Journal of Medical Devices Technology
jmeditec.utm.my

Original Research

Real-Time Fluid Monitoring System Prototype Development Using Load Sensor for Intravenous Infusion Bottle Replacement Management

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ARTICLE INFO

Article History:
Received 30 March 2026
Accepted 30 June 2026
Available online 30 June 2026

Keywords:
IV automation,
IoT in healthcare,
Load cell,
Mobile monitoring,
Real-time tracking

ABSTRACT

The backbone of contemporary healthcare lies in intravenous (IV) therapy, but human-generated errors during manual monitoring create risks for patients through improper dosing and excessive fluid intake and air embolism. The resulting safety concerns affect patients while simultaneously adding more work to medical teams. This paper introduces a new automated IV fluid monitoring system that leverages Internet of Things (IoT) technology. Through the system, two separate load cell sensors work with HX711 amplifier modules to provide accurate weight measurements of IV fluid bottles. The sensor data assessment and remaining fluid volume and infusion time calculation take place within an ESP32 microcontroller before the information is sent to a Firebase cloud database through Wi-Fi connectivity. The system generates three levels of warning through visual and audio cues, which include traffic lights and buzzers to notify fluid level conditions. Users receive real-time status information through a companion mobile application that uses MIT App Inventor to perform remote monitoring and push notifications. By using established reference weights to calibrate the prototype, followed by practical testing, the system achieved a measurement precision with an error margin of less than 5 % across various weight levels. The results of a survey with 26 healthcare professionals confirmed the medical field requires this system because it can decrease mistakes made by staff and boost operational effectiveness together with protecting patients. Hence, the development of this low-cost prototype proves that automated IV infusion management can become a practical solution.

INTRODUCTION

Intravenous (IV) therapy is a significant medical procedure that delivers fluids, medications, and nutrients into the circulatory system. It is essential in emergency medicine, major surgeries, and treatment of chronic ailments, with more than 80 % of patients being given IV therapy during hospital stay (Open Resources for Nursing (Open RN); Ernstmeyer, 2023; Tomobi et al., 2024). Regardless of its enormous use, the traditional monitoring methods of IV infusion rely on manual checks, making the process labor-intensive and susceptible to human error (Sang et al., 2024; Van Regenmortel et al., 2021). Inaccurate flow rates, unnoticed completion of infusions, and delays in bottle replacements may lead to serious clinical complications, including fluid overload, dehydration, medication errors, and, in the worst times, air embolism (Kuitunen et al., 2024; Van Regenmortel et al., 2021). These risks are exacerbated in fast-paced clinical settings where healthcare staff ratios are low and are often diverted to attend to other critical situations (Park et al., 2022). The absence of automated alerts to warn of low fluid levels renders continuous performance of visual inspections both time-consuming and

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DOI: https://doi.org/10.11113/jmeditec.v5.79

impractical, often results in delayed interventions (Kuitunen et al., 2021). This gap in continuous monitoring is a serious threat to patient safety and a huge bottleneck in hospital workflow, especially during demanding situations where there is a shortage of staff in comparison with hospitalized patients.

In recent years, the Internet of Things (IoT) has proven to be a in healthcare and has guided the development of smart monitoring systems that can automate manual processes, increase accuracy, and ultimately improve health outcomes (Mohammed et al., 2019). One key application area is IV therapy, where researchers have explored and tested different types of sensors that can be used for optimizing fluid monitoring processes. For example, the combination of optical sensors with LiDAR technology can deliver precise drip rate measurements, yet their performance depends on environmental factors and requires accurate sensor alignment (Hwang et al., 2023; Jauregui-Vazquez et al., 2023). On the other hand, the implementation of capacitive sensors provides a contactless monitoring solution, but their precision may fall short for determining exact volume measurements (Kok et al., 2024). As an alternative, the load cell sensors based on strain gauges are preferred owing to direct measurement approach. For instance, the system achieves dependable fluid volume computations through continuous weight monitoring of the IV bottle. The HX711 module with its 24-bit ADC system, enables precise weight detection which makes it an ideal device for consistent monitoring purposes (Al-Dahiree et al., 2022; Goyal et al., 2020).

To facilitate intelligent monitoring, the system implements IoT technologies. The ESP32 presents itself as a cost-effective and high-performance solution that integrates with built-in Wi-Fi and microcontroller functions to manage sensor data and local processing before sending data to cloud platforms (Hercog et al., 2023). Through network connectivity, healthcare providers can monitor data through either a centralized dashboard or mobile applications from remote locations. The system follows the modern Connected Healthcare standard which uses real-time data for enhancing both clinical decision effectiveness and patient treatment control (Awad et al., 2021). The implementation of IoT monitoring systems has generated multiple research findings that demonstrate their ability to minimize documentation errors and reduce response durations while boosting the quality of patient care (Swedarma et al., 2023).

Building upon these foundational concepts, this study proposed the use of IoT principles to reduce the challenges associated with manual IV monitoring by developing real-time IV fluid monitoring system. The system utilizes load cell sensors connected to an ESP32 microcontroller to automate fluid measurement through remote alerts when necessary (Oladunjoye John et al., 2025). Specifically, the present study was carried out with the following primary objectives. First, to calibrate the load cell sensors for consistent measurement of a standard 500 ml IV infusion bottle and to establish a reliable correlation between weight and fluid volume. Second, to design and develop a mobile application with wireless communication capabilities, enabling real-time display of IV fluid levels in a user-friendly interface. Third, to analyse IV fluid levels through continuous monitoring and to provide timely notifications that facilitate efficient IV infusion bottle replacement.

The organization of this paper is as follows. The study begins with a discussion of the difficulties regarding current IV monitoring practices and highlights the intended objectives. Section 2 describes the system development process, which includes a survey of healthcare professionals to conceptualize the three-tier alert mechanism and define critical volume levels. Independent tests and validations of the hardware electronic components are also presented. The prototype is then fully integrated, including calibration, implementation of the alerting functions, and testing of the companion mobile application for functionality. The system evaluation in Section 3 shares results of testing, which focus on the accuracy of the sensors, automatic data relay in real time, and the ability of the alerting system. Lastly, the major key findings on the consistency of the system, its ability to stream real-time data, and its general effectiveness are discussed.

METHODOLOGY

The systematic project execution followed a multi-phase methodology which began with user data collection and ended with full system integration and verification. The reliability and functionality of the final prototype were achieved through a structured approach that tested each subsystem independently before integration.

Phase 1: User Data Collection

A detailed questionnaire was designed and distributed to 26 healthcare professionals using Google Forms to evaluate the current IV monitoring practices in clinical settings. This method was selected for its ease of distribution in aggregating response. Through this survey, healthcare professionals shared quantitative statistics and subjective feedback about their current IV monitoring approaches as well as difficulties faced and preferred features in automation systems. The survey results directly shaped the physical structure of the system, guiding the development of calibration standards and user interface elements. The findings identified 500 ml IV bottles as the standard volume.

This cross-sectional survey was adopted and designed to investigate IV fluid monitoring practices, system limitations, and the technology needs of healthcare professionals. The selected participants included medical officers, registered nurses, and assistant medical officers working directly with IV fluids. A convenience sampling method was used to sample a wide range of departments across Malaysian healthcare facilities to obtain feedback from a variety of perspectives, including General Medicine, Emergency, Intensive Care Unit, Oncology, and specialized departments, including the National Blood Bank and others (Ilker et al., 2015).

Data were collected via a structured questionnaire with four distinct sections. The initial part of data collection included demographic and professional background information related to gender, age, department, years of service, and highest qualification. The second part of data collection focused on the IV fluid such as Normal Saline, Ringer's Lactate, and others, as well as volume administered, predefined volume thresholds at which alerts are triggered to indicate low fluid levels, and practices related to IV fluids administration.

The third part of the evaluation included ratings utilizing 5-point Likert scales to assess system effectiveness. Rating reliability of current alert systems, training completeness, technical barriers, and explicit patient safety improvement. The fourth part evaluated mobile application-based strategies, level

DOI: https://doi.org/10.11113/jmeditec.v5.79

of importance placed on real-time alerts, features in future mobile applications, and concerns of automation.

The survey has been validated and reviewed, as well as tested to ensure validity for content and accessibility. Approval was sought from the Department of Biomedical Engineering & Health Sciences, Universiti Teknologi Malaysia. Data was collected through Google Forms or physically distributed from December 2024 to May 2025. Confidentiality was maintained throughout the procedure without extracting personal data information. Quantitative data were analyzed descriptively, with cross-tabulation performed for key variables, while qualitative responses were analyzed thematically to identify suggestions and areas of concern.

Phase 2: System Integration and Firmware Development

This phase step included the actual assembly of the prototype and the development of core control software for the ESP32, focusing on a reliable system for accurate conversion of weight into volume for IV fluids. Individual testing, calibration, and integration of each hardware component were performed on its own, including the dual load cells, HX711 modules, I2C LCD, push buttons, and alerts, with a continuous dual-source power supply. While the firmware was developed in Arduino IDE using non-blocking functions, the firmware also included calibration constants and the solution density measurements to track live fluid volume and provide continuous operation.

Component Testing and Validation

Before the system was assembled, every hardware component was tested separately to confirm it was working appropriately. The modular testing of each component makes it easier to debug the system during final assembly and ensures that weight to volume conversion calculations will be performed diligently.

The dual LCD I2C module testing had the main challenge of operating two I2C LCDs from one microcontroller, since both modules come with a default address of 0 × 27. To give each display a different address, the A0 address jumper pad on the PCF8574 adapter of the second module was soldered in a closed position. In this way, the I2C address of the second LCD was changed to 0 × 26. During testing, both displays were given their own controls and could show different messages, like weight readings and volume displays, allowing them to keep track of two separate bottles at the same time.

Testing of the red panel mount push button focuses on reliable signal detections for the manual tare function. Each momentary push-button was wired with a 1 kΩ pull-down resistor to prevent floating input states that could lead to errant readings. Testing determined the signal for a single press was a clear "HIGH" signal (1), as well as that the debouncing circuit was reliable and performed without multiple trigger events.

Buzzer testing confirmed that the 5 V active buzzers delivered audible tones appropriate for alerting functions when IV fluid levels pass predetermined volume levels by testing the reliable operational performance, and acceptable appropriate noise levels that must be audible yet not disturb people within the surrounding area.

Load cell and HX711 modules testing established the groundwork for gaining weight to volume conversion throughout the tracking process. The first step in testing was to ensure communication was functional between the ESP32 and both HX711 modules so that the appropriate sensor communication could be ensured prior to full calibration. This first set of tests involved connecting each load cell to each HX711 module to verify that the data was indeed being received by the ESP32. Raw values were monitored from the sensors via serial communication to ensure stable reading.

Hardware Assembly and Configuration

The system architecture involved four interconnected subsystems which are a sensing unit, processing unit, local alert unit, and remote monitoring unit. Each of these components was selected using well-established methods prior to integration to ensure a reliable product.

The sensing unit relied on two independent 1 kg capacity strain gauge load cells. They were specifically selected for their considerable acceptable ranges associated with standard IV bottles. To ensure stable and reliable electrical connections, the load cells were soldered with the thin flexible wires that come with the load cells to more robust metallic jumper wires, which kept the load cells from losing signal or disconnecting during the operation. The two load cells were connected to an HX711 amplifier and 24-bit ADC module that converted the linear analog strain signal into a stable digital weight value as well as conversion to volume using the known density of IV fluids.

The processing unit centered around an ESP32-WROOM-32 microcontroller and was chosen as the processing because of its dual-core capabilities, built-in Wi-Fi and Bluetooth capabilities, enough GPIOs to drive all his peripherals, and the ability to abstract tasks and process them to make use of the mass parallelization potential. Due to these processing features, the ESP32 was well suited to handle the complex coordination between sensing, processing, and communication functions.

The local alert and display unit contained several key components. Two standard 16 × 2 character LCDs, with I2C adapter backpacks, for local data display. One important preparation step was to modify the I2C address of one unit, as both units are shipped with a default address, in most cases 0 × 27. The A0 address jumper pad on the PCF8574 I2C adapter of the second unit was soldered, which changed the address to 0 × 26, allowing the two displays to function independently on the same I2C bus without conflicts. The alert peripherals included traffic light-style LED modules, and 5 V active buzzers were chosen for visual and audible alerts, as well as the physical alerts provided for each load cell with a red panel mount push button to manually tare.

The power supply system was designed with the operational reliability of the ESP32 microcontroller and its peripherals as the main consideration. This was achieved using a dual-power-source implementation deployment strategy to secure that any voltage drops stemming from losing the source of supply would never affect its operational continuity. Two independent 9 V alkaline batteries were used in the alternating power architecture to provide two inputs into the two separate LM2596 step-down buck converters. One was regulated to 3.3 to 4.0 V to power the ESP32 and all the sensors, and the second regulated at 5 V to power the two LCDs. This outlined strategy ensured consistent performance of all components in the power supply system by providing stable power source.

As illustrated in Fig. 1, the system comprises an ESP32-WROOM-32 microcontroller as the main processing unit, while load cells and push buttons are processed to directly control the

DOI: https://doi.org/10.11113/jmeditec.v5.79

LCD displays, buzzer, and traffic light-style LED indicators. All tested components that were assembled according to the system schematic and appropriately pinned during the hardware assembly and configuration stage as detailed in Table 1. The use of two pairs of 9 V batteries and LM2596 buck converters adhered to the dual-power-source design to provide isolated and regulated 3.3 to 4.0 V and 5 V output supplies. This approach effectively minimized voltage fluctuations, thereby preserving the precision of sensitive weight measurements during prolonged operation.

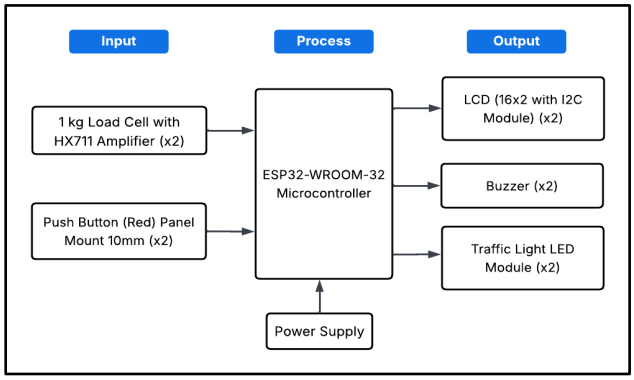

Fig. 1 Electronic block diagram of IV monitoring system

Table 1 ESP32 pin configuration for IV monitoring system

ESP32 pin (GPIO)	Component connected	Signal/Pin on component	Firmware define
GPIO 4	HX711 Module 1 (for Load Cell 1)	DOUT (Data Out)	HX711_dout_1
GPIO 5	HX711 Module 1 (for Load Cell 1)	SCK (Serial Clock)	HX711_sck_1
GPIO 18	HX711 Module 2 (for Load Cell 2)	DOUT (Data Out)	HX711_dout_2
GPIO 19	HX711 Module 2 (for Load Cell 2)	SCK (Serial Clock)	HX711_sck_2
GPIO 12	Traffic Light Module 1	Green LED Anode	ledG1
GPIO 13	Traffic Light Module 1	Yellow LED Anode	ledY1
GPIO 14	Traffic Light Module 1	Red LED Anode	ledR1
GPIO 25	Traffic Light Module 2	Green LED Anode	ledG2
GPIO 26	Traffic Light Module 2	Yellow LED Anode	ledY2
GPIO 27	Traffic Light Module 2	Red LED Anode	ledR2
GPIO 15	Buzzer 1	Positive (+) Terminal	buzzer1
GPIO 33	Buzzer 2	Positive (+) Terminal	buzzer2
GPIO 32	Momentary Push Button 1 (Tare 1)	Signal Out	resetButton1Pin
GPIO 35	Momentary Push Button 2 (Tare 2)	Signal Out	resetButton2Pin
GPIO 21 (SDA)	I2C Bus (LCD 1 & LCD 2)	SDA	Standard I2C (Wire.h)
GPIO 22 (SCL)	I2C Bus (LCD 1 & LCD 2)	SCL	Standard I2C (Wire.h)

Firmware Development and Calibration

The system firmware was developed in the Arduino IDE using C++. The HX711_ADC.h library was chosen for its non-blocking functions, which enable readings from two load cells without interrupting the program flow. This non-blocking capability was essential for continuous IV bottle monitoring, real-time weight-to-volume calculations, and uninterrupted system operation.

During calibration, the system tare operation automatically occurred with the startMultiple function having a standing time and tare enabled from startup. The firmware zeroed both load cells to neglect the initial weight of the IV bottle and tubing for measuring only the fluid in the bottles. Experimental calibration was next, where a calibration weight of 500 g was suspended from each load cell, the raw ADC value was read, and the calibration factor was adjusted iteratively until the output of getData matched the known weight precisely. The empirically determined calibration values of 922.0 g for Load Cell A and 905.0 g for Load Cell B were coded as constants in the firmware for further use.

With consistent experimental data on the Infusol NS 0.9 % solution as shown in Table 2, density was calculated based on direct measurement. A sample solution of 100 ml weighed 100.45 g. Hence, its density was calculated to be 1.0045 g/ml, an almost exact match to the reported literature range of 1.0046 to 1.006 g/ml for a 0.9 % NaCl solution at room temperature. From experimental data, the net solution weight was verified with an empty beaker weighing 51.00 g and 51.45 g plus 100 ml solution. Based on these values, the estimated weight of 500 ml of solution was calculated to be 502.25 g. In contrast, the total weight of a 500 ml container was measured at 544.35 g, indicating that the plastic bottle itself weighed 42.1 g. These measurements were fed into the firmware as calibration parameters to enable the conversion of raw weight measurements into calibrated fluid volume calculations.

The main program loop continually polled both sensors, determined net fluid weight by subtracting the known weight of an empty IV bottle, converts weight into volume using the carefully measured Infusol NS Sodium Chloride 0.9 % IV Infusion solution density being 1.0045 g/ml and approximated remaining infusion time based on the current flow volume. This thorough approach provides healthcare professionals with real-time information about IV fluid levels and anticipated completion times.

DOI: https://doi.org/10.11113/jmeditec.v5.79

Table 2 Experimental data for calibration of Infusol NS 0.9% solution monitoring

Parameter	Value
Weight of empty beaker	51.00 g
Weight of beaker + 100 ml solution	151.45 g
Net weight of 100 ml solution	100.45 g
Estimated weight of 500 ml solution	502.25 g
Measured total weight of 500 ml with container	544.35 g
Estimated container weight in 500 ml measurement	42.10 g
Calculated density of 100 ml solution	1.0045 g/ml

Tiered Alert System and Local Indicators

The alert system emphasizes a hierarchical, three-level system based on the amount of fluid occupying the IV bottle. The ranges of this system are explicitly outlined and set within helper functions like getStatus () and are then utilized in the update desperately within updateIndicators (). The breakdown of the levels is as follows as "Normal" is for fluid levels above 50 %, "Warning" will trigger when the fluid levels are between 15 % and 50 % whereas "Critical" is used when the fluid levels are at 15 % or below. These percentages are the core of the triggers for the visual and auditory alerts can be seen in the Fig. 2.

The alert triggers are included in updateIndicators (), which is executed for each IV channel in the main loop. The updateIndicators () function automatically creates physical outputs using conditional statements. The buzzer, which is the needed auditory alert, is not triggered as freely as light, which will be triggered if it is positive. The buzzer sound only activates when the system detects 15 % or less. However, the buzzer sound is put into cooldown timing (buzzerCooldown) and will herald for two seconds if the critical condition exists.

```
// Function to control all physical indicators based on set ranges
void updateIndicators(int percentage, int greenPin, int yellowPin,
int redPin, int buzzerPin, unsigned long &lastBuzzTime) {
  // Set LED based on percentage range
  digitalWrite(greenPin, percentage > 50);
  digitalWrite(yellowPin, percentage <= 50 && percentage > 15);
  digitalWrite(redPin, percentage <= 15);
  // Trigger buzzer only in "Critical" state (<= 15%) if cooldown
has passed
  if (percentage <= 15 && millis() - lastBuzzTime >
buzzerCooldown) {
    tone(buzzerPin, 1000);
    delay(2000);
    noTone(buzzerPin);
    lastBuzzTime = millis(); // Reset the cooldown timer
  }
}
```

Fig. 2 Alert trigger logic code

Phase 3: Cloud Management and Mobile Application Development

The remote monitoring functions were implemented by using a three-layer architecture that allows for real-time tracking and data access response for IV fluid monitoring. This system integrated the Firebase Realtime Database for keeping the data constantly updated from the ESP32 side, a mobile app for bedside monitoring via InfuTrack+, and an automated record-keeping system for infusion records based on Google Apps Script. Technical validation highlighted the useableness of the system through precision testing and structured feedback from healthcare professionals.

Firebase Realtime Database Integration

In the remote monitoring system, the Firebase Realtime Database is the real-time data backend. A Firebase project was created and the ESP32 microcontroller takes data from the load cells scales and sends each load cell reading as a separate database entry as opposed to one JSON object. The ESP32 sends data into the database about the load cells every three seconds, organizing the specific parameters to be sent for each load cell. The data structure includes weight measurement strings with 2 decimal places of precision (loadcellweight1/2), volume data in milliliters (loadcellvolume1/2), percentage remaining as integers (loadcellpercentage1/2), status indicators (loadcellstatus1/2), status description messages (loadcellstatusdesc1/2), timestamps for sync with the database (loadcelltimestamp1/2), and estimated time remaining in minutes (loadcelltimeleft1/2). Structuring the data in this manner allows the health care providers to have all the information about their patients they require in real-time, in an organized manner, while accessing the information in the least possible amount of time.

Mobile Application Development

Mobile application development focused on creating "InfuTrack+," an integrated monitoring solution built on MIT App Inventor. MIT App Inventor is a block-based coding platform that provides simple opportunities for rapid prototyping and rapid design improvement. The user interface created has a simple dashboard that allows two patient beds to be monitored at the same time. The interface has circular progress charts that allow a quick glance percentage of remaining IV fluid levels with further indicators of remaining volume, estimated time to completion, and further textual indications to users about system notifications, or any anomalies that need attention.

Data Logging System Design

A data logging system was created using Google Apps Script to ensure accurate record-keeping and allow for more distant analysis of infusion patterns. The automated script runs multiple times and enable pulls new data entries from the Firebase database and adds them to a formatted Google Sheet that maintains records of all infusion events in chronological order. The logging system records important variables such as the start times, volume drained, alerts, and stop times, which creates records that can be used as part of a quality assurance program and allow to study infusion trends for improvements in the process.

Technical Validation and Data Collection Verification

The verification of all technical and data collection used a mixed-methods method for extensive validation of the system,

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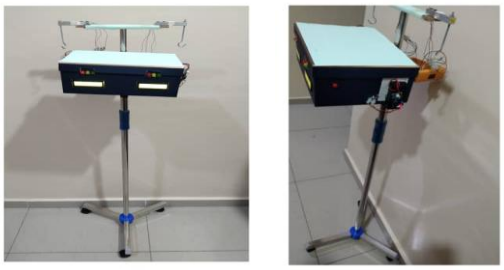
thus conforming to the technical verification required for usability of such a device in a suitable setting. The technical verification involved significant testing for accuracy. This was carried out using the actual device with known weights that were assessed from an empty bottle to a full 500 ml IV bottle where comparison was made against precision balances ensuring that accuracy was maintained within the acceptable tolerances when converting weights to volumes. In addition, the user data collection was collected through structured surveys administered to healthcare professionals to assess perceived utility, ease of use, integration into current workflows, and suggestions for additional features to improve system delivery and monitoring.

Fig. 3 provides external views of the device. Fig. 3 (a) illustrates front view includes an LCD (I2C) and traffic light module, whereas the back view has the HX711 modules. Fig. 3 (b) below shows a left-side view that has a 9 V battery, an LM2596 for system power, and a push button for Bed 2, while the right-side view has a rocker switch, a 9 V battery and an LM2596 for the LCD, and a push button for Bed 1. However, equipment is needed to test and troubleshoot, and load cell-connected wires must be soldered with metallic contact in configuration to ensure data value gaining accuracy.



(a) (b)

Fig. 3 External Views of the IV Fluid Monitoring Device: **(a)** Front Views of the Device, **(b)** Left Side Views of the Device

Fig. 4 details the entire pre-testing process for the load cell component system prior to integrating the components into the final assembly. The demonstration of both Load Cell A and Load Cell B respectively in physical installation and fixing approaches, ensuring stable and accurate sensor placement for optimal performance. The applicable IV T-shaped steel fixture featured a long, flattened cuboidal wooden support, with load cells mounted on it. The setup also included screw and screw hook components to securely fasten the IV bottle in place. Subsequently, individual pre-test setup configurations were conducted for each load cell, Load Cell A and Load Cell B, by hanging a 500 ml IV bottle on one side, for the purpose of recording calibration data. The concurrent serial monitor outputs for the weight response are presented on showing real-time readings. As in Fig. 4 (a) when both IV bottles are positioned on respective load cells, the dual-sensor system demonstrates synchronization with consistent readings of approximately 544 g without excluding empty bottle weight. Original output data verification shows alignment with digital electronic weight of 544.35 g, maintaining stability with minimal fluctuation, confirming proper detection. When Load Cell A operates within a range of 544.70 to 544.96 g, while similarly Load Cell B shows a range of 544.82 to 544.87 g, verifying simultaneous monitoring capability with consistent. As shown in Fig. 4 (b) under single-bottle configurations, the system exhibits clear differentiation where loaded cells maintain a 544 g range while unloaded cells drop to near-zero baseline values of 0.50 to 0.82 g.

(a) (b)

Fig. 4 Preliminary Testing of Load Cells Before Complete Assembly: **(a)** Dual Load Cell Pre-Test with 500 ml IV Bottles Showing Synchronized Weight Readings, **(b)** Individual Load Cell Performance with Range Validation for Simultaneous Monitoring

RESULTS AND DISCUSSION

The integrated system was evaluated for accuracy and real-time capabilities and followed up with the healthcare professional requirement. Evaluation showed the system demonstrated and managed to prove effectiveness and reliable real-time performance in all functional modules. This performance not only met the established benchmarks but also exceeded expectations in several key areas.

Healthcare Professional Survey Results and Validation

This study utilized a survey to present healthcare professionals' perspectives on IV fluid infusion and mobile monitoring systems. Part 1 focuses on the distribution of the professional demographics of survey respondents and indicates the participants' backgrounds and level of experience. Part 2 emphasizes how respondents currently administer IV fluids, outlining the various existing clinical protocols. Part 3 includes questionnaire answers that evaluated the participants' knowledge, attitudes, and experience regarding IV therapy management. Lastly, Part 4 is based on the intervention results regarding mobile application use for IV monitoring systems, indicating the acceptance, use, and perceived benefit of digital monitoring technologies for clinical practice.

The design and developed system were assessed for its real-time capability and appropriateness to clinical needs resulting from a broader survey of 26 healthcare professionals. The results demonstrate both technical feasibility and a strong relevance to clinical need. The survey presented a clear picture of the type of intended end-user, which is primarily female (76.9 %), experienced (42.3 % with > 10 years), and primarily nurses (65.4 %). This targeted demographic provided valuable insight to design a system that was strong and intuitive from a professional perspective.

DOI: https://doi.org/10.11113/jmeditec.v5.79

The survey had a major finding that was instrumental in developing the project's focus on the current IV administration practices. In addition, the survey found that almost half of the group are using electronic infusion pumps (54.5 %) rather manual IV setups with roller clamps (45.5 %) when administering IVs, demonstrating an opportunity to implement a non-pump-based automation solution such as InfuTrack+ and safely and efficiently support healthcare professionals where manual practice is prevalent. Survey and data analysis identified 500 ml IV bottles (72.7 %) and 0.9% normal saline (95.5 %) as the predominant standards in clinical use. These insights were used to define key design parameters and calibration constants for the prototype, ensuring alignment with routine clinical application. When asked about the standard administration time for a 500 ml bottle, 50 % of respondents indicated an administration time of 60 minutes. Therefore, enable the programmed estimate TimeLeft() function within the system to ensure clinical relevance.

The survey data strongly reaffirmed the performance of the InfuTrack+ three-tier alert system. Surveyed healthcare professionals presented an escalating perception of urgency associated with decreasing fluid levels, leading collaboratively to a 100 % consensus that a remaining volume < 10 ml requires a critical alert. This longitudinal perceptual priority directly conveyed the alert thresholds of the firmware, which are Normal > 50 %, Warning 15-50 %, and Critical ≤ 15 %, with known clinical reasoning and judgment. Further, the survey also revealed the top key barriers associated with manual monitoring being human error (69.2 %), inefficient monitoring of multiple patients (42.3 %), and length of monitoring (> 38.5 %). The system's features are designed to mitigate these key issues, and the positive indicative qualitative responses from the healthcare professionals, highlighted by 92.3 % believing the system would help significantly enhance patient safety, give a clear call to action for its implementation. All requested top features, including real-time tracking (57.7 %), user-friendly interface (53.8 %), and automatic notifications (50 %), mentioned in the survey, were included in the final prototype.

Sensor Calibration and Accuracy Assessment

The calibration of the system was an integral part of the assessment of system reliability. Load Cell A (Bed 1) and Load Cell B (Bed 2) were rigorously calibrated prior to completing the functional tests and calibrated to certain specifications (Oladunjoye John et al., 2025). Subsequently, calibration of both load cells involved repeated testing with known standard masses, cross-verification against a high-precision electronic balance, and adjustments performed in a controlled environment to ensure reproducibility and accuracy in measurement. The system performed as expected based on the performance of the load cells compared to a digital scale using six common items with known weights ranging from 28 g to 300 g. Each item was weighed three times on both the load cells to test for reproducibility and to determine the average percent error. The readings from the digital scale served as the baseline to assess Load Cell A and Load Cell B. Results in Table 3 and Table 4 show both load cells performed reliably, with a mean percentage error of less than 5 %. This level of accuracy is acceptable for clinical applications where detecting reliable changes in fluid volume is essential.

For the heavier items like the 300 g organic chia seeds and the 200 g coffee mixture, both load cells were shown consistency. In fact, load cell A had an exceptionally low error of 0.03 % for the 200 g weight, and load cell B achieved a low error of 0.24 %. For heavier items specifically, the measurements between the two load cells were very comparable to the digital scale. On the other hand, for the lighter items such as the 35 g OldTown White Coffee and the 28 g Nestum, both load cells demonstrated a slight change in percentage error. This is a natural behaviour of load cell sensors since relative error increases towards the lower end of their relative measurement range. Nonetheless, even for the lightest item, the error remained at an acceptable level for the application. Therefore, the validation tests confirmed that the calibration method was effective and that the load cell sensors produced logical measurements across a wide range of weights. This level of consistency is critical to the system's ability to track IV fluid levels and serves as a solid foundation for subsequent volume and infusion timing calculations.

Table 3 Comparison of average measurements reading of Load Cell A with a known weight item

Item name	Known weight (g)	Net measured		Difference (g)	Error (%)
		Digital scale (g)	Load Cell A (g)		
Organic Chia Seeds	300	308.85	309.62	0.77	0.25
Hang Tuah Coffee	200	210.71	210.65	-0.06	0.03
OldTown White Coffee	35	37.28	37.71	0.43	1.15
Instant Noodles	79	79.96	82.93	2.97	3.71
Cream-O Cookies	51	57.82	57.76	-0.06	0.10
Nestum	28	29.23	29.69	0.46	1.57

Table 4 Comparison of average measurements reading of Load Cell A with a known weight item

Item name	Known weight (g)	Net measured		Difference (g)	Error (%)
		Digital scale (g)	Load Cell B (g)		
Organic Chia Seeds	300	308.85	310.48	1.63	0.53
Hang Tuah Coffee	200	210.71	211.21	0.50	0.24
OldTown White Coffee	35	37.28	38.14	0.86	2.31
Instant Noodles	79	79.96	83.32	3.36	4.20
Cream-O Cookies	51	57.82	58.20	0.38	0.66
Nestum	28	29.23	30.06	0.83	2.84

DOI: https://doi.org/10.11113/jmeditec.v5.79

System Performance Evaluation

The system underwent controlled testing using INFUSOL Sodium Chloride 0.9 % NS IV BP 500 ml IV bottle with a recording of dispensing time as shown in Table 5. The test was carried out to determine volume flow without having any component attached to it, an open flow going into a basin with a timer started until the entire volume was completed draining. The roller clamp was held in position as set forth in the instructions and as prescribed by experienced healthcare professionals to maintain the flow rate.

Table 5 Comparison of average measurements reading of Load Cell B

Test No.	Weight (g)	Time (min)	Test No.	Weight (g)	Time (min)
1	500	60	6	250	29
2	450	53	7	200	25
3	400	49	8	150	17
4	350	43	9	100	11
5	300	34	10	50	5

Real-Time Data Flow and Alerting Functionality

The InfuTrack+ system combines real-time data flow through a multi-modal alerting mechanism with traffic light module, buzzers, vibration, and text-to-speech notifications for imminent interventions during IV fluid depletion. Through the application interface, the user can securely view the live levels of IV fluids, status alerts, and estimated time remaining to reduce the cost of care. Dual load cell sensors, tested under both static and dynamic conditions, reliably monitor two patient beds. These sensors form the core of the InfuTrack+ system, enabling continuous fluid tracking and supporting predictive care management.

Multi-Modal Alert System Configuration

The system has three unique alert levels for both Bed 1 (Load Cell A) and Bed 2 (Load Cell B). Normal Status is Green LED activation when IV fluid is greater than 50% capacity indicating adequate sufficient fluid. Warning Status activation is Yellow LED illuminations when IV fluid is between 15 to 50% capacity indicating liquid replacement is coming soon. Critical Status activation is Red LED and alarm when IV fluid drops below 15% capacity indicating immediate attention is needed.

The system uses other notification options beyond the system's notification methods to ensure complete notification coverage. Buzzers activation occurs during critical stages with a buzzing intermittent alarm, to limit disruptive noise. Vibration notification is provided through the mobile application for silent alerting options. Text-to-speech notifications are clear verbal notifications stating "Urgent: IV Fluid 1 Critically Low - Immediate Replacement Needed" or "Urgent: IV Fluid 2 Critically Low - Immediate Replacement Needed" for immediate attention. Pop-up notifications can combine the modalities and provide multiple alerts to maximize notification effectiveness regardless of environment.

Mobile Application Interface Design and Workflow

The application interface consists of four screens developed for user experience and better workflow with a full interface flow appearing in Figure 5. The Fig. 5 (a) first screen is called the Splash Screen Interface. The splash screen displays the InfuTrack+ logo with the caption tagline, “Real-Time Care, Safeguarding Every Life,” with images of a hospital entrance. This screen showcases the application's brand and healthcare focus while giving users a professional first impression of the monitoring system.

The Fig. 5 (b) second screen is the login system. This includes the process of logging in by providing user and password criteria to authenticate to access monitoring data. The authentication process provides a layer of security to protect the privacy of the patient using the monitoring device. It further provides assurance to access sensitive medical data and monitoring capabilities.

The Fig. 5 (c) third screen shows the Main Menu with a patient bed selection layout that includes well labeled "Patient Bed" options in a fashion that should provide an intuitive experience for navigation throughout the system and use for bed assignment management.

The Fig. 5 (d) fourth screen displays the IV Monitoring Dashboard that functions as the main layout for real-time IV monitoring. The dashboard has a light blue background with the InfuTrack+ logo displayed on it and a home navigation button for easy access to the main menu. The live monitoring capability is presented with the last receiving update date and time shown in conjunction with the live updates of usage.

The Sensor Data Reading section shows volume readings in milliliters, and percentage values for each patient bed. The Status indicators for each bed display a range of different icons to communicate whether icons require attention to address an urgent situation. The alert management system provides descriptions about the status for each bed, showing both iconic alerts were “Urgent: IV Fluid Critically Low - Immediate Replacement Required” when a fluid level has reached a critical point as it came under the without IV bottle hanging condition.

Visual depictions of IV bottles are shown for each bed available for quick suggestive understanding of where their fluid levels are in the absence of data points. The estimated time remaining displays zero for both beds indicating their critical situation and need for intervention. Both bed data trend graphs provide historical information related to fluid level over time. Charting the information as semicircles is intended to assist users in recognizing how fluid levels have declined over time and can use that information for interventions. Graphing enables the user to observe patterns and is intended to create a basis for predictive care planning, making care more proactive rather than reactive. The Fig. 5 (e) urgent notification messages for critical IV levels to promptly alert users when immediate intervention is required.

DOI: https://doi.org/10.11113/jmeditec.v5.79

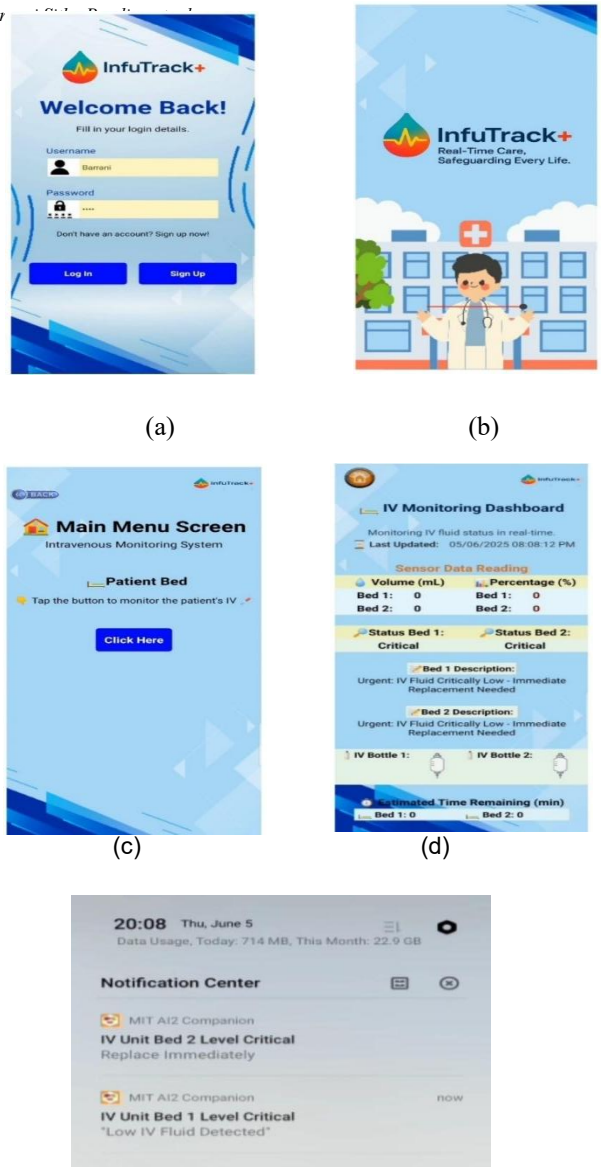


Fig. 5 Interface Screens of InfuTrack+ Application: **(a)** Splash Screen, **(b)** Login Interface, **(c)** Main Menu with patient bed selection, **(d)** Real-time IV Monitoring and **(e)** Urgent notification messages for critical IV levels.

LCD 12C Display Interface Analysis

The initial screen displays "Connecting WiFi..." on the LCD while the system is attempting to connect to the network. Both screens display red LEDs indicating normal startup status while the ESP32 microcontroller attempts to connect to the wireless network as defined in the code. The system will remain on this screen until a successful Wi-Fi connection has been established, at which point it will then configure the connection to the Firebase database and initialize the load cell sensors to show the actual weight readings.

When the user presses the tare push button on either bed, this confirmation screen appears displaying as “Taring..”, followed by "Tare Done" after the load cell has been zeroed. The tare function zeroes the weight of the IV bottle, meaning the system will now measure only the weight of the actual fluid flowing. This step is an important part of calibration to correctly measure the volume which typically only takes about 2 seconds to perform. After the tare is done, the system automatically goes back to the monitoring cycle.

On the measurement screen the display repeat by starting with, "Bed1/Bed2: [weight]g" is visible on the first line. The next line displays "Vol: [volume]ml". The monitoring system estimates gross fluid weight and subtracts the weight of the plastic bottle from that gross measure to calculate net fluid weight, and then converts weight to volume using a predetermined scaling factor where 502.25 g equals 500 ml. The red LEDs that can be seen in the image indicate that both monitoring stations have been assessed as critical, which means that the fluid level has dropped below 15 % capacity and should be supplemented by the user.

The third screen displayed in the rotation is the estimated time until the IV fluid completion and alert status. The LCD has "Time Left: [minutes]:[seconds]" which is determined using the total infusion time of 60 minutes, meaning the time left will be proportionate to the remaining fluid volume. The second line has "Status: [Normal/Warning/Critical]". Normal indicates that there is more than 50 % capacity, Warning is between 15 to 50 % remaining, and Critical is below 15%. The critical status will be signaled using illuminated red LED indicators, and in the case of being critical, visual alerts and buzzer alerts every two minutes will require staff response to clear the alerts. Control of any IV discontinuities will be for the user to prevent.

The last screen displays as a timestamp for when measurements were taken in the following format of DD/MM/YYYY HH:MM: SS. This information is valuable when reviewing their records and documenting actions. The clock on this screen obtains its timing information from an NTP server synchronized to the Malaysia timezone, basically MYT. This timestamp is a critical feature of documentation to specific measurements, and knowing the time that a measurement was made is important, particularly when handover occurs, or subsequent documentation.

Dual Load Cell Performance Analysis Under Static Condition

The first static testing was carried out using normal saline IV bottles without active dispensing to provide a baseline measurement and to test the stability of the system. For both Load Cell A and Load Cell B, observable slight drift over extended periods indicated stable measurements and relatively good performance. During on-demand dispensing, both load cells were able to track volume changes over time with measurements updating every 3-4 seconds. Both load cells successfully detected weight changes corresponding to fluid volume variations throughout the entire dispensing cycle, consistently tracking the administration of IV fluids. This ability to monitor two beds simultaneously directly mitigates the challenge of monitoring and keeping track of multiple patients at once, which was a challenge noted by 32 % of respondents in the survey.

Fig. 6 illustrates the complete version of InfuTrack+ functionality with static 500 ml IV bottles for monitoring verification. Fig. 6 (a) reports on Load Cell A for Bed 1, in real time, providing weight measurements and IV fluid level calculations. Fig. 6 (b) reports on Load Cell B for Bed 2, allowing for parallel monitoring for dual-bed management. Fig. 6 (c) is the real-time detection display interface in the mobile application, allowing healthcare professionals to see both monitoring stations, with continuously updated data, current

DOI: https://doi.org/10.11113/jmeditec.v5.79

status alerts, and full monitoring of the IV fluid administered for the patient bed areas. Table 6 presents calibration error analysis for the InfuTrack+ system across two load cells, with Load Cell A representing Bed 1 and Load Cell B representing Bed 2. The results show measurement accuracy with minimal weight errors, confirming consistent system performance clinical monitoring. Electrical noise, mechanical vibrations, imperfect calibration of the load cell, and ambient issues such as air temperature fluctuations may cause these inaccuracies. Loose connections could also cause data to change. To prevent this, the load cell must not be in direct contact with metallic steel surfaces. Wooden or acrylic materials are instead recommended for fixing the structure. In addition, the four wires from the load cell must be soldered very well with jumper wires using metallic header contacts so that readings remain stable and highly accurate.

(a) (b)

(c)

Fig. 6 Full demonstration of InfuTrack+ System with Static 500ml IV Bottle Monitoring: **(a)** Load Cell A measures weight for Bed 1, **(b)** Load Cell B measures weight for Bed 2, and **(c)** Corresponding mobile application displays

Table 6 Calibration error analysis

Bed	Measured		Expected weight (g)	Relative error (%)
	Weight (g)	Volume (ml)		
Bed 1	503.83	500.00	502.25	0.31
Bed 2	502.60	500.00	502.25	0.07

Individual Load Cell Performance Analysis Under Dynamic Condition

Dynamic testing consisted of simulating actual IV fluid administration to validate load cell performance under genuinely active dispensing conditions. The dynamic portion of testing examined the ability of the system to chronicle volume change in real-time, while measuring changes to the accuracy of measure.

During the active dispensing implementation tests as shown in Table 7, Load Cell A and Load Cell B both demonstrated real-time volume tracking capabilities, reporting measurable changes every 5 to 10 seconds. The load cells provided precise volumetric weight changes corresponding to the fluid volume changes throughout the complete dispensing cycle. Each unit was able to demonstrate the ability as a continuous monitoring application.

The operational status verification for Bed 1 confirms the relative consistency of readings across different fluid levels. The normal level recorded readings of 457.24 g and 455.19 ml, suggesting that the IV bottle was at an appropriate normal capacity condition and reported the true volume with the green LED on. The warning level recorded readings of 81.67 g and 81.31 ml, indicating the IV bottle was near low fluid and recommending a replacement soon, with the yellow LED on. The critical level recorded readings of 50.25 g and 50.02 ml, indicating the IV bottle was near empty and required immediate replacement with the red LED on, vibration, and notification pop-up in mobile with text-to-speech that read "Urgent: IV Fluid 1 Critically Low—Immediate Replacement Needed".

The operational status verification for Bed 2 confirmed its parallel monitoring capabilities with a reliable level of accuracy. The normal level recorded at 473.46 g and 471.34 ml, confirming that the IV bottle was at full capacity and precise measurement reliability with the green LED on. The warning level recorded at 178.95 g and 178.15 ml, indicating the IV bottle was near low fluid in medium level, which might require replacement attention soon with the yellow LED on. The critical level recorded at 17.46 g and 17.38 ml, suggesting that the IV bottle was almost empty and required immediate action with the red LED on, vibration, and notification pop-up in mobile with text-to-speech that said, "Urgent: IV Fluid 2 Critically Low—Immediate Replacement Needed".

Each bed unit was able to demonstrate continuous monitoring application capability, thereby proving its suitability for healthcare contexts with real-time tracking curves showing the correlation between actual fluid volume dispensed and measurement while providing users with consistent, reliable monitoring data across different fluid depletion stages for both patient beds.

Table 7 Detailed status monitoring for Bed 1 and Bed 2

Status level	Bed 1			Bed 2			Application display
	Weight (g)	Volume (ml)	Fluid capacity (%)	Weight (g)	Volume (ml)	Fluid capacity (%)	
Normal (Full-Green LED ON)	457.24	455.19	91.00	473.46	471.34	94.30	Monitoring Normal - No Action Require

DOI: https://doi.org/10.11113/jmeditec.v5.79

Warning (Medium-Yellow LED ON)	81.67	81.31	16.30	178.95	178.15	35.60	d (> 50 %) Observation: IV Level Sufficient - Continue Monitoring (15 - 50 %)
Critical (Low-Red LED ON)	50.25	50.02	10.00	17.46	17.38	3.50	Caution: IV Fluid Decreasing - Prepare Replacement (< 15 %)

Data Transmission Performance

The end-to-end data flow system worked as the ESP32 microcontrollers constantly transmitted data to the Firebase Realtime Database. This system provided consistent data capture and long-term storage for not only real-time monitoring but also historical analysis. The flow of data from the hardware to the cloud database was seamless. Overall testing demonstrated effective correlation between mobile application display and LCD display in the full prototype, showing similar values within a 3 to 5 second gap, confirming system-wide synchronization and reliability. Real-time updates were consistently displayed in both the mobile application interface and Google Sheet logs of sensor readings using Google App Scripts by programmed coding, satisfying the real-time monitoring requirement. The effectiveness of data transmission allows for immediate response in critical situations. The analysis of data transmission across various network conditions verified consistent performance specifications. The Google Apps Script integration shows the Excel-based data visualization by displaying it in an organized table form for systematic monitoring of each bed with an integration.

The implementation of the Firebase real-time database for IV monitoring and load cells enables the review of analytical-based observations of the values recorded simultaneously. Within the system, the critical parameters for monitoring included uploading the critical metrics of bed scale weights, fluid weight use, volume readings, percentage levels, time estimates to depletion, and status descriptions of a continuous two-bed monitoring process. The implementation captures and sends structured JSON formatted data to the Firebase endpoints in real-time, which stores units of observations for both IV_Monitoring/Readings and LoadCells directories, while doubling the information for an integration in monitoring, which can justify improved integrated knowledge awareness and therefore protective measures for monitoring.

CONCLUSION

The data consequently formed this low-cost, cost-effective, IoT-based real-time IV fluid monitoring system, attempting to tackle all key research objectives through single integrated prototype. Calibration of the load cell sensors was primarily the first objective, the sensors produced consistent and reliable under minimal measurements errors with an average error margin of less than 5 %, thereby enabling a precise between the weight and volume to be drawn. The second objective was addressed by creating the InfuTrack+ mobile application, intended to work with the system and provide a straightforward interface for wireless, real-time remote monitoring. Continuous monitoring was implemented as the third objective, which gently alerts the users upon reaching certain defined fluid level limits, through both visual and auditory signals. Crucially, the survey of 26 healthcare professionals strongly supported the need for such a solution, highlighting not only the "risk of human error" in current methods but also recommending the adoption of an automated system. The features included in the prototype, real-time tracking, the mobile-friendly interface, and automatic notifications, were consistent with the top three features requested by the respondents. All in all, this work signifies a pragmatic and meaningful step toward improving the monitoring of IV fluids and thereby supporting patient care. Although the prototype is a breadboard-based assembly at the current time, it has established a strong proof of concept through this work. The next step is to design a custom Printed Circuit Board (PCB) and a compact and sterilizable enclosure for the prototype that will transform it into a clinical grade device ready for formal trials in the hospital. Moving forward, there will be efforts in reducing system size, to focus on power efficiency, and perform clinical evaluation.

ACKNOWLEDGMENT

The authors would like to thank the Ministry of Higher Education (MOHE), the School of Postgraduate Studies (SPS), the Research Management Centre, the Advanced RF and Microwave Research Group, the IJN-UTM Cardiovascular Engineering Centre, and Universiti Teknologi Malaysia (UTM), Johor Bahru, for their support of the research under the UTM Fundamental Research Grant Q.J130000.3823.24H07 and the Fundamental Research Grant Scheme titled FRGS/1/2023/TK07/UTM/02/23. Special thanks are extended to Mrs. Almi Mahmod for her assistance in developing and formatting the survey in accordance with healthcare standards, as well as to the Department of Biomedical Engineering & Health Sciences, Faculty of Electrical Engineering, UTM, for the support approval, and to the healthcare professionals who participated in the survey for their invaluable feedback and contributions to the project.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

ETHICS DECLARATION

This study did not involve human participants, animal subjects, or sensitive data. Consequently, formal ethical approval was not required.

DOI: https://doi.org/10.11113/jmeditec.v5.79

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