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Indigenous Development of a Clinically Safe, Low Cost Microcontroller-Based Blood Warmer for Resource Limited Healthcare

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ABSTRACT

Blood transfusion is a critical medical procedure in trauma care, surgery, and obstetrics. However, transfusion cold-stored blood without proper warming can induce hypothermia, cardiac arrhythmias, and increase mortality rates, particularly in resource-limited healthcare environments such as rural Pakistan. In the present study, we design and fabricate an indigenous, low-cost, microcontroller-based blood warming system optimized for deployment in resource-limited medical settings. The device incorporates Positive Temperature Coefficient (PTC) ceramic heating elements, a servo-actuated shaking mechanism to ensure uniform heat distribution, thermocol insulation for thermal retention, and an MLX90614 infrared sensor for precise, non-contact temperature monitoring. A simple on-off control algorithm maintains stable and reliable temperature regulation at the clinical threshold of 37 °C, with an integrated buzzer and Liquid Crystal Display (LCD) interface providing real-time operational feedback and safety alerts. Bench-top in vitro tests demonstrated that the prototype effectively elevated a 500 mL blood bag from 4-6 °C to 37 °C within 12-14 minutes, achieving high accuracy (±0.4 °C) and uniform warming without inducing hemolysis, as confirm by plasma free hemoglobin analysis. Comparative evaluation against a laboratory water bath highlighted the device's faster and more controlled heating profile. Cost analysis revealed a fabrication cost of approximately PKR 29,000 (<100 USD), substantially lower than commercial alternatives. Thus, the developed system offers an affordable, safe, power efficient (~300 W), and ease of local fabrication, presenting a clinically viable and scalable solution for safe blood transfusion in emergency and resource-limited healthcare settings.

INTRODUCTION

Blood is a vital biological fluid that sustains life by transporting oxygen and nutrients to the body cells, while also facilitating the removal of metabolic waste products(Goodnough *et al.,* 2013). Hemorrhage, characterized by severe blood loss, accounts for more than half of the nearly five million trauma-related fatalities occurred worldwide annually, commonly arising from accidents, armed conflicts, and surgical interventions (Brohi *et al.,* 2019. In these critical situations, blood transfusion is often a crucial, life-saving procedure. To facilitate timely access to blood during emergencies, blood banking systems have been established, where donated blood is generally preserved within a controlled temperature range of 1- 6 °C (Roxby *et al.,* 2020). This thereby extends storage duration, retards the metabolic degradation of the Red Blood Cells (RBCs), and prevents the growth of pathogens. Other blood components apart from White Blood Cells (WBCs) and RBCs such as cryoprecipitate and plasma are kept frozen while platelets are stored at controlled ambient temperature. Purified plasma derivatives, including albumin and immunoglobulins are preserved under conditions prescribed by the manufacturer.

However, before transfusion it is essential to warm the cold blood components to physiological core temperature to prevent the risk of transfusion induced hypothermia (Mommsen *et al.,* 2013). Hypothermia is identified as a core body temperature below 35°C, which can result in complications such as arrhythmic heart activity, dehydration, vasoconstriction, insufficient oxygen delivery to tissues, impaired drug metabolism, weakened immune response, and increased risk of surgical wound infection (Cherry *et al.,* 1981). Notably, over 42% of hospitalized patients are susceptible to hypothermia, and trauma patients experiencing it face higher mortality rates compared to normothermic individuals (Henker *et al.,* 1995).

Moreover, hypothermia is commonly occurred in surgical patients under anesthesia, as anesthetic agents suppress the body's thermoregulatory responses and patients are subjected to the low ambient temperature of the operating room (Insler & Sessler, 2006; Vaughan *et al.,* 1981; Leslie, 2003). This effect is particularly pronounced in surgeries involving open body cavities, where heat dissipation is significantly greater (Hendolin & Lansimies, 1982). In the context of blood transfusion, hypothermia is observed among different categories of patients:

- Patients instantly required high-volume blood transfusions
- Trauma patients treated surgically under anesthesia

Patients who need transfusions that involve replacing the total blood volume within 24 hours need to receive fast warming of the fluid (Cherry *et al.,* 1981; Insler & Sessler,

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2006). In cases of slow transfusion, particularly among pediatric patients, infusion rates are generally maintained between 5 and 20 ml/min (Insler & Sessler, 2006)..

The theoretical consequences of infusing cold blood are discussed in (Vaughan *et al.,* 1981). In the case of intravenous (IV) fluid infusion, it is indicated that by the injection of 3 liters of crystalloid solution at 21 °C into a 70 kg adult with a core temperature of 37 °C results in a negative thermal balance of approximately 48 kcal. In an anesthetized adult, this amount of heat loss approximately equals one hour of heat generation and can decrease body temperature by 0.75 °C or greater during general anesthesia with neuromuscular blockade (Smith *et al.,* 1998).

Hence, warming equipment is utilized to warm blood prior to transfusion. The equipment should precisely regulate physiological temperatures without damaging blood constituents. Sessler D et al reported that red blood cells heated to 45 °C for an hour do not cause hemolysis (Iserson & Huestis, 1991).

However, fluid-warming devices must be capable of rapidly elevating the fluid temperature to the desired range (35 ± 2 °C) while accommodating transfusion rates from a few ml/min to several hundred ml/min.

Over the years, multiple techniques have been developed to heat blood and intravenous fluids, such as pre-transfusion warming (Iserson & Huestis, 1991), temperature-controlled water bath (Cherry *et al.,* 1981; Iserson & Huestis, 1991; Sumpelmann, 2001), countercurrent heat exchangers, warmed saline mixing (Sumpelmann, 2001; Iserson, 2014), dry electric coil heating, and inline microwave based warming systems (Leaman & Maclean, 1985). In healthcare facilities, where expensive, modern warmers equipment are not available, blood bags are typically placed in warm water baths using convection and conduction to transfer heat. Although the initial rise in temperature tends to follow a linear pattern, but maintaining a stable target temperature is challenging due to the difficulty of achieving precise thermal regulation in water baths. Moreover, the majority of commercial warmers employ direct contact heat through hot plates, utilizing resistance or inductive heating [(Platts-Mills *et al.,* 2007).

In contrast the counter-current heat exchange methods, the warm water is circulated through multi-lumen tubing that comes into contact with the blood or fluid (Sessler, 1994; Uhl *et al.,* 1992; Muth *et al.,* 1996).

This technique is efficient for high flow rates and requires a relatively low priming volume (Sumpelmann, 2001; Muth *et al.,* 1996). However, the specialized tubing makes the design more complex and expensive whereas introducing potential leakage risks. Another commonly employed procedure is dry heating via resistive electric coils (Poppa *et al.,* 2009). In this technique, the blood is passed through a disposable cartridge housed within the heating chamber, where heat is transferred primarily by conduction. Although this configuration supports flow rates exceeding 150 ml/min, it introduces significant concerns. Studies have reported that the formation of hotspots during the heating process, which can lead to hemolysis or degradation of blood components [(Poppa *et al.,* 2009). Furthermore, the necessity of disposable cartridges contributes to increased operational costs, while the non-uniform heat distribution along the fluid pathway raises potential safety issues. In Infrared-based dry heating systems such as Fluido warmer (Turner *et al.,* 2006), blood warming is achieved through the use of two infrared lamps which offered more uniform distribution of thermal energy and warm the fluids up to 37°C at flow rates of 150 mL/min. However, these devices rely on specialized disposable cassettes, which limit reusability and impose a substantial financial burden.

Portable military devices based exothermic chemical reactions have also been developed, offering the advantage of not requiring an external power source. However, these devices lack precise temperature control, and heating duration depends on the chemical reaction, limiting their reliability for extended clinical transfusions (Turner *et al.,* 2006; Hijji *et al.,* 2012). Microwave-based warming techniques have been explored as a potential solution for rapid and volumetric heating (Leaman & Maclean, 1985). The device was designed to utilize microwave energy to rapidly elevate blood temperature from storage (4-6 °C) to the physiological range of ~37 °C. However, concerns remain regarding non uniform thermal distribution within the blood bag or infusion line, which create localized hot spots, potentially leading to cellular damage and hemolysis.

A comparative evaluation of these studies reveals a consistent challenge in term of slow heating times, high costs, reliance on consumables and risks of hemolysis due to uneven thermal distribution. Such limitations are particularly critical in resource-limited healthcare environments, where cost-effectiveness, reliability, and ease of maintenance are as important as clinical performance. To address this limitation, the present study aims to design and develop a low-cost, microcontroller-based blood warmer utilizing readily available local materials and open-source technology. This novel design ensures accurate temperature management, operational safety, energy efficient, and ease of fabrication, making it a sustainable alternative to an expensive commercial warmer for deployment in low-resource healthcare settings.

MATERIALS AND METHODOLOGY

This section describes the design approach, and fabrication process of the indigenous blood warmer prototype. The device is engineered to deliver reliable clinical performance tailored for low-resource medical environment.

Design of Blood Warmer

The entire system was designed using SolidWorks 2023, creating a detailed 3D representation containing two separate chambers as illustrated in the Figure 1. The one consists of electronics component integration and the

other dedicated to blood warming consist of Positive Temperature Coefficient (PTC) heater, a temperature sensor, and a shaker mechanism driven by a servo motor to ensure uniform heating and agitation of the blood bag. This segregation helps to prevent electrical interference and optimized thermal management within the device.

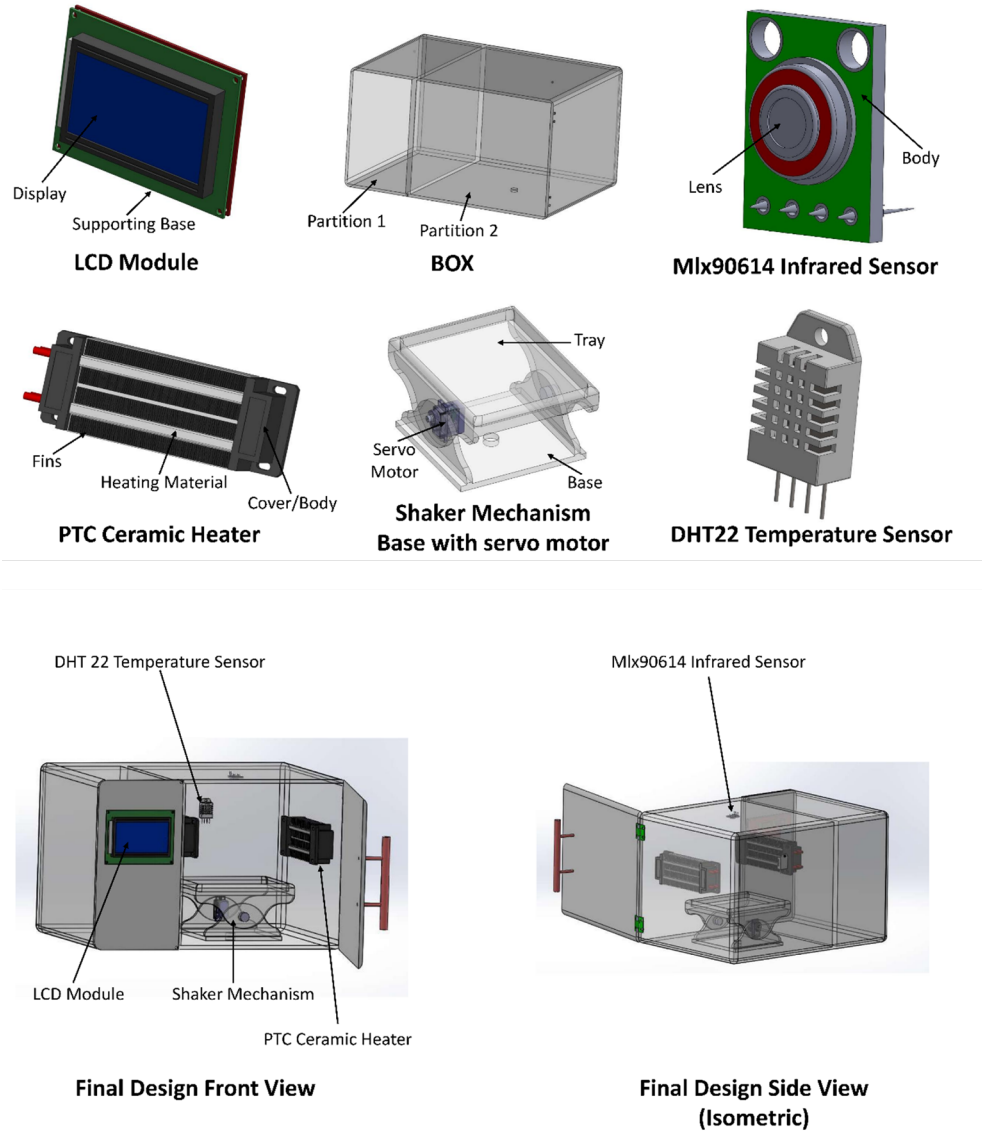

Figure 1: CAD model of components and final assembly design of blood warmer

The design carefully positioned the PTC ceramic heaters, temperature sensors (DHT22 and MLX90614 sensors), fans, and the servo-driven agitation mechanism was ensured within the CAD environment. The design incorporated airflow paths and mounting provisions to maximize thermal efficiency and mechanical reliability. The control system, based on an Arduino Uno microcontroller, employed sensory input from an MLX90614 infrared temperature sensor positioned above the blood bag. This sensor measures continuous surface temperature monitoring and uses simple hysteresis on-off control to regulate heating, ensuring reliable and easy-to-use operation.

Fabrication of Blood Warmer

The box assembly was precisely fabricated from laser-cut acrylic sheets, which were shaped and bonded to form a durable, well-insulated housing as shown in Figure 2. Acrylic was chosen for its strength, transparency and cost-effectiveness, allowing visual access to internal components. To enhance heat retention and improve energy efficiency, expanded polystyrene (thermocol) was layered along the inner surfaces of the enclosure. This insulation significantly reduced heat loss, ensuring consistent internal temperatures even in cooler ambient environments. The core of the warming element, a Positive Temperature Coefficient (PTC) ceramic heater, selected for its inherent thermal self-regulation, safety, and reliability. Mounted on the inner side wall of the enclosure, ensuring controlled and uniform heating to the blood bag while preventing overheating without the need for complex control systems.

To maintain uniform temperature distribution, two fans were installed, one in the electronics chamber to dissipate heat from sensitive control electronics, and another within the blood warming chamber to circulate warm air evenly. The blood bag temperature was monitored by an

MLX90614 infrared sensor positioned above the blood bag for non-contact, while chamber conditions were tracked using a DHT22 sensor. These inputs enabled Arduino-based hysteresis control, ensuring ±0.5 °C accuracy and reliable regulation. A servo motor-driven shaker was incorporated beneath the blood tray, designed with an eccentric load on the servo shaft to gently oscillate the blood tray at an angle 30°, ensuring uniform heat

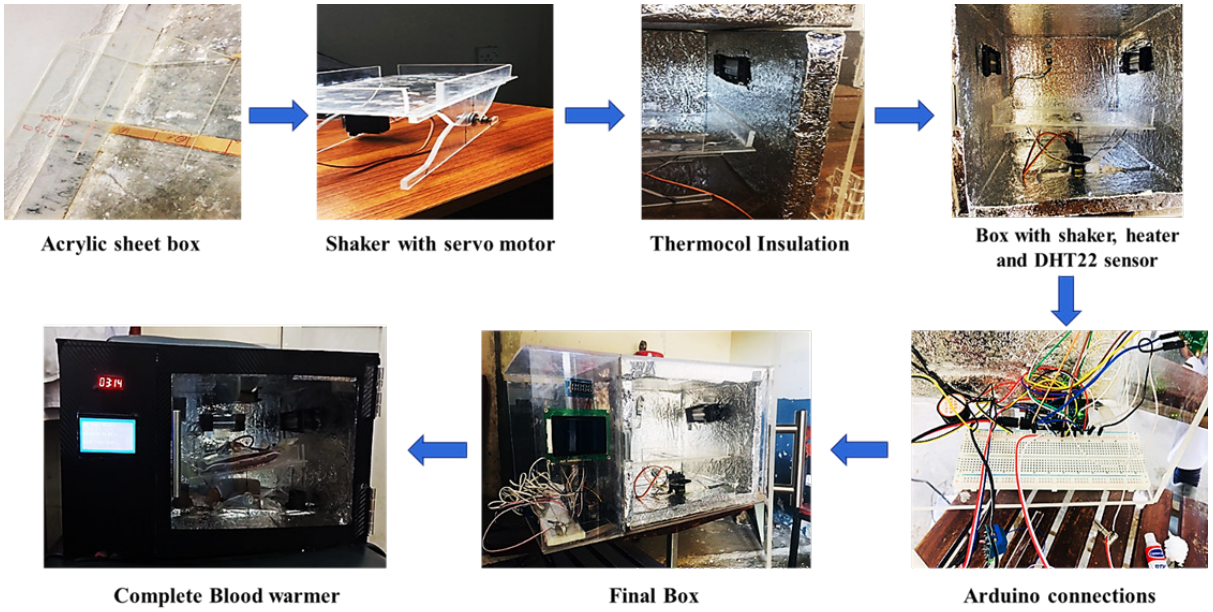

Figure 2: Schematic of stepwise fabrication of indigenous blood warmer

distribution, preventing red blood cell sedimentation, and avoiding hemolysis. A 16x2 LCD screen is integrated on the front panel to display real-time temperature feedback and system status, complemented by an audible buzzer alarm that activates if the temperature exceeds 37°C, which automatically stopped the heater from further heating to ensuring an additional safeguard against overheating. The blood warmer device operated on 220 V AC, stepped down and regulated for control electronics, ensuring reliable operation across typical clinical environments. A flowchart summarizes the stepwise fabrication process from material preparation through final integration and testing as shown in Figure 2.

RESULTS AND DISCUSSION

In this work, a novel blood warming device was designed for rapid infusion and evaluated through bench-top in vitro tests, focusing on thermal performance, blood integrity evaluation, and cost analysis. The results obtained from these evaluations are presented as follows.

Thermal Rise Over Time

The heating trials exhibited that the developed blood warmer successfully raised stored blood from ~4-6 °C to the required clinically temperature of 37 °C within

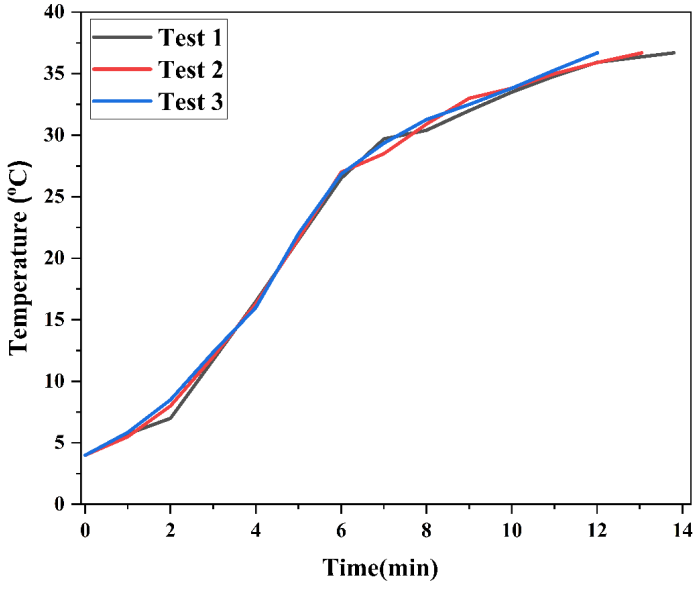

Figure 3: Temperature rises vs time graph

12-14 minutes. Three independent tests were performed on the desired blood warmer, and the resulting heating profiles are presented as three separate curves in Figure 3, the heating curves demonstrated a smooth and steady rise without overshoot, ensuring precise and stable thermal regulation throughout the process. This rapid heating rate is significantly faster than many conventional devices, which typically take 20-35 minutes to achieve similar performance. The ability to consistently reach body temperature in such a short time frame reveals the effectiveness and reliability of the heating mechanism, making this device highly practical for emergency and low-resource healthcare environments.

Thermal Stability Evaluation

For clinical validation, a blood warming device must demonstrate precise and reliable thermal regulation. To assess the performance of the developed prototype, a bench-top temperature stability test was conducted. A blood bag initially cooled to 4 °C was placed inside the developed indigenous warmer and its core temperature was continuously monitored using a centrally positioned T-type thermocouple. The device reliably elevated the fluid temperature to 37 °C within 12 minutes, corresponding to a temperature rise coefficient of 2.67 °C/min. For benchmarking, the same blood bags stored at 4°C were subjected to two reference conditions. One

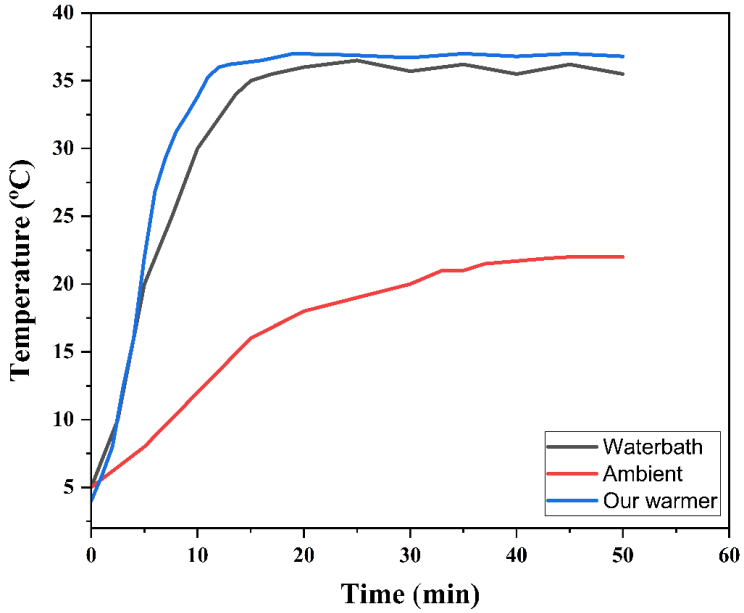

Figure 4: Temperature-rise profiles of indigenous warmer vs water bath and ambient

blood bag was immersed in a standard laboratory water bath (5 L capacity, 1000 W), while another was left at ambient room conditions (23 ± 2 °C). The water bath exhibited a steeper initial heating rate of ~3 °C/min but required 15-20 minutes to stabilize at 37 °C, with notable temperature fluctuations during steady state. Conversely, the ambient sample exhibited a negligible temperature rise over the same period. Notably, despite the higher power rating of the water bath, the indigenous warmer achieved the clinical cutoff temperature in a shorter overall time with a more controlled heating profile as depicted in Figure 4. This steady and reliable performance underscores the device's effectiveness in providing safe and precise blood warming suitable for transfusion applications.

Blood Integrity Evaluation

Preserving the structural and functional integrity of blood is crucial to avoid hemolysis, degradation of plasma proteins or reduced red blood cell viability during warming process. In present work, blood bag was warmed gradually to the physiological temperature of 37 °C under controlled conditions. This moderate heating rate ensured a uniform rise in temperature of blood bag without subjecting the cells to sudden thermal stress. Unlike rapid-heating systems that may induce localized hotspots and uncontrolled temperature overshoot, this controlled approach ensured stable and uniform heat transfer. As illustrated in Figure 5 the visual appearance of warmed blood samples exhibited clear plasma separation and intact erythrocyte layers after centrifugation, with no signs of plasma coloration or red blood cell sedimentation, thereby confirming that the warming process neither induced hemolysis nor compromised the blood's viability. The integrity of red blood cells was further verified by plasma free hemoglobin (fHb) testing, which showed concentrations of 0.25 g/L which is well below the critical threshold. The agreement between visual inspection and biochemical evaluation provides

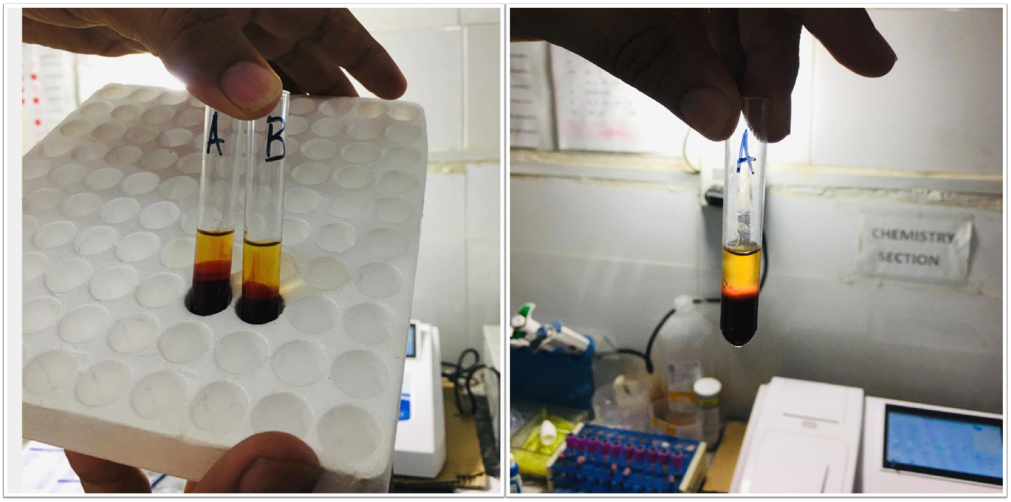

Figure 5: Visual comparison of blood samples: Before testing (B) vs After testing (A)

strong evidence that the warming method-maintained RBC viability and effectively prevented heat-induced hemolysis.

In Comparison with other designs, such as Peltier-based warmers reported by Park et al [23] which utilized EPDM cushion sheets and multiple peltiers modules to significantly reduced heating time up to 8 minutes, but carried the risk of localized overheating. However, our proposed device emphasizes a balance between safety and efficiency. Similarly, the infusion-type devices [24] often emphasize flow-through heating, but such designs require continuous monitoring to prevent hemolysis at high flow rates. Thus, the present system demonstrates an optimized trade-off maintaining safe blood properties while achieving a clinically acceptable warming time.

Cost Analysis

The device was developed with a strong emphasis on cost effectiveness. As detailed in Table 1, the total fabrication cost of our prototype is PKR 27,000 (under USD 100), that includes all essential components such as heating elements, sensors, microcontrollers and acrylic housing. This budget is considerably lower than the cost of commercially available blood warmers such as Belmont Rapid Infuser R2 (20000 USD) and Techno care Medisystems ET3 Liquid and Blood Warmer (1000 USD) [24], placing them out of reach for many low-resource healthcare facilities. For instance, high-end commercial warmers with in-line infusion systems not only have high purchase prices but also demand recurring costs for proprietary consumables, making them less practical for smaller healthcare facilities. By integrating off-the-shelf components and modular configuration, our proposed device provides a cost-effective solution while maintaining clinical safety and performance comparable to high-end systems.

Table 1: Component-wise cost breakdown of the proposed blood warmer

Sr. No	Component	Quantity	Price (PKR)
1	Fan	2	800
2	Thermostat	1	800
3	Heating element	1	1000
4	Power socket	1	300
5	Relay switch	1	400
7	Servo motor	1	700
8	LCD module	1	3000
9	Supporting stain/Base	1	1500
10	Acrylic sheet box	1	10000
11	Sensor module	1	5000
12	Arduino UNO	1	5000
13	Manufacturing cost	1	11500
	Total Cost		**29,000**

CONCLUSION

In this study, a low-cost, microcontroller-based blood warmer was successfully designed and fabricated using readily available local components. The prototype integrates PTC ceramic heating elements, an MLX90614 infrared sensor, and a servo-controlled shaker mechanism to ensure precise and uniform heating. Experimental

evaluation exhibited that the device is capable of warming a 500 mL blood bag from 4-6 °C to the required physiological temperature of 37 °C within 12-14 minutes corresponding to a temperature rise coefficient of 2.67 °C/min. The temperature was consistently maintained by the device within stable clinical threshold of 37 °C with high accuracy (± 0.4 °C), ensuring reliable thermal regulation throughout the process. Evaluations of blood integrity via visual examination and plasma-free hemoglobin test verified that red blood cells retained their structure and function, showing no evidence of hemolysis during the warming process. These findings confirm that the system can warm blood without compromising its viability. The device is further equipped with essential safety features such as a simple on-off control system, an LCD interface for continuous real-time temperature monitoring, and an audible alarm system that activates when the temperature exceeds 37 °C. With a total fabrication cost of approximately PKR 29,000 (<100 USD), the prototype demonstrates affordability, energy efficiency, and feasibility for local manufacturing. Overall, the results highlight that the developed blood warmer offer a reliable, safe, and practical solution, making it well-suited for emergency applications and deployment in resource-limited healthcare environments where commercial blood warmers remain inaccessible.

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Author Contribution Statement

Yasir Ali Shah Conceived the study, designed and fabricated the blood warmer prototype, conducted experimental evaluation, and prepared the initial manuscript draft. Malik Muhammad Aqib Khan Assisted in device assembly, testing setup, and data collection, contributed to analysis of thermal performance results. Muhammad Awais Khan Contributed to cost analysis, result validation, and literature review, assisted in manuscript editing. Malik Sarmad Zahid Assisted in sensor integration, control system calibration, and data verification. Mushaf Ur Rehman Contributed to overall proofreading, technical review, and refinement of the manuscript.

Conflict of Interest Statement

All the authors declare that there are no conflicts of financial or any other competing interests.

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