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COMPARISON OF THERMAL CONDITIONS UNDER A COMMERCIAL NEONATAL RADIANT WARMER AND A NEWLY DEVELOPED LARGE-SURFACE RADIANT WARMER

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Abstract

Active temperature management is a critical component in the treatment of preterm and sick neonates, significantly impacting morbidity and mortality. Improvements in neonatal survival have been closely tied to the development of medical devices capable of precise thermal control, most notably infant incubators. To facilitate access during neonatal resuscitation and clinical procedures, open care systems were introduced, with high-temperature resistive warmers (RHWs) - reaching up to 700 ℃ - becoming standard. Safety requirements for these devices are defined in IEC 60601-2-21:2020.Due to their high heat source temperatures, RHWs emit energy primarily in the IRB and IRC spectra, with up to 10 mW/cm² in the IRA range. However, RHW use is associated with increased insensible water loss and exposure to airflow, light, and noise.

This study tested a low-temperature (below 52 ℃) large surface radiant warmer (LSW) prototype, based on patent-pending technology (US18/855,652 and EP23704839.2), which emits only IRC radiation. The aim was to verify that the LSW maintains mid-point mattress temperature within 36–37 ℃ per IEC 60601-2-21:2020 (Subclause 201.3.209) and meets the distribution accuracy required by Subclause 201.12.102. Performance was compared with a commercial RHW, and energy consumption was measured in watt-hours.

Results showed that both warmers maintained stable mattress temperatures within the target range and met distribution accuracy standards. However, RHW consumed more than twice the energy compared to LSW.

Conclusion: The LSW prototype met thermal performance and accuracy standards defined in IEC 60601-2-21:2020 while consuming significantly less energy and emitting only IRC radiation, suggesting it may offer a gentler and more energy-efficient alternative for neonatal thermal care.

Keywords: *Neonatal thermoregulation, Radiant warmer, Infrared-C, Energy efficiency, Preterm infants*

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1. INTRODUCTION

1.1Thermoregulation in Neonates

Newborns, especially those born prematurely, are highly susceptible to cold stress due to immature thermoregulatory mechanisms, including limited subcutaneous fat, a high surface area-to-weight ratio, and thin epidermal barriers [*Silverman et al., 1966]. The World Health Organization (WHO) and the International Liaison Committee on Resuscitation (ILCOR) recommend maintaining neonatal body temperature between* 36.5–37.5℃ *[Kariuki et al., 2021; World Health Organization, 1997]. Upon birth, neonates transition from the warm intrauterine environment to relatively cooler delivery areas, resulting in rapid heat loss via convection, radiation, evaporation, and conduction—processes that directly impact the survival and metabolism of preterm and sick infants.*

In 2024, Emma A. Dune et al., on behalf of the European Society for Paediatric Research (ESPR) Infant Resuscitation Section Writing Group, published a review of thermoregulation practices for very preterm infants in the delivery room. The review summarized research from 1943 onward, highlighting abnormal temperature as an independent risk factor for neonatal mortality, while also noting the emerging risk of hyperthermia caused by overly aggressive hypothermia prevention strategies [*Dunne et al., 2024]*.

1.2. Historical Background of Neonatal Warming

The importance of neonatal temperature management has long been recognized. As early as 1808, James Currie emphasized carefully regulated warming to avoid temperature extremes that could harm physiological stability [*Currie, 1808]. In 1857, Jean Louis Paul Denuce published on a primitive incubator in the* Journal de Médecine de Bordeaux [*Denucé, 1857; Cone, 1981], followed by Carl Credé's incubator in 1860 and Stéphane Tarnier's improvements by 1881* [*Rebovich, 2017*]. *A pivotal moment came in 1896, when Pierre Budin and Martin Couney exhibited six incubated premature infants at the Berlin Exposition - all of whom survived, drawing significant medical interest. Budin later published data showing that* mortality decreased from 98% to 23% *as rectal temperature normalized [Budin, 1900].*

1.3. Evolution of Thermal Devices

A landmark 1958 randomized trial by William Silverman demonstrated improved survival in preterm infants housed at 31.7℃ (89°**F**) compared to 28.9℃ (84°**F**) [*Silverman et al., 1958]. Later studies showed significant* radiative heat loss from infants to cooler incubator walls, leading Agate and Silverman in 1963 to explore infrared radiant heating with a conductive glass plate [*Agate, Silverman, 1963]. By 1966, the goal of* "neutral thermal state" was defined—requiring minimal oxygen and energy for temperature regulation [*Wood et al., 2022; Friedman et al., 1967]*.

In 1967, Sierracin Corporation introduced an open-end incubator using low-energy radiant warming inside a transparent plastic canopy - originally adapted from aerospace technology [*Du, Oliver, 1969]. The results showed successful maintenance of neonatal temperature above* 36.0°C.

1.4. High-Power Radiant Warmers and Clinical Concerns

High-power resistive heat warmers (RHWs), with outputs of 400 W, were later introduced for neonatal resuscitation and routine care [*Malin S et al., 1985*]. These warmers lacked early safety features but demonstrated superior heating speed compared to incubators. Over time, RHWs were refined with servo-control and safety alarms [*Meyer et al., 2001; Zimmer D et al., 2020*]. Research confirmed their efficiency in warming neonates during hypothermia and invasive procedures [*Handhayanti et al., 2017; Baumgart et al., 1981*], though they were also associated with increased insensible water loss and fluid needs [*Baumgart S et al., 1981; Flenady V J, Woodgate P G, 2000*]. Meyer & Co (2001) showed RHWs achieved higher abdominal temperatures but required significantly more fluid intake across the first few days of life [*Molgat-Seon Y et al., 2013]*. The increased water loss was attributed to high power density and low ambient vapor pressure [*Kjartansson S et al., 1995]*.

1.5. Family-Centered Neonatal Care and Incubator Limitations

In 2020, the WHO issued updated quality-of-care standards for small and sick newborns, emphasizing minimal separation and family participation [*World Health Organization, 2020]. Prolonged in-*

cubator use may hinder parent-infant bonding and potentially impact neurodevelopment [*Richter M et al., 2022; Romeo R et al., 2023]. Several studies have linked extended incubator care to increased risk of* behavioral disorders, including ADHD, ASD, anxiety, and social skill deficits [Chawla S et al., 2023; Hofheimer et al., 2023; Pravia, Benny, 2020]. Creating a family-friendly thermal care environment is increasingly recognized as critical for both bonding and long-term development [*Soto-Icaza P et al., 2015; Brecht et al., 2012]*.

1.6. Weaning from Incubators and the Lack of Radiant Alternatives

Very preterm neonates often require weeks in thermal support, mainly via incubators. In 2024, Ria Koppen and Virginia Stulz conducted a systematic review of 126 studies on weaning neonates to open cots [*Koppen R, Stulz V, 2024*]. *They noted* wide variation in clinical practice, with most infants moved to un-warmed open cots or cots with conductive heating – and no use of radiant heat in any study. The absence of radiant warming was not explained but may reflect concern about hyperthermia in otherwise stable infants.

1.7. Study Background and Objective

The present study was conducted to test a prototype of an arched large-surface radiant warmer (LSW) developed by the R&D team of SIA Armgate, within an EU co-funded research project titled: “Development of Portable Patient Warming Screens Using Innovative Combination of Low-Temperature Directed Warmer Technology and Switchable Smart Film” (Project duration: 15.02.2023–14.02.2025, supervised by the Smart Materials and Technology Competence Centre)

As part of this project, two types of portable warming systems - rectangular and arched - were developed using a transparent, low-temperature smart film embedded in heated panels.

2. MATERIALS AND METHODS

2.1. Experimental Conditions

The study was conducted in a research laboratory under controlled environmental conditions in accordance with IEC 60601-2-21:2020, at an ambient room temperature of 23 ± 2 °C and an air velocity below 0.1 m/s.

The temperatures of the heating elements of both warmers were measured at their approximate central points using a FLIR T640 thermal imaging camera manufactured by Teledyne FLIR LLC, and a Type K (chromel–alumel) thermocouple connected to a testo 480 data acquisition system manufactured by Testo SE & Co. KGaA, at the beginning of each temperature cycle and periodically throughout the experiment.

2.2. Radiant Warmers

Two infant radiant warmers were evaluated. A prototype large-surface radiant warmer (LSW) - a newly developed low-temperature large-area radiant warmer - and a commercial resistive heat warmer (RHW) - a high-temperature resistive warmer currently used in Latvian hospitals.

Their technical characteristics (test setup, warmer installation, temperature and heat flux measurements, and comparison of measured and theoretical heat flux) were described in a previous article in this issue of The New Armenian Medical Journal [*Kreicberga I. et al., 2026*].

2.3. Test Setup

Five standard black-painted aluminum test objects (numbers 20, 14, 15, 17, and 19) from the Fluke INCU II Incubator/Radiant Warmer Analyzer were positioned on a warmed 36 °C mattress for temperature measurements. Each warmer was tested by being placed, one at a time, over the same test surface.

As the warmer stands were positioned at opposite ends of the mattress, a mirrored layout was applied to the test object numbering for accurate comparison. The central test object (No. 20) was labeled A for both setups. The two test objects closest to the warmer stand were labeled D and E (No. 17 and 19 for LSW; No. 15 and 14 for RHW), representing the upper body region of the neonate. The two furthest were labeled B and C (No. 14 and 15 for LSW; No. 19 and 17 for RHW), representing the lower body region (Figure 1). These labels (A – E) are used throughout the analysis.

2.4. Temperature and Heat Flux Measurements

Each test object was equipped with a Hukseflux FHF05-15X30 temperature/heat flux sensor attached to its upper surface and covered with black Kapton tape. The servo-control temperature sensor

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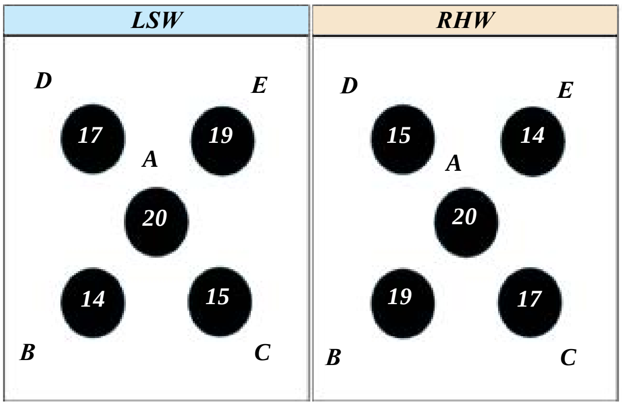

Figure 1. *Placement of the warmer stands and test objects on the mattress under large-surface radiant warmer (LSW) and resistive heat warmer(RHW).*

of the warmer was mounted on the central test object (A) to regulate the power output and maintain the target temperature. The warmers were operated alternately, with the temperature set sequentially from 36.0 °C to 37.0 °C at 0.2 °C intervals.

Temperature and heat flux data were recorded using a Keysight DAQ970A data acquisition system every 15 seconds for 60 minutes, starting from the moment when the target temperature stabilized on test object (A). Data analysis was performed using Microsoft® Excel for Mac. Descriptive statistics and the Student's t-test were applied, with $p < 0.05$ considered statistically significant.

2.5. Energy Consumption Measurement

The electrical energy consumption of each radiant warmer during operation was recorded using an EMG-7 CAT II electricity meter.

2.6. Statistical Analysis

Statistical analysis was performed using Microsoft® Excel for Mac. Quantitative data are presented as mean and variance. Temperature and heat flux measurements were recorded at 15-second intervals over a 60-minute period for each experimental condition. 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. When variances were assumed to be equal, the standard t-test was applied. In cases where variance heterogeneity was considered, Welch's correction was used. The t-statistic, degrees of freedom, and p-values were calculated. A p-value < 0.05 was considered statistically significant. Comparisons were carried out across different temperature settings (36.0 - 37.0 °C) and across test object positions (central and peripheral). Variability between groups was assessed by comparison of variances. Data distribution was illustrated using graphical methods, including boxplots, to present median values, interquartile ranges, and outliers.

3. Results

3.1. Radiated Temperature and Spectral Range

The surface temperature of the large-surface warmer (LSW) heating element was measured at 49 ± 0.5 °C, whereas the resistive heat warmer (RHW) reached 640 ± 5 °C. According to Planck's law, these temperatures correspond to markedly different infrared emission spectra.

The LSW emitted radiation predominantly in the infrared-C (IR-C) range, with a peak wavelength at approximately 9 µm. In contrast, the RHW emitted across a broad-spectrum encompassing infrared-A (IR-A), infrared-B (IR-B), and infrared-C (IR-C), with a peak emission at approximately 3.17 µm (Figure 2).

Infrared radiation is classified as follows:

√ IR-A: 0.78 – 1.4 µm
√ IR-B: 1.4 – 3.0 µm
√ IR-C: 3.0 – 1000 µm

Beyond spectral differences, these ranges have distinct interactions with biological tissue:

- ➢ IR-A radiation penetrates deeply into the skin, reaching the dermis and subcutaneous tissues. It produces volumetric heating, enhances local blood flow, and may influence cellular metabolism via mitochondrial chromophores. Prolonged exposure has been associated with oxidative stress and dermal matrix changes.
- ➢ IR-B radiation is absorbed primarily in the superficial dermis due to strong interaction with water molecules, resulting in more localized heating. Compared to IR-A, it produces a faster surface temperature rise and carries a higher risk of thermal injury under high-intensity exposure.
- ➢ IR-C radiation is almost entirely absorbed within the stratum corneum and upper epidermis, leading to surface-dominant heating with minimal penetration. Its effects are largely limited to superficial warming and secondary thermoregulatory responses such as vasodilation and sweating. [Vaupel P, 2022]

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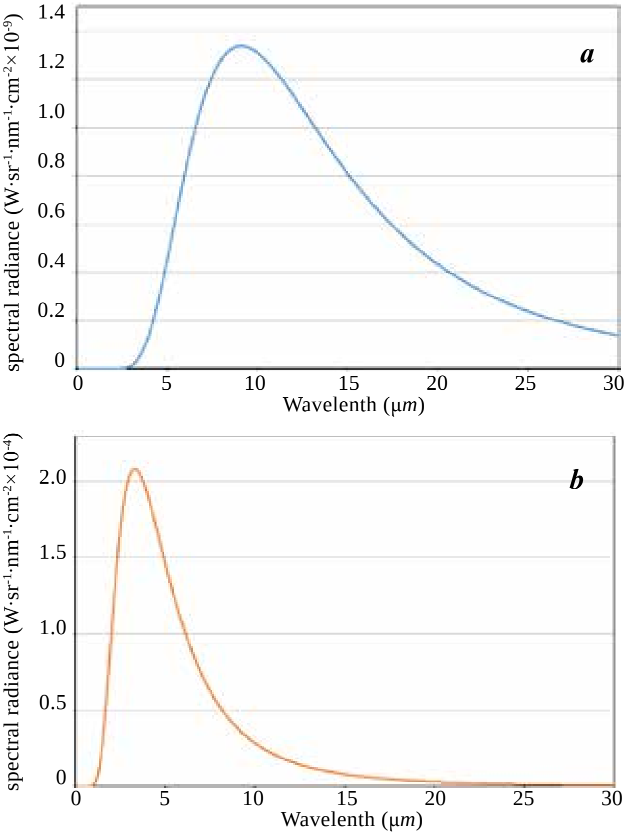

Figure 2. *Spectral radiance a of large-surface radiant warmer (LSW) (a) and of resistive heat warmer(RHW) (b).*

Given these properties, LSW is emitting exclusively IR-C radiation and provides uniform, superficial heating, whereas the RHW produces a mixed - depth thermal effect, including deeper tissue energy deposition associated with IR-A and IR-B components with a higher risk of thermal injury and tissue damage.

3.2. Temperature Stability at 36 °C Setting

Initial testing was performed under Standard IEC 60601-2-21:2020 guidelines, using a set temperature of 36.0 °C. Data was collected every 15 seconds for one hour, totaling 241 data points per warmer (exceeding the required minimum of 30). Measurements began after stabilization of the midpoint test object (A).

Both warmers maintained the temperature of test object A within ±1.0 °C of the set value, meeting standard compliance. While both stayed close to the target, the RHW showed statistically significantly higher mean temperatures (Table 1), with some outliers slightly exceeding 36.5 °C *(Figure 3).*

3.3. Statistical Significance Across All Settings

To verify consistency across settings, temperature readings from the mid-point test object A were analyzed across all 36.0–37.0 ℃ intervals. A statistically significant difference in temperature was found between LSW and RHW warmers ($p = 0$) (Table 2, Figure 4).

3.4. Peripheral Temperature Distribution

Peripheral test objects (B, C, D, and E) remained within ±2.0 ℃ *of the set value under both warmers, confirming that the LSW provided* comparable spatial coverage to the RHW (Figure 5). As expected, peripheral objects farther from the heat source (B and C) recorded slightly lower temperatures under both systems.

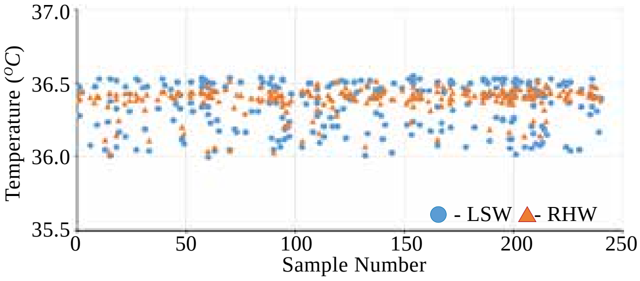

Figure 3. *Temperature distribution at test object A under large-surface radiant warmer (LSW) and resistive heat warmer(RHW) at 36 ℃ setting.*

Table 1.

Students t-Test for temperature distribution at test object A under large-surface radiant warmer (LSW) and resistive heat warmer(RHW) at 36 ℃ setting.

Parameter	**LSW**	**RHW**
Mean	36.35	36.39
Variance	0.03	0.01
Observations	241.00	241.00
Pooled Variance	0.02	
Hypothesized Mean Difference	0.00	
df	480.00	
t Stat	-3.42	
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	

Note: *Statistical Significance Across All Settings, (LSW)- large-surface radiant warmer, (RHW) - resistive heat warmer*

3.5. Mean Temperatures at All Settings

At all six tested temperature settings (36.0 *℃ to*

TABLE 2.

Students t-Test for Two-Sample Assuming Equal Variances for mid-point test object **A** temperature comparison under all settings.

Parameter	LSW	RHW
Mean	36.57	36.66
Variance	0.07	0.09
Observations	1466.00	1446.00
Pooled Variance	0.08	
Hypothesized Mean Difference	0.00	
df	2890.00	
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	

NOTE: *(LSW)- large-surface radiant warmer, (RHW) - resistive heat warmer*

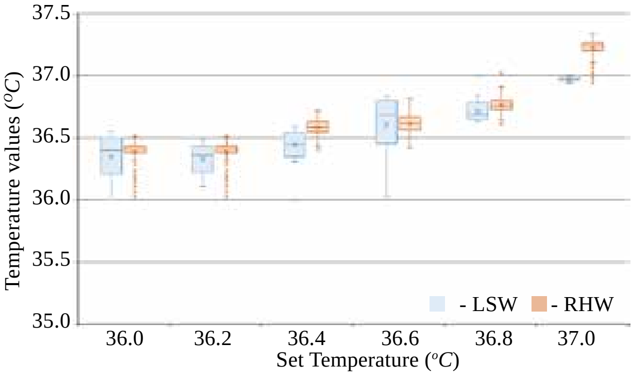

FIGURE 4. *Mid-point test object A temperature comparison under all settings.*

37.0 ℃ in 0.2 ℃ intervals), the RHW consistently produced higher mean temperatures across the five test objects. The smallest difference was observed at the mid-point object A (Table 3, Figure 6).

3.6. Performance at 37.0 ℃ Setting

To assess clinical reliability, temperature stability at the common clinical setting of 37.0 *℃ was analyzed.*

- ➢Under LSW, the temperature of object A showed a very slight downward trend but remained close to the set value.
- ➢Under RHW, temperature rose immediately to approximately 37.25 ℃ and remained stable (Table 4, Figure 7).
- ➢Both warmers fulfilled the requirement of maintaining temperature within ±1.0 ℃ of the target.

3.7. Peripheral Objects at 37.0 ℃

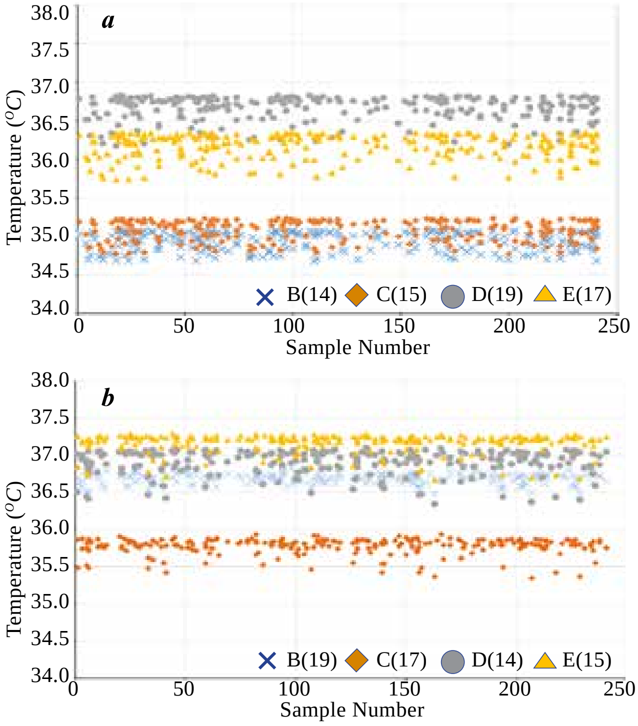

FIGURE 5. *Temperature of peripheral test objects under LSW warmer (a) and RHW warmer (b).*

TABLE 3.

t-Test: Two-Sample Assuming Equal Variances for five test objects under both warmers at all settings

Parameter	LSW	RHW
Mean	36.06	37.15
Variance	0.49	0.51
Observations	30.00	30.00
Pooled Variance	0.50	
Hypothesized Mean Difference	0.00	
df	58.00	
t Stat	-6.01	
P(T≤t) one-tail	0.00	
t Critical one-tail	1.67	
P(T≤t) two-tail	0.00	
t Critical two-tail	2.00	

NOTE: *(LSW)- large-surface radiant warmer, (RHW) - resistive heat warmer*

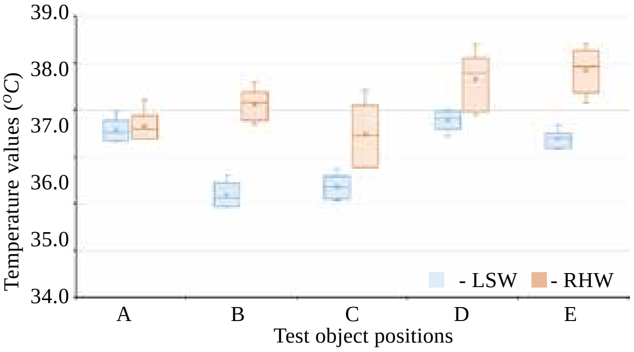

FIGURE 6. *Mean temperatures of five test objects under both warmers at all settings.*

At the 37.0 ℃ *setting, peripheral object temperatures remained within the acceptable ±2.0 ℃ range under both devices. However, significant differences were observed:*

Test objects closer to the heat source (D and E) recorded the highest temperatures, with RHW reaching over 38.0 ℃.

Test objects farthest from the source (B and C) showed lower readings, especially under LSW (minimum slightly above 35.5 ℃) (Table 5, Figures 8 & 9).

3.8. Energy Consumption

From the moment test object A stabilized at the set temperature, average energy consumption was:

LSW: ~ 230 *Wh*

RHW: ~ 590 *Wh*

This indicates that LSW consumed less than half the energy of the RHW while achieving standard-compliant performance.

4. DISCUSSION

TABLE 4.

t-Test: Two-Sample Assuming Equal Variances for temperature of the mid-point test object A under LSW and RHW. Setting of 37℃.

Parameter	LSW	RHW
Mean	36.97	37.23
Variance	0.00	0.00
Observations	241.00	241.00
Pooled Variance	0.00	
Hypothesized Mean Difference	0.00	
df	480.00	
t Stat	-59.11	
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	

***NOTE:** (LSW)- large-surface radiant warmer, (RHW) - resistive heat warmer*

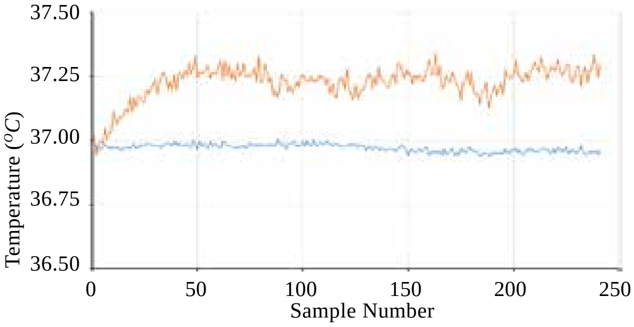

***FIGURE 7.** Temperature of the mid-point test object A under large-surface radiant warmer (LSW) and resistive heat warmer(RHW) Setting of 37℃.*

4.1. The Unmet Need in Neonatal Thermal Management

Despite the wide availability of medical devices for thermoregulation in neonates, recent publications—such as Laptook's commentary "Neonatal Thermoregulation: A Cornerstone of Care or Forgotten Principles?" in Pediatric Research (2024)

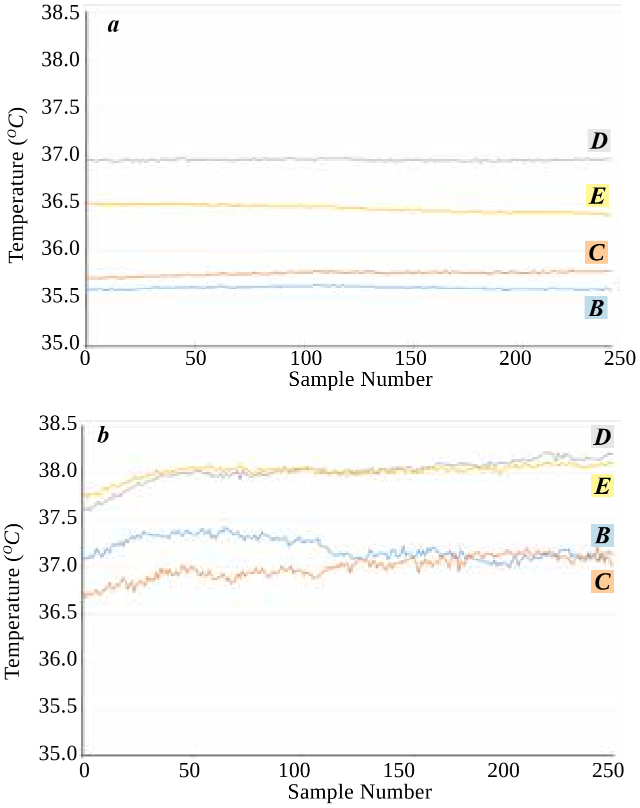

***FIGURE 8.** Temperatures of peripheral test objects under LSW (a) and RHW (b) at 37.0 ℃.*

TABLE 5.

t-Test: Two-Sample Assuming Equal Variances for peripheral object temperatures under both warmers.

Parameter	LSW	RHW
Mean	36.19	37.56
Variance	0.29	0.23
Observations	964.00	964.00
Pooled Variance	0.26	
Hypothesized Mean Difference	0.00	
df	1926.00	
t Stat	-58.85	
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	

***NOTE:** (LSW)- large-surface radiant warmer, (RHW) - resistive heat warmer*

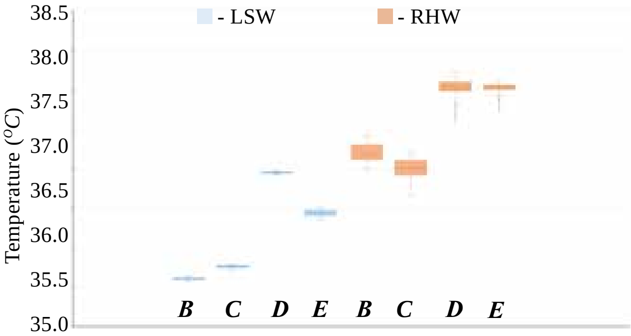

Figure 9. *Statistical comparison of peripheral object temperatures under both warmers.*

and Mishra et al.'s review in the World Journal of Pediatrics (2024)—indicate that thermal management remains an unresolved issue [*Laptook A R, 2024; Mishra U et al., 2024]. We support this perspective and propose the* large-surface radiant warmer (LSW) as a novel, safer, and more physiologically aligned alternative for specific neonatal patient groups.

4.2. Historical Evolution: From Incubators to Radiant Heating

Thermal support for neonates began with heated air in closed compartments, eventually evolving into modern incubators. These advances led to significant reductions in preterm infant mortality [*Philip A G, 2005].Earlier views considered neonates as* poikilothermic, entirely dependent on ambient temperature. However, studies from the 1930s onward redefined neonates as homeothermic, possessing immature but functional thermoregulation [*Bell E F, 1983].*

Radiant heating entered neonatal care in 1963, when Silverman and Agate introduced a "low-energy" infrared heating system using a heated top wall of the incubator [*Agate F J Jr, Silverman W A, 1963]. Although described as "low-energy," the heater likely exceeded 100 °C and radiated in the* IR-B and IR-C spectrum, presenting potential safety concerns. The reasons this design did not progress into clinical use are unclear, but risk of hyperthermia or burns may have been a factor.

In contrast, the LSW prototype evaluated in our study emits only IR-C radiation, with a surface temperature of 50 ± 0.5 ℃*, closely mimicking* maternal body radiation. This makes it inherently safer, both for neonates and their caregivers, and removes the risk of thermal injury.

4.3. High-Power Warmers: Effective but Aggressive

High-output resistive heat warmers (RHWs) were introduced in the 1960s for neonatal resuscitation and are still widely used. They are effective for rapid rewarming in critical moments but generate high surface temperatures, often above 600 ℃*, and can increase* insensible water loss and risk of overheating if used for extended periods. Researchers have addressed these risks primarily by developing monitoring protocols and using physical barriers rather than reengineering the heat source itself.

Chaseling et al. suggested multiple skin temperature sensors to enhance safety under radiant warmers [*Chaseling G K et al., 2016].*

Ozdemir et al. proposed the use of real-time infrared thermography (IRT) for patient monitoring [*Ozdemir M et al., 2022*].

Dey and Deb modeled heat transfer in neonates and recommended placing 500 *W* warmers at 70 *cm* distance [Dey K, Deb U K, 2021].

These strategies help mitigate risks, but do not eliminate the high energy density exposure intrinsic to RHW technology.

4.4. Toward Gentler Technologies

While past innovations like Sierracin Corporation's transparent radiant warmer (1967) showed promise, they never reached clinical implementation – likely due to cost or complexity [*Du J N, Oliver T K Jr, 1969]. In contrast, the LSW evaluated here is made from* cost - effective materials **and is** suitable for scalable production. Importantly, it delivers mild, even heating over a large surface without the drawbacks associated with RHWs.

Emerging technologies such as water – filtered infrared A (wIRA) are also being explored, though concerns remain about deep tissue penetration and its unknown effects on infant physiology [*Vaupel P, 2022]. The* IR-C-only emission profile of the LSW makes it more appropriate for non – invasive, continuous use during extended care.

4.5. Supporting Adaptation, Not Just Stabilization

Neonatal resuscitation is increasingly viewed as a transition support, not merely life-saving intervention. Thermoregulation is a core part of this process. Tveiten et al. (2024) observed hypothermia followed by hyperthermia in full-term neonates under standard care, underscoring the need for stable and adaptive thermal environments [Tveiten L et al., 2024].

An LSW could provide a gentle thermal envelope for neonates undergoing procedures like phototherapy or those in family – centered care, where continuous contact and reduced physical barriers are critical.

4.6. A Missing Link Between Incubators and Open Cots

We propose that the LSW could serve as a "missing link" between incubator care and open cot transition – especially for very or extremely preterm infants. Its safe thermal profile enables earlier weaning from the incubator, while maintaining warmth and improving parental access and bonding.

In addition, the LSW could be used:

In Kangaroo care settings for pre-terms

For bedside treatment of sick neonates in family-friendly environments

Both applications have been shown to reduce sepsis rates and improve outcomes [van Veenendaal N R et al., 2020; Arya S et al., 2023].

4.7. A Step Toward Humanized, Safer Care

Introducing the LSW into neonatal care holds the potential to reshape the standard of thermal management by prioritizing:

- Physiological relevance
- Energy efficiency
- Safety for prolonged use
- Enhanced parent-infant interaction

In conclusion, the LSW offers a promising alternative for sustained neonatal thermoregulation, complementing high-power devices used in emergencies, while creating a mild, safe, and developmentally supportive environment during the critical early days of life.

5. CONCLUSIONS

The LSW surface temperature was measured at 49 ± 0.5 ℃, emitting exclusively infrared-C (IR-C) radiation, while the RHW surface temperature reached 640 ± 5 ℃, emitting across the IR-A, IR-B, and IR-C spectrum.

The LSW prototype met the accuracy requirements for temperature distribution over the mattress as specified in EN IEC 60601-2-21:2020.

At all six servo-controlled settings (36.0 ℃ to 37.0 ℃), both warmers maintained temperature within ±2.0 ℃ of the mid-point reference, as required by the standard; however, RHW temperatures were consistently and significantly higher**.**

Energy consumption during equivalent tasks was significantly lower for LSW (230 *Wh*) compared to RHW (590 *Wh*).

The performance and core features of the LSW, as demonstrated by the current prototype, indicate strong potential for future development and introduction into clinical practice.

These findings support the large-surface radiant warmer as a viable and energy-efficient alternative for stable, prolonged thermal management in neonatal care, with clear potential for clinical application pending further validation.

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