-the-loop: clinicians set the prescription, guardrails, and alarm policies; the device maintains rate within constraints and escalates deviations. Fail-safe mechanisms include default-to-closed behavior on power loss, watchdog-supervised motor disable, and manual release to restore conventional operation.

Risk management should follow ISO 14971 processes for hazard analysis and risk control [9]. Medical device software lifecycle practices should follow IEC 62304 [10], and cybersecurity engineering should consider IEC 81001-5-1 lifecycle activities for health software [11]. Patient data should be minimized, encrypted in transit and at rest, and governed by institutional policies (e.g., HIPAA/GDPR as applicable). Any AI component should be validated for robustness across tubing sets, viscosities, and environmental conditions, with conservative limits that prioritize patient safety over aggressive control.

X. CONCLUSION AND FUTURE WORK

An AI-based smart IV drip controller with IoT connectivity was presented to improve safety and reduce human error in gravity-driven infusion. The architecture integrates real-time flow sensing, motorized clamp actuation, a lightweight regression control policy, and a rule-based safety supervisor for overdose prevention and anomaly detection. Simulation results under representative disturbances demonstrate improved tracking and timely alerts compared with intermittent manual adjustment.

Future work includes (i) benchtop testing with medical-grade sensors and standardized infusion-device analyzers, (ii) integration with EHR systems to import prescriptions and document delivered volumes, (iii) expanded patient-context modeling for ICU workflows, and (iv) a staged clinical evaluation roadmap toward regulatory-grade evidence.

APPENDIX A. SUGGESTED RESULT TABLES FOR FUTURE BENCHTOP AND CLINICAL STUDIES

To support journal-quality evaluation beyond illustrative simulations, the following tables are recommended:
A1) Flow accuracy across tubing sets and viscosities (MAE/RMSE, steady-state error, overshoot).
A2) Alarm performance (time-to-detection, sensitivity/specificity for occlusion and disconnection under controlled faults).
A3) Dose delivery accuracy over long infusions (cumulative volume error vs reference analyzer).
A4) Network performance (telemetry latency, packet loss, alert delivery time) under hospital Wi-Fi conditions.
A5) Power and reliability (battery runtime if applicable, watchdog events, mean time between failures).
A6) Human factors (task completion time, usability scores, alarm acknowledgement behavior).

APPENDIX B. FUTURE CLINICAL DEPLOYMENT ROADMAP

Phase 0 - Engineering verification: mechanical robustness, clamp repeatability, sensor calibration, and watchdog/fail-safe validation.
Phase 1 - Benchtop performance testing: accuracy and response characterization using infusion-device analyzers; occlusion/disconnection detection validation; cybersecurity testing.
Phase 2 - Clinical simulation: use in training labs with simulated patients and staff to assess usability, alarm burden, and workflow integration.
Phase 3 - Pilot clinical study (IRB-approved): limited deployment for low-risk fluids under close supervision; collection of performance and human factors data.

Phase 4 - Expanded clinical trial: multi-ward/multi-center evaluation; EHR interoperability; health-economic analysis.

Phase 5 - Regulatory submission and post-market monitoring: safety case documentation, risk management file, software lifecycle evidence, and continuous vulnerability management.

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