



DOI: <https://doi.org/10.56936/18290825-2026.20v.1-81>

COMPARISON OF RADIANT HEAT FLUX FROM A LARGE-SURFACE AND CONVENTIONAL NEONATAL WARMER USING STANDARDIZED BLACK BODY PLACEMENT

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Received 3.09.2025; Accepted for printing 14.05.2026

ABSTRACT

Background: Maintaining thermal stability in neonates remains a clinical challenge. Conventional resistive heat warmers (RHWs) may cause localized overheating, while large-surface warmers have been proposed as a safer alternative.

Objective: The objective of this study was to compare surface temperature stability and heat flux characteristics of test objects exposed to a conventional resistive heat warmer (RHW) and a prototype large-surface warmer, using a regulatory reference test methodology for incubators and radiant warmers.

Methods: Five calibrated Fluke Corporation test objects were placed on a pre-warmed mattress and exposed to each heating system. Both systems were evaluated across six servo-controlled temperature settings ranging from 36.0 to 37.0 °C. Surface temperature and heat flux at the upper surfaces of the test objects were recorded at 15-second intervals over a 60-minute period. Theoretical radiant heat flux requirements were calculated using the Stefan–Boltzmann law. Collected data were analyzed using descriptive statistics and independent *t*-tests to assess differences between the two warming modalities.

Results: The RHW delivered heat flux values approximately 6–7 times higher than those measured under the large-surface radiant warmer ($p < 0.001$), with substantially greater temporal variability. In several settings, RHW heat flux exceeded the calculated theoretical requirements. In contrast, the large-surface radiant warmer maintained lower, more stable, and more uniform surface temperatures across all test objects. Both systems complied with the applicable standard thermal performance criteria.

Conclusion: The prototype large-surface radiant warmer demonstrated gentler and more consistent heat delivery compared with the RHW, supporting its potential as a safer thermal support method in neonatal care. Continuous heat flux monitoring may provide an additional indicator of thermal readiness and stability during neonatal warming.

KEYWORDS: neonatal warming, heat flux, radiant warmer, servo control, thermal safety

CITE THIS ARTICLE AS:

KREICBERGA I., REZEBERGA D., MISKOVA A., VARDANYAN R., ARBUZOVS G., TĒRVIDS T. (2026). Comparison of Radiant Heat Flux from a Large-Surface and Conventional Neonatal Warmer Using Standardized Black Body Placement; The New Armenian Medical Journal, vol.20 (1), 81-89; DOI: <https://doi.org/10.56936/18290825-2026.20v.1-81>

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1. INTRODUCTION

1.1. Importance of Thermoregulation in Neonatal Care

Thermoregulation has been a cornerstone of neonatal care for over two centuries, with a persistent focus on minimizing thermal stress, particularly in preterm infants [Waldron & MacKinnon, 2007]. Owing to their high surface-area-to-volume ratio, limited brown fat stores, and immature thermoregulatory mechanisms, neonates are highly susceptible to both hypothermia and hyperthermia. These vulnerabilities have led to the development of sophisticated external heating systems, including servo-controlled radiant warmers. However, concerns persist regarding the safety of localized high-intensity heat application, particularly when radiant heat flux exceeds physiologic tolerance [Bell, 1983; Singer, 2022].

1.2. Evolution of Radiant Heating Technologies

Historical accounts underscore the long-standing importance of warmth in neonatal resuscitation and care [O'Donnell et al., 2006]. Radiant warmers introduced in the 1960s—such as the low-energy canopy design by Friedman et al. (1967) - enabled non-contact heat delivery. Du and Oliver (1969) demonstrated their effectiveness in maintaining abdominal temperature, while Darnall and Ariagno (1978) demonstrated stable oxygen consumption under such systems, but also warned of increased insensible water loss.

1.3. Persistent Challenges in Modern Neonatal Warming

Despite advances, maintaining normothermia remains a challenge. The 2024 international consensus on neonatal resuscitation guidelines [Greif et al., 2024] and recent epidemiological data [Tveiten et al., 2024] highlight ongoing deviations from thermal targets. Research using thermal modeling [Delanaud et al., 2019; Katić et al., 2016] and CFD simulations [Jiang & Li, 2024; Wrobel et al., 2010] indicates that surface temperature alone may not adequately reflect internal thermal states under radiant heat exposure. These findings raise questions about how heat is distributed, sensed, and regulated in current systems.

1.4. The Need for Safer and More Uniform Warming

Several recent studies stress the importance of heat distribution and duration over sheer intensity. Li et al. (2021) and Lakhoo et al. (2024) have demonstrated that uneven or excessive heating adversely affects physiological stability. Likewise et al. (2019) and Bell (1983) caution against single-sensor servo control when used with focused heat sources. These findings suggest the need for technologies that distribute thermal energy more gently and evenly - especially for delicate patients.

1.5. Objective of the Present Study

This study compares two neonatal warming systems: a conventional resistive heat warmer (RHW) and a novel large-surface radiant warmer (LSW) developed using smart film technology. The LSW prototype was developed by the R&D team at SIA Armgate within an EU co-funded research project, “Development of Portable Patient Warming Screens Using Innovative Combination of Low-Temperature Directed Warmer Technology and Switchable Smart Film” (15.02.2023–14.02.2025), supervised by the Smart Materials and Technology Competence Centre.

Two types of warming panels - arched and rectangular - were developed, incorporating transparent low-temperature smart film embedded within heated panels.

Study Aim: The study aimed to compare the thermal performance of a large-surface warmer (LSW) and a radiant heat warmer (RHW) under controlled conditions.

The objectives were:

- to evaluate whether both systems could maintain the temperature of FLUKE test objects in accordance with IEC 60601-2-21:2020;
- to measure and compare heat flux at the mid-point test object across six servo temperature settings from 36.0 °C to 37.0 °C;
- to measure and compare heat flux at peripheral test objects (proximal and distal);
- to assess whether the measured heat-flux values were consistent with theoretical expectations based on Stefan–Boltzmann calculations;
- to explore the potential relevance of heat-flux data as an indicator of thermal control efficiency and neonatal thermal readiness.

2. MATERIALS AND METHODS

2.1. Experimental Conditions

The study was conducted in a controlled research laboratory environment, in accordance with IEC 60601-2-21:2020. Ambient temperature was maintained at 23 ± 2 °C, with air velocity kept below 0.1 m/s.

2.2. Radiant Warmers

Two infant radiant warmers were evaluated:

1. Prototype large-surface radiant warmer (LSW) – A newly developed low-temperature large-surface radiant warmer (Figure 1).
2. Commercial resistive heat warmer (RHW) – A high-temperature resistive heat warmer currently used in Latvian hospitals (Figure 2).

2.3. Test Setup

Five standard black-painted aluminum test objects (Nos. 20, 14, 15, 17, and 19) from the Fluke

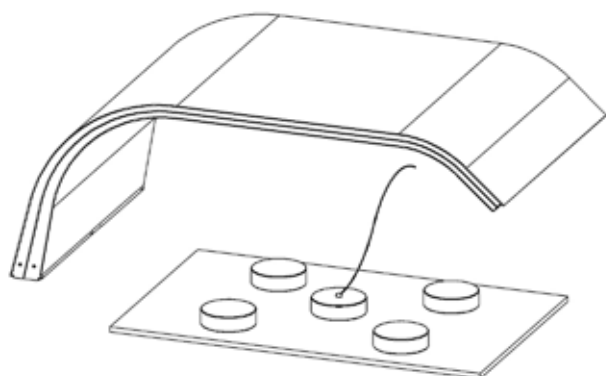


FIGURE 1. Experimental setup of the large-surface radiant warmer (LSW) prototype.

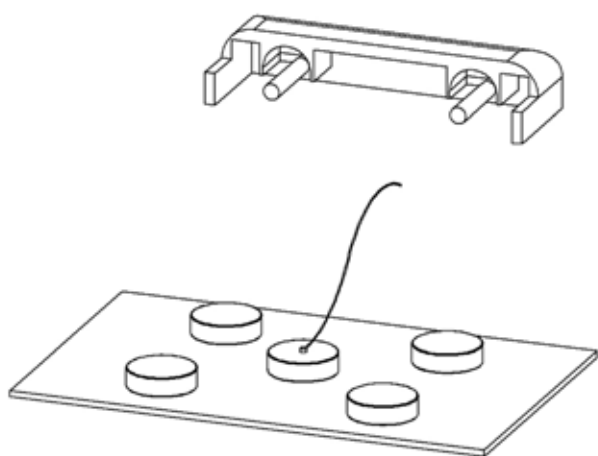


FIGURE 2. Experimental setup of the resistive heat warmer (RHW).

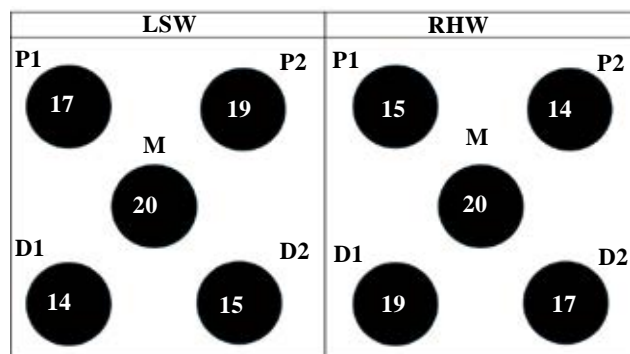


FIGURE 3. Placement of the test objects on the mattress. These labels - M, P1, P2, D1, D2 - are used consistently throughout the analysis.

INCUB II Incubator/Radiant Warmer Analyzer were placed on a pre-warmed mattress maintained at 36.0 °C. Each warmer was tested individually over the same mattress setup (Figure 3).

To account for the differing positions of the warmer stands (mounted at opposite ends of the mattress), a mirrored configuration of test objects was implemented for each setup.

- The central test object (No. 20) was designated as M (mid-point) in both configurations.
- The two objects nearest to the warmer stand (proximal) were labeled P1 and P2 (Nos. 17 and 19 for LSW; Nos. 15 and 14 for RHW), representing the upper body region.
- The two farthest objects (distal) were labeled D1 and D2 (Nos. 14 and 15 for LSW; Nos. 19 and 17 for RHW), representing the lower body region.

2.4. Temperature and Heat Flux Measurement

Each test object was equipped with a Hukseflux FHF05-15X30 temperature/heat flux sensor mounted on the upper surface and secured using black Kapton® tape. The servo-control temperature sensor of each warmer was fixed to the mid-point test object (M) to regulate power output and maintain the target temperature.

Each warmer was tested in alternating cycles. Temperature settings were incremented from 36.0 °C to 37.0 °C in 0.2 °C steps. For each setting, data collection began after the system stabilized at the target temperature on test object M. Measurements were recorded every 15 seconds for 60 minutes using a Keysight DAQ970A Data Acquisition System.

Data were analyzed in Microsoft® Excel for Mac using descriptive statistics and Student's t-test, with $p < 0.05$ considered statistically significant.

2.5. Comparison of Measured and Theoretical Heat Flux

To estimate the theoretical heat flux required to maintain the black test object at 36.0 °C, the Stefan–Boltzmann law was applied for radiative heat transfer in ambient air:

$$Q = \sigma \times \epsilon \times (T_{\text{object}}^4 - T_{\text{ambient}}^4)$$

where: (Q) is the heat flux (W/m²), (σ) is the Stefan–Boltzmann constant (5.67 × 10⁻⁸ W·m⁻²·K⁻⁴), (ε) is the emissivity of the surface (assumed to be 1 for a black body), (T_{object}) is the temperature of the object in Kelvin, (T_{ambient}) is the ambient temperature in Kelvin. [t(°C)=T(K)-273.15]

In our calculations, the ambient temperature (T_{ambient}) was fixed at 296.15 K (23.0 °C), in accordance with IEC 60601-2-21:2020. The object temperature (T_{object}) corresponded to the real-time servo-control setpoints, which ranged from 36.0 °C to 37.0 °C in 0.2 °C increments (i.e., 309.15 K to 310.15 K). For each temperature setting and each 15-second time point during the data collection period, the Stefan–Boltzmann equation was applied to compute a corresponding theoretical heat flux value.

These dynamic theoretical heat flux profiles served as a benchmark for evaluating the actual measured heat flux data. This comparison enabled assessment of the heat delivery efficiency and thermal regulation strategies of the two radiant warming systems (LSW and RHW) across the full range of tested temperature settings.

2.6. Statistical Analysis

Statistical analysis was performed using Microsoft® Excel for Mac. Quantitative data are presented as mean and variance. Measurements of surface temperature and heat flux were recorded at 15-second intervals over a 60-minute period for each servo-controlled temperature setting. Due to the large number of observations, the data were considered to be approximately normally distributed. Comparisons between the large-surface radiant warmer (LSW) and the resistive heat warmer (RHW) were performed using the independent two-sample Student’s t-test. In the presence of unequal variances, Welch’s correction was applied. When variances were assumed to be equal, the standard t-test was used. The t-statistic, degrees of freedom, and p-values were calculated.

TABLE 1.

Comparison of temperatures of the mid-point test object under large-surface radiant warmer (LSW) and resistive heat warmer(RHW).

t – Test: Two – Sample Assuming Unequal Variances		
Statistical parameter	LSW	RHW
Mean	36.57	36.66
Variance	0.07	0.09
Observation	1446.0	1446.0
Hypothesized Mean Difference	0.00	
df	2853.0	
t Stat	-8.95	
P (T≤t) one-tail	0.00	
t Critical one-tail	1.65	
P(T≤t) two-tail	0.00	
t Critical two-tail	1.96	

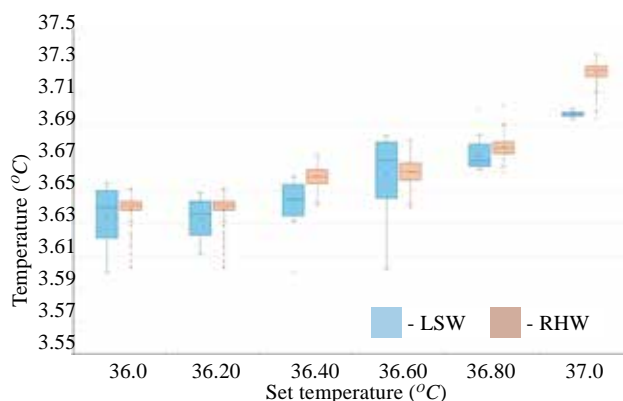


FIGURE 4. Temperatures of the mid-point test object under large-surface radiant warmer (LSW) and resistive heat warmer(RHW) in six servo settings.

A p-value < 0.05 was considered statistically significant. Comparisons were carried out across different temperature settings (36.0 - 37.0 °C) and test object positions (mid-point, proximal, and distal). Variability between groups was assessed by comparison of variances. Data distribution was illustrated using boxplots, presenting median values, interquartile ranges, and outliers. Measured heat flux values were compared with theoretical values calculated according to the Stefan-Boltzmann law. These calculations were used for analytical comparison only.

3. RESULTS

3.1. Mid-Point Surface Temperatures

Across all six servo temperature settings, the upper surface temperatures of the mid-point test object were significantly higher under RHW compared to

TABLE 2.

Comparison of heat flux on the upper surface of the mid-point test object under large-surface radiant warmer (LSW) and resistive heat warmer(RHW) in six servo settings.

t – Test: Two – Sample Assuming Unequal Variances		
Statistical parameter	LSW	RHW
Mean	11.39	74.34
Variance	78.47	713.97
Observation	1446.0	1446.0
Hypothesized Mean Difference	0.00	
df	1759.00	
t Stat	-85.04	
P (T≤t) one-tail	0.00	
t Critical one-tail	1.65	
P(T≤t) two-tail	0.00	
t Critical two-tail	1.96	

LSW. As shown in Figure 4, the RHW system exhibited consistently higher medians and greater variability at each setpoint. This difference was statistically significant ($p < 0.001$), as detailed in Table 1.

Figure 4 presents a boxplot comparison of surface temperatures under both warmers across all servo setpoints. Despite identical control temperatures, RHW consistently produced higher and more variable surface temperatures - particularly at higher settings (≥ 36.6 °C). In contrast, LSW demonstrated narrower interquartile ranges and lower median values, indicating more stable and controlled heating. Notably, at the 37.0 °C setting, RHW temperatures approached or exceeded 37.3 °C, while LSW remained closer to the target temperature.

These findings support the t-test results and suggest a greater degree of thermal control and safety under the LSW system.

3.2. Heat Flux at Mid-Point Test Object

Measured heat flux values at the mid-point test object revealed markedly larger differences between the two warmer types. As shown in Figure 5 and Table 2, the average heat flux delivered by

RHW was 74.34 W/m², significantly higher than the 11.39 W/m² delivered by LSW ($p < 0.001$).

- The variance in RHW measurements was also substantially higher (713.97 vs. 78.47), indicating less consistent heat delivery.
- A two-sample t-test assuming equal variances yielded a t-statistic of -85.04 (df = 2890), strongly confirming the statistical significance of this difference.

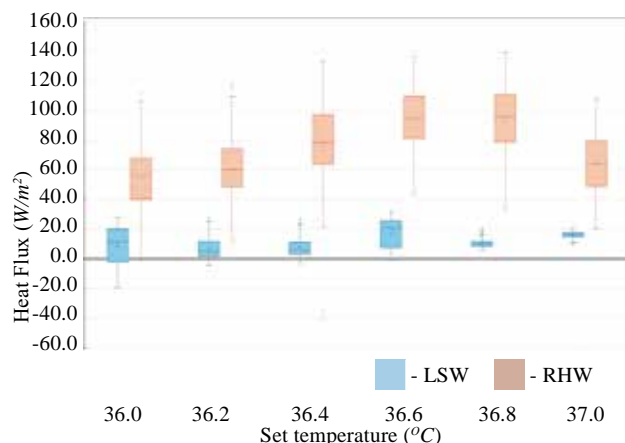


FIGURE 5. Heat flux on the upper surface of the mid-point test object M under large-surface radiant warmer (LSW) and resistive heat warmer(RHW) in six servo control temperature settings

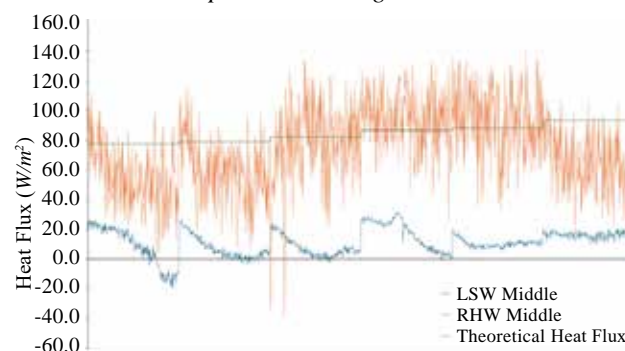


FIGURE 6. Heat flux on the upper surface of the mid-point test object under LSW and RHW in 6 settings and a net heat flux according to Stefan–Boltzmann law

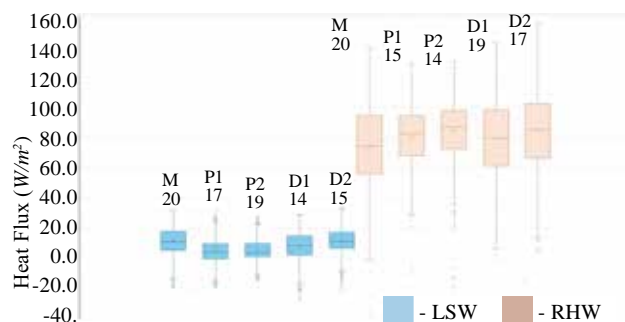


FIGURE 7. Boxplot of heat-flux of all the test objects under LSW and RHW in all 6 servo settings of the temperature of the mid-point test object

TABLE 3.

Calculated theoretical radiant heat flux required to maintain surface temperature

Temperature (°C)	36.0	36.2	36.4	36.6	36.8	37.0
Net Radiant Heat Flux (W/m ²)	77.6	79.0	82.3	86.7	88.2	93.3

3.3. Comparison with Theoretical Heat Flux

Using the Stefan–Boltzmann law, theoretical radiant heat flux values were calculated for each servo setting based on the required object temperature and fixed ambient conditions (Table 3).

As shown in Figure 6, the measured heat flux under LSW was consistently lower than the theoretical values, indicating a more controlled and potentially more energy-efficient heat delivery profile. In contrast, RHW heat flux not only exceeded LSW values but also frequently surpassed the theoretical requirements - raising concerns about potential overheating risk.

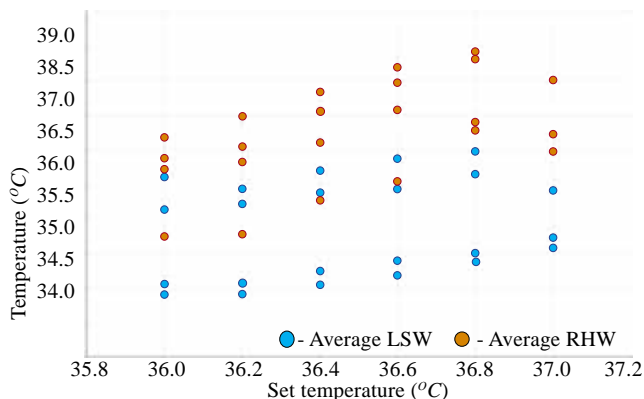


FIGURE 8. Average temperatures of peripheral test objects P1, P2, D1, and D2 in all six temperature settings under LSW and RHW.

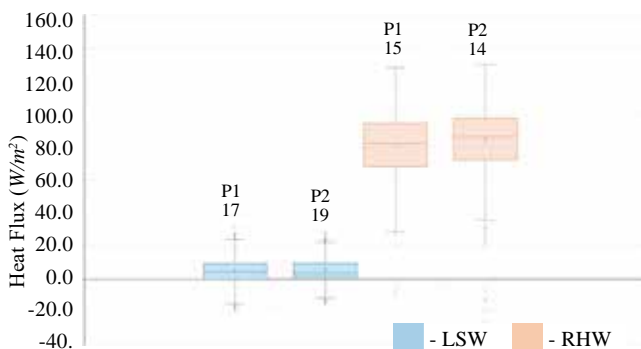


FIGURE 9. Heat flux on the upper surfaces of the proximal test objects across all six temperature settings.

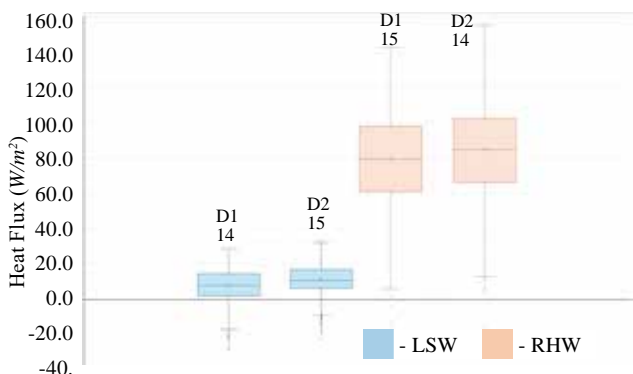


FIGURE 10. Heat flux on the upper surfaces of the distal test objects across all six temperature settings.

3.4. Heat Flux Across All Test Objects

Boxplot analysis of all five test objects across the six temperature settings (Figure 7) showed consistently higher median values and greater variability under RHW.

These findings reflect a broader trend of less stable and more intense heat delivery with the resistive warmer.

3.5. Peripheral Temperature Maintenance

Despite these differences, both LSW and RHW systems were able to maintain the one-hour average temperature of the four peripheral test objects within ± 2.0 °C of the target, as required by IEC 60601-2-21:2020 (Figure 8). This confirms that both devices met baseline thermal performance criteria over time.

3.6. Heat Flux on Proximal and Distal Test Objects

Heat flux values on the proximal (P1, P2) and distal (D1, D2) test objects are shown in Figures 9 and 10. Greater variability was observed under RHW, particularly in the distal objects, which showed elevated fluctuations and outliers.

Interestingly, under both warmers, lower outlier values were more frequent on the proximal objects, suggesting occasional underheating near the sensor control region. This observation may have implications for the uniformity of heat distribution.

4. DISCUSSION

4.1. Key Differences in Heat Delivery

This study revealed substantial differences in the thermal behavior of two neonatal warming systems tested under identical servo-controlled conditions. The resistive heat warmer (RHW) consistently delivered approximately 6 - 7-fold higher heat flux at the mid-point test object compared to the large-surface warmer (LSW), with greater variability and frequent outliers. These results reflect a more aggressive and less regulated thermal output from RHW, which may increase the risk of localized overheating or uneven heat distribution - particularly concerning in thermally vulnerable neonatal patients.

In contrast, the LSW system demonstrated a lower, more stable heat flux profile across all servo settings. Despite delivering less radiant energy, it effectively maintained target temperatures within the required range, suggesting more controlled and

uniform thermal regulation.

4.2. Support from Computational and Clinical Literature

The observed patterns align with findings from both computational and clinical studies. Fic et al. (2010, 2014) and Dey & Deb (2021) reported that concentrated radiant energy can result in thermal gradients, leading to overheating of localized regions while inadequately warming peripheral areas. Similarly, Feki et al. (2017) and Zermani et al. (2023) demonstrated that non-uniform radiation can compromise thermal stability, even under servo control.

4.3. Alignment with Historical and Contemporary Principles

The performance of the LSW prototype reflects long-standing concepts of neonatal thermal care. Its design echoes the early principles of gentle, non-contact radiant heating introduced by Friedman et al. (1967) and is consistent with modern reviews advocating uniform thermal delivery [Singer, 2022; Pereira et al., 2016]. Muntean et al. (2022) reported cases of iatrogenic burns associated with conventional RHW systems, while Basutkar and Hippargi (2019) advocated for redundant temperature sensors to mitigate the risks of single-point servo control—findings that reinforce the need for broader, more diffuse warming solutions.

4.4. Toward Individualized Thermal Support

An additional noteworthy observation was that under LSW, heat flux frequently approached zero while the target temperature was maintained. We propose this finding may reflect a condition of near thermal self-sufficiency in the simulated patient, suggesting that minimal external heat input is required. This interpretation is supported by Koppen and Stulz (2024), who advocate for individualized markers to guide the weaning of neonates from thermal support. Such real-time thermal metrics may contribute to safer and more personalized care protocols.

4.5. Clinical Implications and Future Directions

Lakhoo et al. (2024) and Tveiten et al. (2024) emphasize the dual risks of hyperthermia and sub-clinical hypothermia in neonates. Our findings suggest that LSW may reduce both risks by delivering low, uniform heat with greater control and consistency. This is particularly relevant during procedures or exposure-prone moments in the NICU.

Overall, the comparative analysis of RHW and LSW systems contributes to a growing body of evidence in favor of neonatal warming devices that emphasize thermal stability, safety, and physiological appropriateness. Our findings support a future direction in neonatal care where warming systems are not only effective but also inherently protective.

5. CONCLUSION

This study addressed five core objectives:

1. Both warming systems (LSW and RHW) successfully maintained FLUKE test object temperatures within the ± 2.0 °C limit defined by IEC 60601-2-21:2020, confirming basic thermal performance compliance.

2. Measured heat flux on the mid-point test object was significantly lower and more stable under the LSW system compared to RHW. Despite identical servo settings, RHW generated approximately 6–7-fold higher heat flux with greater variability ($p < 0.001$), suggesting less controlled thermal delivery.

3. Heat flux measurements on peripheral (proximal and distal) test objects further confirmed this pattern, with RHW producing higher variance and more outliers - particularly at distal positions - indicating less uniform heating. LSW provided a more consistent heat distribution across the tested surface area.

4. Comparison with Stefan–Boltzmann-derived theoretical heat flux showed that RHW frequently exceeded the calculated thermal requirement, while LSW remained below or near the theoretical line - implying lower risk of overheating and more energy-efficient performance.

5. Heat flux data under servo control suggest potential for using declining heat flux values as a marker of thermal self-sufficiency. When heat flux approached minimal values under LSW while maintaining target temperature, it may signal readiness to initiate gradual weaning from external thermal support.

Final Summary Statement

In summary, the LSW system demonstrated more controlled, uniform, and physiologically appropriate heat delivery under experimental conditions. These findings support further experimental and clinical evaluation of large-surface warmers as a potentially safer alternative to conventional RHW systems in neonatal care.

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The Journal is founded by
Yerevan State Medical
University after M. Heratsi.

Rector of YSMU

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Our journal is registered in the databases of Scopus, EBSCO and Thomson Reuters (in the registration process)



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Print in "Monoprint" LLC
Director: Armen Armenakyan
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