Smart Phototherapy and Bilirubin Management in Neonatal Jaundice: Emerging Technologies, Decision Support, and Equity Considerations

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Abstract: *Neonatal jaundice is common, but delayed recognition and suboptimal treatment can still lead to acute bilirubin encephalopathy and kernicterus, particularly where bilirubin testing and effective phototherapy are inconsistently available. This narrative review critically examines recent developments in bilirubin assessment, phototherapy delivery, and digital decision support, with attention to both the promise and the limitations of current evidence. Transcutaneous bilirubin devices remain useful screening tools, and measurements from photo-protected skin sites can improve accuracy during phototherapy, although confirmatory total serum bilirubin testing remains important when management decisions are uncertain. Smartphone-based screening tools and low-cost point-of-care devices may expand access, especially after discharge and in resource-constrained settings, but external validation, calibration, and skin-tone performance remain major concerns. LED phototherapy has improved irradiance control and energy efficiency, while filtered sunlight and other context-appropriate systems may help bridge treatment gaps where electricity is unreliable. Digital nomograms and electronic follow-up pathways can support safer care, yet they should complement rather than replace clinical assessment and laboratory confirmation. Overall, smarter bilirubin management is promising, but equitable implementation requires validated devices, accurate reference standards, strong clinical governance, and careful adaptation to local resources.*
Keywords: hyperbilirubinemia, neonatal phototherapy, bilirubin, point-of-care systems, infant, newborn

INTRODUCTION

Neonatal jaundice, presenting as the yellow discoloration of the skin and sclerae, affects up to 80% of term and preterm infants in the first week of life. Although largely physiological and self-limiting, a critical subset of neonates develops severe hyperbilirubinaemia. If untreated, elevated levels of unconjugated bilirubin cross the blood-brain barrier, precipitating bilirubin-induced neurologic dysfunction and kernicterus - a devastating condition characterised by irreversible athetoid cerebral palsy, hearing loss, and intellectual disability.[1-3]

For more than half a century, the cornerstone of preventing bilirubin neurotoxicity has been phototherapy, supported by measurement of total serum bilirubin.[2] Nevertheless, conventional care remains limited by the inaccuracy of visual assessment, the invasiveness and intermittent nature of serum testing, and variable control of phototherapy dose and irradiance. Recent interest has therefore shifted toward technologies that may improve detection, treatment delivery, and follow-up, including transcutaneous bilirubinometry, smartphone-assisted screening, point-of-care bilirubin devices, and digitally supported phototherapy pathways. This review appraises these approaches as adjuncts to clinical care, with particular emphasis on evidentiary strength, implementation constraints, and equity across high- and low-resource settings.

Clinical Burden of Neonatal Jaundice and the Need for Smarter Management

The global burden of severe neonatal jaundice is immense. It is estimated that approximately 481000 term and near-term neonates experience severe hyperbilirubinaemia annually, resulting in 114000 deaths and over 63000 survivors with moderate to severe long-term neurological impairment.[3,4] Strikingly, over 80% of this morbidity and mortality occurs in low- and lower-middle-income countries, notably in sub-Saharan Africa and South Asia.[3,4]

This stark disparity highlights systemic flaws in jaundice management. In high-income countries, the challenge lies in the premature hospital discharge of seemingly healthy neonates who subsequently develop severe jaundice at home, leading to hospital readmissions and an overreliance on subjective visual assessment by parents.[1,5] In contrast, low- and middle-income countries grapple with late presentations, a high prevalence of glucose-6-phosphate dehydrogenase deficiency, Rhesus disease, and a lack of reliable diagnostic and therapeutic infrastructure.[6] Consequently, there is an urgent need for smarter, decentralised management pathways that reduce reliance on complex laboratory infrastructure while providing precise, objective, and timely interventions.

Advances in Bilirubin Measurement and Monitoring

Accurate quantification of bilirubin is the prerequisite for safe phototherapy initiation and cessation. While total serum bilirubin remains the gold standard, its reliance on venepuncture, trained phlebotomists, and laboratory analysers limits its utility for continuous or remote monitoring.

Transcutaneous bilirubinometry: Modern TcB devices employ multi-wavelength spectral reflectance to estimate bilirubin concentration in the subcutaneous tissue. TcB has proven highly effective as a screening tool to avoid unnecessary blood draws in both term and preterm infants.[7] Historically, TcB was contraindicated during and immediately after phototherapy due to the photo-bleaching effect on the skin. However, recent meta-analyses demonstrate that if a photo-opaque patch is applied to the infant's skin prior to phototherapy, TcB measurements taken from the protected site remain accurate and correlate strongly with TSB during treatment.[8] In resource-limited settings, TcB acts as a vital triage tool to rule out the need for phototherapy, though its tendency to produce false positives requires careful clinical correlation to prevent overtreatment.[9]

Point-of-care and smartphone screening: The proliferation of smartphones has spurred the development of optical algorithms capable of estimating bilirubin from digital images of the newborn's skin, calibrated against reference colour cards. Smartphone-assisted assessments have demonstrated significant correlation with TSB, offering an accessible, low-cost screening adjunct for home follow-up and rural clinics.[10,11] Additionally, low-cost point-of-care devices such as BiliSpec and Bilistick are emerging. These battery-operated spectrophotometric readers require only a single drop of whole blood via heel prick and deliver TSB-equivalent results within minutes, bypassing the need for expensive laboratory centrifuges and reagents.[12,13]

Smart Phototherapy Technologies and Dosing Strategies

Phototherapy relies on the absorption of light, optimally in the 460-490 nm blue-green spectrum, by bilirubin molecules, converting them into water-soluble photoisomers that are excreted in bile and urine.[2] The efficacy of treatment depends on the light spectrum, irradiance intensity, and the exposed body surface area.

LED innovations and smart dosing: The transition from fluorescent tubes to light-emitting diodes has revolutionised phototherapy. LEDs are durable, generate minimal heat, and emit a narrow, targeted spectrum.[2] Smart phototherapy units now incorporate integrated radiometers that continuously monitor irradiance, ensuring that the delivered dose matches clinical protocols. Advanced prototypes are exploring servo-guided dosing, wherein the device adjusts light intensity dynamically based on real-time continuous or intermittent non-invasive bilirubin readings, thereby preventing overtreatment and minimising the infant's exposure time.

Filtered sunlight phototherapy: In settings lacking reliable electricity, standard electric phototherapy is often unavailable or interrupted. To address this, filtered sunlight phototherapy has been rigorously tested. Using specially designed, low-cost commercial window-tinting films that filter out harmful ultraviolet and infrared radiation while transmitting therapeutic blue light, filtered sunlight phototherapy has been shown in randomised controlled trials in Africa to be safe and non-inferior to intensive electric-powered phototherapy for treating moderate-to-severe hyperbilirubinaemia.[14,15]

Digital Decision Support, Post-discharge Surveillance, and Home Pathways

Clinical guidelines, such as the revised 2022 American Academy of Pediatrics guideline, rely on complex, hour-specific nomograms intersecting with gestational age and neurotoxicity risk factors to determine phototherapy thresholds.[1,5] Manual plotting is prone to human error.

App-based nomograms and decision support: Digital calculators and integrated electronic health record dashboards can reduce plotting errors by automatically estimating how far an infant's bilirubin value is from the treatment threshold and by prompting follow-up actions. Their main value is operational rather than diagnostic: they help clinicians apply existing guidelines more reliably. However, these tools do not replace bedside assessment. Gestational age, haemolysis risk, feeding adequacy, hydration, and the infant's overall clinical condition still require direct clinical interpretation, and algorithm outputs require local validation before routine implementation.

Home-based phototherapy: With the miniaturisation of LED blankets and improved outpatient bilirubin surveillance, home treatment is increasingly feasible for carefully selected otherwise well neonates with uncomplicated jaundice. Potential benefits include improved maternal-infant bonding, support for breastfeeding, and reduced hospital use. However, this model is only safe when eligibility criteria are strict, bilirubin monitoring is timely, caregivers receive clear return instructions, and rapid escalation pathways to in-patient care are available.

Implementation Challenges in High- and Low-Resource Settings

While the technological horizon is promising, practical implementation involves distinct challenges across different health systems. In high-income countries, the rapid integration of AI and smartphone apps raises concerns about algorithmic bias, particularly regarding skin tone, and calibration drift. Algorithms trained predominantly on lighter-skinned populations may misclassify jaundice severity in neonates with darker skin pigmentation, risking delayed interventions. Furthermore, data governance, patient privacy, and the interoperability of standalone digital tools with hospital electronic health record systems remain substantial hurdles.

In low- and middle-income countries, implementation barriers are fundamentally infrastructural. Frequent power outages compromise electric phototherapy and electronic monitoring.[6] Although low-cost point-of-care devices and filtered-sunlight phototherapy are highly effective, they require sustainable supply chains for consumables and local biomedical engineering support for maintenance. Furthermore, the management of preterm infants younger than 35 weeks remains exceptionally complex; their heightened susceptibility to bilirubin neurotoxicity at much lower TSB levels demands highly accurate, frequent monitoring and aggressive treatment thresholds that stretch the capacity of under-resourced neonatal units.[16]

Future Directions

Future research should prioritize prospective external validation of smartphone-based and non-invasive bilirubin tools across diverse skin tones, gestational ages, and care settings. Comparative studies should evaluate not only correlation with total serum bilirubin but also clinically important outcomes such as treatment delay, readmission, exchange transfusion, breastfeeding continuity, and neurodevelopment. In parallel, pragmatic implementation research is needed to determine which combinations of low-cost diagnostics, reliable phototherapy, and digital follow-up are sustainable in under-resourced neonatal services.

CONCLUSION

In summary, smart phototherapy and digital bilirubin-management tools should be viewed as adjuncts to high-quality neonatal care rather than stand-alone solutions. The most credible advances are those that improve objective bilirubin assessment, irradiance delivery, and continuity of follow-up while remaining anchored to validated reference standards and clinical judgment. Their impact will depend not only on technological sophistication but also on transparent evaluation, reliable infrastructure, and equitable adaptation to the settings where the burden of severe neonatal jaundice remains greatest.

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Contributors

SB conceptualised the review, led manuscript development, synthesised the literature, and is guarantor for the overall content. GINN and TOA provided critical revisions focusing on biomedical technology, digital decision support, and engineering aspects. KIN-U, ABY and AMJ contributed to the clinical sections, including pathophysiology and equity considerations. During manuscript preparation and revision, the authors used the Genspark AI writing assistant to support draft organisation and language refinement. After editorial feedback, all references and factual statements were independently checked by the authors against the original sources, and the manuscript was substantially revised before final approval. All authors reviewed and approved the final manuscript and take responsibility for the final content.

Ethics statements

Ethical approval and patient consent for publication were not required for this review article, as it relies entirely on previously published literature and does not contain personal medical information about identifiable living individuals.

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What is already known on this topic

- Severe neonatal hyperbilirubinemia carries a significant risk of irreversible neurologic damage (kernicterus), with a disproportionately high burden in low- and middle-income countries.
- Standard LED phototherapy and total serum bilirubin testing form the foundation of jaundice management, but visual assessment is unreliable and blood sampling is invasive and resource-intensive.

What this review adds

- It critically evaluates emerging smart management tools, including smartphone-based jaundice assessment, automated clinical decision-support nomograms, and feedback-enabled LED phototherapy.
- It highlights recent evidence on transcutaneous bilirubin accuracy before, during, via photo-opaque skin patches, and after phototherapy, extending its clinical utility.

How this review might affect research, practice or policy

- Promotes the integration of digital tracking and low-cost point-of-care diagnostics into routine clinical pathways, particularly supporting safe post-discharge surveillance.
- Underscores the urgent need for equitable resource allocation and the adoption of context-appropriate technologies, such as filtered-sunlight phototherapy and battery-powered LED devices in resource-limited settings.