

Wireless Power Transfer for Neonatal ECG Monitoring: Technologies, Challenges, and Future Prospects

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Abstract: Continuous monitoring of neonatal electrocardiogram (ECG) is an essential aspect of diagnostics in neonatal intensive care units (NICUs). Traditional wired systems restrict mobility, obstruct skin-to-skin bonding, and increase infection risks, while battery-powered alternatives are constrained by limited lifetime and thermal safety issues. Wireless power transfer (WPT) offers a promising solution for unobtrusive, contactless, and continuous energy delivery to neonatal monitoring devices. This paper provides an overview of WPT fundamentals, current state-of-the-art for neonatal ECG monitoring, challenges inherent for implementing WPT and considerations for real WPT implementation within NICU environments. A particular focus is placed on the critical role of power transfer efficiency (PTE), which is essential for enabling multi-sensor powering and battery-assisted operation to support skin-to-skin bonding also known as kangaroo care.

1 INTRODUCTION

Continuous monitoring of vital signs like ECG, oxygen saturation, and respiration is essential in neonatal intensive care units (NICUs) to detect life-threatening conditions in preterm and critically ill infants. However, current wired systems restrict infant mobility, hinder skin-to-skin bonding, and pose risks of infection and skin damage (WHO (World Health Organization), 2023). Efforts to adopt wearable or wireless monitors have improved flexibility but still rely on cables or batteries, which introduce limitations such as bulkiness, short battery life, and thermal risks (E. Senechal et al., 2025).

Wireless Power Transfer (WPT) offers a promising solution by enabling safe, contactless, and continuous energy delivery to monitoring devices (Kim, et al., 2020). This technology supports unobtrusive

monitoring and enhances parental bonding, but its clinical adoption faces challenges, especially around power transfer efficiency (PTE), which affects safety, reliability, and device size. Improving PTE is crucial for powering multiple low-energy sensors and ensuring compliance with safety standards. High-efficiency WPT could enable a truly wireless NICU, aligning with modern, family-centred care practices (E. Senechal, E. Jeanne, L. Tao et al., 2023).

This paper explores the fundamentals of WPT in biomedical applications, providing a comprehensive overview of WPT technologies applied to neonatal ECG monitoring, highlighting the challenges of achieving high PTE and exploring future research directions. Specifically, this paper is divided into the following sections: (2) introduces the fundamentals of WPT in biomedical context and presenting the state-of-the-art in neonatal monitoring, (3) identifies

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Table 1: Reported Prototypes of WPT for Neonatal and Paediatric Monitoring.

Study (Year)	WPT Modality	Distance/ Setup	Reported PTE	Application	Development stage
So et al. (2022)	RF + Ultrasound hybrid	2–5 cm	~40%	Across tissue powering	Proof of concept of adaptive hybrid system
Hazrati Marangalou et al. (2024)	Inductive, 3-coil	2–3 cm	~75%	NICU WPT case study vital monitoring	Bench/lab experiment of multi-coil improves alignment
Kim et al. (2020)	Inductive	1–2 cm, planar coils	~65%	Implantable ECG patch	Inductive coupling/ Proof of concept (Rat testing)
Xu et al., (2024)	SOC /Beamforming	20cm -20mW/ Mattress-integrated Tx	20–25%	NICU vital monitoring	Proof of concept/ simulation
Yuan et al. (2021)	RF harvesting	<1 m	<20%	Contact lens sensors	Very low power, limited use

key challenges such as alignment, safety, and regulatory compliance within WPT devices, and (4) discusses strategies to enhance PTE for WPT-based ECG monitoring of neonates, thus providing clinical translation of such real devices.

2 WPT IN BIOMEDICAL APPLICATIONS

Wireless power transfer enables the delivery of electrical energy without physical connectors, which is especially valuable in biomedical applications like neonatal ECG monitoring. It allows devices to be powered unobtrusively, avoiding the limitations of batteries and wires (J. Moore, S. Castellanos, S. Xu and e. al., 2019). This section presents the overview of WPT technologies, importance of key characteristics like PTE, and applications of WPT in NICU.

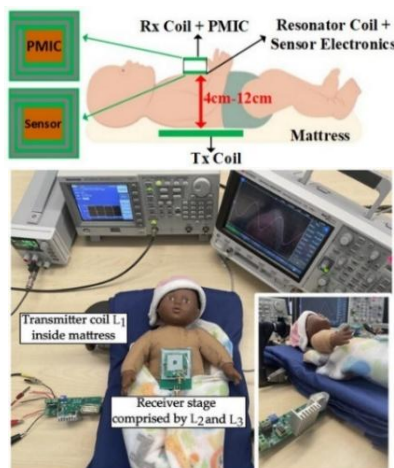


Figure 1: Conceptual set-up for a NICU application (Hazrati Marangalou, 2024).

2.1 WPT Technologies

Among the various WPT methods as shown in Table 1, inductive coupling stands out as the most effective for short-range (1-5 cm), use in neonatal care. It offers high efficiency (75%) and low tissue absorption but is sensitive to alignment and coil distance. Notably, (Hazrati Marangalou, 2024), Figure 1. presented a three-coil inductive link designed for neonatal applications, demonstrating power transfer across 4–12 cm (mattress to infant chest) with efficiencies between 25–75 % and delivering 25–340 mW—sufficient to power wearable ECG sensors. Despite challenges with miniaturization and motion, it remains the leading option for powering devices inside incubators. Capacitive coupling, while lightweight and flexible, struggles with alignment and skin interface issues, making it less suitable for fragile neonatal skin.

RF and microwave methods can power multiple devices over longer distances but suffer from low efficiency and strict safety limits, making them impractical for continuous ECG monitoring. Ultrasound-based WPT shows promise for implants, but the technology is hindered by bulky equipment and safety concerns in neonatal settings. Emerging hybrid systems aim to combine the strengths of different modalities, such as using inductive power in incubators and RF during kangaroo care, to ensure reliable and continuous operation. These systems are still in development but offer a promising path forward. Table 1 presents a good overview of these different WPT technologies. Ultimately, inductive coupling, with optimized designs, currently provides the best balance of efficiency, safety, and practicality for neonatal ECG applications, while other methods offer complementary benefits but face significant limitations.

2.2 PTE Importance for Critical Medical Application

Improving PTE is not just a technical goal, it's a clinical necessity as it ensures reliable, continuous operation of ECG patches even when infants move or shift positions. It also enables the powering of multiple sensors (e.g., ECG, SpO₂, temperature) simultaneously, supporting comprehensive neonatal monitoring. Additionally, efficient systems can recharge backup batteries, ensuring uninterrupted operation during activities like kangaroo care or transport.

Low-efficiency systems pose risks: they may cause unstable device performance, increase local heating near the skin, and require bulkier hardware, which compromises comfort and safety. For WPT to be adopted in NICUs, it must match or exceed the performance of wired systems, with real-world efficiencies ideally above 80–90% as reported by (AirFuel Alliance, 2021).

While capacitive, RF, and ultrasound-based WPT offer unique advantages in form factor or range, they face significant limitations in alignment sensitivity, safety regulations, and practical deployment. Hybrid systems that combine modalities, such as inductive for short-range and RF for backup, are emerging as a resilient solution, potentially enabling seamless, multi-sensor ecosystems that support both clinical needs and parental bonding practices. Figure 2 presents a comparison of different WPT modalities with respect to the achieved PTE vs distances. It is clearly visible that the ideal candidate to achieve higher PTE at short distances is inductive approach.

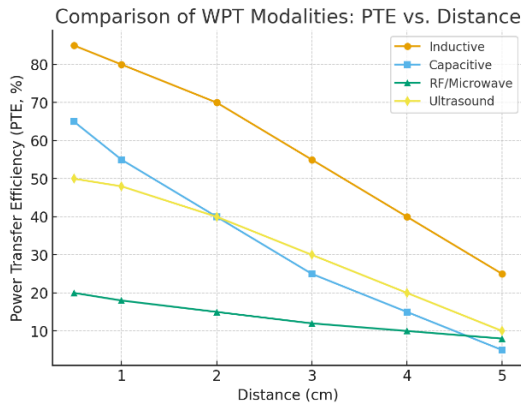


Figure 2: Comparison of WPT modalities based on reported PTE vs. distance.

2.3 Application of WPT in NICU

Neonatal ECG monitoring is critical for detecting

arrhythmias, bradycardia, and apnea episodes, particularly in preterm infants whose cardiopulmonary systems are underdeveloped (H.-U. Chung et al., 2019), (H. U. Chang et al., 2020). Continuous ECG surveillance supports rapid clinical intervention, improving survival rates and long-term outcomes. Despite their importance, current wired monitoring systems in neonatal intensive care units (NICUs) pose several drawbacks:

- **Physical Obstructions:** Wires interfere with parental skin-to-skin contact (kangaroo care), which has been shown to improve thermoregulation, growth, and emotional bonding (E. Senechal et al., 2023).
- **Infection Risks:** Adhesive electrodes and wires increase susceptibility to skin irritation and infections in preterm infants with fragile skin (C. Cunningham et al., 2022).
- **Reduced Mobility:** Wired systems constrain neonatal movement and complicate routine nursing care.

As shown in Table 4 (Appendix), most NICU monitoring systems, including ECG, oxygenation, and respiratory sensing, rely on wired or battery-powered devices that require continuous power and data transmission. Power demands range from a few milliwatts for low-power sensors (e.g., temperature, motion) to over 200mW for high-resolution systems such as electrical impedance tomography (EIT). Similarly, data requirements vary from continuous waveform recording (ECG, SpO₂, CO₂) to periodic or event-driven measurements (biochemical or motion sensors).

However, power constraints remain the major bottleneck preventing truly wireless operation in NICUs. Battery-powered wearables, such as (Secur, 2025) (SurePulse Medical, 2025), though they reduce cable clutter, suffer from limited capacity, frequent recharging, and thermal safety risks that are magnified in preterm infants. Larger batteries add weight and stiffness, compromising comfort and biocompatibility, while high-power devices quickly exceed battery limits, necessitating wired connections or intermittent operation. These limitations highlight a fundamental disparity: while wireless data transmission has advanced rapidly, wireless energy delivery has not kept pace. WPT offers a practical and scalable solution by enabling safe, contactless, and continuous power delivery to neonatal sensors. By eliminating the need for wired connections and minimizing reliance on batteries, WPT can sustain uninterrupted monitoring, support parent–infant bonding and improve clinical workflow efficiency (R. P. Mathews, H. J. Sharemi, I. Habibagahi, J. Jang and

A. R. Babakhani., 2022). Importantly, achieving high power transfer efficiency is essential to ensure sufficient energy for multi-sensor operations while maintaining strict compliance with electromagnetic safety standards (S. Xu et al., 2021) .

Neonatal wearables, unlike implants, sit on the skin, typically on the chest, requiring short-range power transfer (2–5cm). This makes inductive or resonant magnetic coupling ideal, as it offers high efficiency at these distances. Researchers have successfully embedded large-area transmitters into incubator mattresses or walls, reducing clutter and improving coverage. Power demands for neonatal ECG systems are modest (10–50mW per channel) but must be delivered reliably and continuously. Motion tolerance is critical, as infants frequently move, which can disrupt coil alignment and reduce efficiency. Solutions like three-coil systems, beamforming coil arrays, and mattress-wide transmitters help maintain stable power delivery despite movement.

Due to safety reasons, WPT systems must comply with strict electromagnetic exposure limits to avoid overheating or tissue damage. Designs often include dynamic power control to balance efficiency with safety, ensuring Specific Absorption Rate (SAR) and temperature rise remain within acceptable limits. NICU patients often require multiple sensors, and WPT systems must support simultaneous powering of several devices without interference, thus leading to scalability aspects of design choices and requirement of modular scalability approaches. Techniques like load-sharing and multiplexing help achieve this, while power management units in wearables ensure energy is regulated and stored for brief disconnections (S. Khan, S. Pavuluri, G. Cummins and M. Desmulliez , 2020).

WPT for neonatal ECG monitoring is progressing from concept to clinical feasibility, with inductive

coupling emerging as the most promising method. It enables safe, short-range energy delivery within incubators, supporting continuous and unobtrusive monitoring. Flexible receiver coils embedded in skin-adhered ECG patches have demonstrated efficiencies of 60–80% at 1–3cm, with signal quality comparable to wired systems (Hazrati Marangalou, 2024).

Kangaroo care is essential for neonatal development, with WHO recommending up to 8 hours daily. In high-resource settings, sessions typically last 2–4 hours, while resource-limited environments may practice continuous KC. These practices demand WPT systems with integrated battery backups that can sustain monitoring during prolonged parental holding. Efficient incubator-based charging is crucial to ensure batteries are sufficiently recharged between KC sessions.

Inductive WPT is the most mature and clinically viable technology for neonatal ECG monitoring. To transition from lab prototypes to routine NICU use, systems must overcome challenges in alignment sensitivity, multi-sensor support, and battery-assisted operation. Achieving high power transfer efficiency is central to enabling safe, scalable, and uninterrupted monitoring that supports both clinical care and parental bonding.

3 WPT IMPLEMENTATION CHALLENGES IN NICU

Despite its transformative potential, WPT for neonatal ECG monitoring faces significant hurdles before it can be widely adopted in clinical settings. Although wireless power transfer (WPT) shows great promise for neonatal ECG and vital sign monitoring, several barriers must be addressed before clinical

Table 2: Key Challenges for WPT in NICU Environments.

Challenge	Impact on WPT	Clinical Relevance	References
Alignment sensitivity	Efficiency drop >50% with 1–2 cm misalignment	Motion, repositioning by caregivers	(J. P. K. Sampath, A. Alphones and D. M. Vilathgamuwa, 2017)
Miniaturization	Smaller coils = reduced inductance & PTE	Wearability & comfort	(J. -H. Suh, H. Cho and Y. Jeon and M. Je, 2023)
Thermal effects	Risk of skin heating	Fragile neonatal thermoregulation	(R. Bahru, A. Hamzah and M. Mohamed, 2021)
EMC/EMI	Interference with NICU devices	Safety & reliability	(T. Campi, Cruciani, M. F. S. and M. Feliziani., 2023)
Power scaling	Limits multi-sensor support	Holistic monitoring	(W. Tesema, W. Jimma, M. Khan, I. J. Stiens and B. d. Silva., 2024)
Battery integration	High load for simultaneous charging + powering	Kangaroo care/ mobility	(J. Brönneke, J. Müller, K. Mouratis, J. Hagen and A. Stern, , 2021)

Table 3: Future Research Directions in WPT for Neonatal Monitoring.

Research Direction	Description	Expected Benefit	References
Metamaterials	Flux focusing & field confinement	Higher PTE, misalignment tolerance	(W. Onreabroy, S. Piemsomboon, S. Traikunwaranon, N. Wilaiprajuabsang and A. Kaewpradap, 2025)
Multi-coil / MIMO	Adaptive coil arrays	Robust powering zones in incubators	(H. Zhang et al., 2021)
Hybrid WPT	Inductive + RF + ultrasound	Redundancy during infant movement	(Y. Jiang, Y. Ma, J. Liu, L. Hu and M. C. a. I. Humar, 2022)
Smart power management	Dynamic allocation across sensors	Multi-sensor ecosystems	(S. Mohamed, H. Nomer, R. Yousri and e. al., 2023)
Energy harvesting + WPT	Thermoelectric/piezo + wireless	Resiliency against disconnections	(L. Zhou, M. Guess, K. R. Kim, W. Yeo, 2024)
Standardization	Qi / AirFuel biomedical adaptation	Interoperability, regulatory approval	(AirFuel Alliance, 2021)
Battery-free wearables	Direct WPT powering	True unobtrusive monitoring	(H. Yu, N. Li and N. Zhao., 2021)

adoption. Table 3 provides a brief summary of the key challenges for WPT implementations in NICU environments.

- **Alignment and Motion Sensitivity:** PTE drops sharply with coil misalignment or infant movement, making reliable energy delivery difficult without motion-tolerant designs.
- **Miniaturization and Comfort:** Receiver coils must be thin and flexible for neonatal wearability, but miniaturization reduces inductance and efficiency, requiring advanced geometries or metamaterials to compensate.
- **Thermal Safety:** Power losses generate heat that can endanger neonatal skin. Ensuring compliance with SAR and IEC 60601 standards while maintaining high PTE remains a core safety challenge.
- **Electromagnetic Compatibility (EMC):** High-frequency WPT may interfere with sensitive NICU equipment, while metallic surroundings can distort fields. Shielding and EMC testing are essential.
- **Power Scaling:** Multi-sensor systems (ECG, SpO₂, temperature, respiration) require greater total power than current prototypes can supply, limiting scalability without efficiency gains.
- **Battery Backup Integration:** Devices need both continuous powering and wireless recharging for operation during kangaroo care, demanding further improvements in efficiency and energy management.
- **Regulatory and Clinical Barriers:** Compliance with safety and medical device standards, as well as demonstration of reliability comparable to wired systems, is required for approval and adoption.

Current limitations in efficiency, safety, and scalability hinder widespread NICU use of WPT. Overcoming these will require innovations in coil design, field optimization, and power management, coupled with rigorous clinical and regulatory validation to ensure safety and reliability in neonatal care. The most pressing limitation is insufficient PTE, which restricts the ability to support multi-sensor monitoring and reliable battery-assisted operation. Overcoming these challenges will require innovative engineering, interdisciplinary collaboration, and rigorous clinical validation to ensure WPT systems meet the safety, reliability, and scalability demands of modern neonatal care.

4 FUTURE DESIGN CONSIDERATIONS FOR WPT IN NICU

Table 4 summarises the future of WPT using approaches like metamaterials, hybrid WPT systems, multi-coil designs for better contact, smart power management and new energy harvesting mechanisms, appropriate standardisation methods considering relevant ISO standards and battery-free wearables.

Metamaterials and multi-coil architectures are being developed to improve power transfer efficiency and alignment tolerance. Metamaterial-enhanced resonators can focus electromagnetic fields more precisely, maintaining high efficiency even with small, flexible receiver coils. Meanwhile, multi-input, multi-output (MIMO) coil arrays embedded in incubator mattresses or walls can dynamically steer power to the infant's location, ensuring stable energy delivery despite movement.

Table 4: Comparison of Monitoring Systems in NICU and Relevance of WPT.

Measure	System	Disease/ Problem	Current Approach	Proposed Solution	Typical Power Demand	Data Demand/ Rate	Is WPT a Solution?
ECG	Cardiovascular, heart rate	Arrhythmia, tachycardia, bradycardia	Wired electrodes	Wireless ECG electrodes	10–50 mW per channel	250–500 Hz (Continuous)	Feasible for continuous powering and battery charging
Regional Lung Aeration	Respiratory, lung function	Respiratory failure, lung collapse	X-ray, uncomfortable EIT belts	IAM EIT electrode belt (wearable)	50–200 mW	High (kHz–MHz imaging signals)	Partially, requires optimized PTE and safety validation
Oxygenation (SpO ₂)	Respiratory, gas exchange	Hypoxemia, respiratory failure	Wired optical sensor	Wireless SpO ₂ sensor	20–60 mW	~1–10 Hz, (Continuous)	Compatible with short-range inductive WPT
Ventilation (CO ₂ Monitoring)	Respiratory, gas exchange	Hyperventilation, respiratory acidosis	Blood gas analysis, wired heated sensor	Wireless CO ₂ sensor	50–150 mW (heated element)	~1 Hz (Continuous)	Possible, heating elements increase power demand
Inflammatory Markers	Immune response	Sepsis, ventilator-associated pneumonia	Blood tests (CBC, CRP)	Transcutaneous, continuous biochemical sensing	30–100 mW	Low (Periodic or event-driven)	Viable with hybrid or battery-assisted WPT
Temperature & Motion	Thermoregulation, motor activity	Hypothermia, apnea	Wired thermistor and accelerometer	Skin-integrated wireless patch	5–20 mW	~1–10 Hz (Periodic or event-driven)	Ideal for fully wireless powering

Hybrid WPT systems that combine inductive coupling with RF or capacitive methods offer redundancy and flexibility. These can maintain monitoring during kangaroo care or transport, especially when paired with energy harvesting technologies like thermoelectric or piezoelectric devices. Though these harvesters provide only small amounts of energy, they help reduce peak power demands and extend battery life, contributing to safer and more sustainable monitoring.

At the system level, smart power management enables dynamic energy allocation across multiple sensors, supporting comprehensive monitoring of ECG, SpO₂, temperature, and even emerging biosensors like continuous glucose monitors. This transforms WPT platforms into scalable ecosystems capable of adapting to clinical priorities.

To ensure seamless integration into NICU workflows, future WPT designs must accommodate frequent handling and bonding practices. Embedding transmitters into mattresses, swaddles, or garments and enabling smooth transitions between powered and battery modes will reduce caregiver burden and improve usability. Human factors engineering and

usability standards, such as those from the FDA, are essential to guide safe and intuitive device design.

Standardization and interoperability are also key. Aligning with protocols like Qi and AirFuel can accelerate regulatory approval, reduce interference risks, and ensure compatibility across devices and manufacturers.

Ultimately, the vision is for battery-free or battery-assisted neonatal monitoring, where sensors operate continuously without interruption. Achieving this will require breakthroughs in PTE, miniaturization, and system-level innovation. Success depends on close collaboration between engineers, clinicians, and standards bodies to translate technological advances into safer, more effective neonatal care.

5 CONCLUSIONS

Wireless power transfer is set to revolutionize neonatal monitoring by replacing cables and disposable batteries with a safer, more comfortable, and sustainable alternative. It enables continuous,

unobtrusive monitoring of vital signs like ECG, SpO₂, temperature, and respiration, while supporting essential practices such as kangaroo care without interrupting surveillance. This review highlights that power transfer efficiency is the cornerstone of effective WPT systems. High PTE ensures reliable sensor operation despite infant movement and misalignment and is essential for scaling to multi-sensor platforms and battery-assisted modes. Emerging technologies: such as metamaterials, multi-coil arrays, hybrid architectures, and energy harvesting, are addressing current limitations in alignment sensitivity, thermal safety, and electromagnetic compatibility. Beyond technical improvements, WPT also supports clinical workflow integration, reduces electronic waste, and aligns with sustainability goals. Standardization efforts, including alignment with Qi and AirFuel protocols, will be key to ensuring interoperability and accelerating regulatory approval. Ultimately, WPT represents more than a technological upgrade—it marks a shift toward battery-free or battery-assisted neonatal monitoring ecosystems that are efficient, safe, and responsive to both clinical and developmental needs. With continued innovation and collaboration across disciplines, WPT can help shape the next generation of NICU care.

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