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Non-invasive cardiac output monitoring in neonates: From technologic promise to clinical practice

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ABSTRACT

Due to the clinical importance of early detection of hemodynamic compromise and the limitations of transthoracic echocardiography (TTE) as an intermittent, operator-dependent assessment, the introduction of non-invasive cardiac output monitoring (NICOM) in the neonatal population has generated considerable interest. Electrical biosensing technology (EBT), one type of NICOM modality, offers non-invasive, continuous, bedside assessment of multiple hemodynamic parameters, yet its clinical utility is limited by variable accuracy and precision, lack of interchangeability with TTE and limited trending studies. Despite this, EBT is progressively being used in research and even clinical domains.

Advancing continuous EBT-enabled cardiac output monitoring from technologic promise to clinical accountability requires specific neonatal-based refinements of the technology and a strategic shift in research emphasis, moving from method-comparison studies to rigorously designed, outcome-based trials, in order to determine whether EBT-informed management can meaningfully improve neonatal morbidity and mortality.

1. Introduction

Accurate and timely diagnosis of hemodynamic instability remains a core challenge in neonatal care. Up to one-third of very low birth weight (VLBW) infants in the first day of life develop low systemic blood flow (SBF), which has been inconsistently associated with intraventricular hemorrhage (IVH), periventricular leukomalacia (PVL), necrotizing enterocolitis (NEC), neurodevelopmental impairment (NDI), and increased mortality [1,2]. Early recognition and management of low SBF are therefore critical. However, clinical indicators used to detect impaired systemic perfusion are often subjective and have demonstrated limited diagnostic accuracy [3,4]. Transthoracic echocardiography (TTE) has partially addressed this limitation by enabling real-time, bedside evaluation of cardiac structure and function [5], yet its episodic nature and dependence on specialized expertise have stimulated interest in continuous, non-invasive hemodynamic monitoring technologies [6].

Non-invasive cardiac output monitoring (NICOM) refers to bedside technologies that estimate cardiac output (CO) continuously, without the need for vascular catheterization, by deriving stroke volume (SV) and CO from electrical signals [7]. Electrical biosensing technologies (EBT) represent one such group and include thoracic electrical biosensing technologies (TEBT)—such as thoracic bioimpedance, electrical velocimetry (EV), electrical cardiometry (EC), impedance cardiography, and bioreactance (BR)—and whole-body electrical biosensing technology (WBEBT) (7). These systems apply a high-frequency, low-amplitude electrical current across the thorax or body. Variations in impedance, largely determined by blood flow and extracellular fluid conductivity, occur with each cardiac cycle and allow estimation of SV and CO. Differences between various EBT techniques are shown in Table 1.

Beyond CO measurement, EBT can provide continuous beat-to-beat assessment of additional hemodynamic variables including heart rate (HR), cardiac contractility, systemic vascular resistance (SVR), and thoracic fluid content (TFC). While CO can be assessed with TTE, many of these hemodynamic parameters are not routinely available during TTE evaluation, and comprehensive characterization of systemic blood flow may remain incomplete [6].

EBT may offer additional insights into neonatal hemodynamic physiology and pathophysiology. However, EBT's clinical value depends not only on measurement accuracy, relative to reference methods, but also on whether its application ultimately improves neonatal outcomes [8].

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This review aims to address the current gaps between technological promise and clinical reliability of neonatal EBT use, critically assessing the available evidence and proposing a pragmatic, clinically grounded framework for its cautious integration as a trend-based adjunct within a multimodal hemodynamic assessment strategy.

2. From numbers to meaning: EBT accuracy in context

The central issue is not whether EBT can generate physiologically plausible haemodynamic values, but whether these measurements retain sufficient accuracy, precision, and directional reliability across the dynamic and heterogeneous physiological states encountered in neonatal practice [9]. When evaluated against this standard, the evidence remains heterogeneous for EV/EC and consistently unfavourable for BR [9].

Within EV/EC literature, more favourable performance is reported in relatively stable or selected populations, with percentage error (PE) occasionally approaching the conventional 30% threshold [10–12]. Systematic reviews demonstrate wide variability, with bias ranging from −0.23 to 70.3 mL/kg/min, limits of agreement (LOA) from −173.2 to 233.5 mL/kg/min, and PE from 5.3% to 71.9% (Fig. 1) [9]. Such variability substantially limits clinical interpretability, further compounded by a variety of units of measurement for SV (ml, ml/kg) and CO (L/min, L/min/m^2).

Performance deteriorates in the presence of transitional physiology, extreme prematurity, shunt-dependent circulation, inotropic requirement and ventilation support [9,11,13–17]. This is mechanistically plausible: EV assumes that impedance changes reflect aortic flow, yet intracardiac and extracardiac shunts alter current pathways and disrupt forward flow assumptions. Contemporary studies confirm marked context dependence, influenced by population characteristics, ventilation, device type, and methodological variability [18–21].

In contrast, BR demonstrates consistently poor performance, with systematic underestimation of CO and SV, poor precision, and lack of interchangeability with TTE (Fig. 1) [17,22,23]. Importantly, BR also performs poorly as a trending tool, with inadequate concordance for detecting directional change [24].

Across modalities, comparative studies consistently report moderate accuracy, poor precision (wide LOA), limited trending ability, and high mean percentage error (MPE) relative to TTE [9,25].

Few studies have been performed using whole-body EBT in neonates [26–31], of which even less can be characterized as validation studies [28,29].

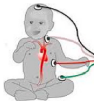
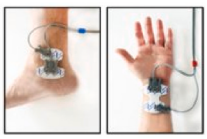
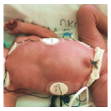
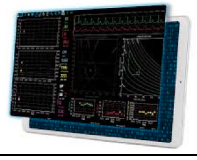
3. Clinical demand vs. technical validation: accuracy has not kept pace with expectations

Hemodynamic instability remains a major contributor to neonatal morbidity and mortality [4]. In practice, clinicians often rely on indirect surrogates of perfusion—lactate, capillary refill, urine output, and blood pressure—despite limited diagnostic accuracy [3]. While TTE enables physiologic assessment of cardiac function, its intermittent, operator-dependent nature sustains an interest in continuous monitoring technologies such as EBT [5].

Despite this clinical demand, validation has not kept pace. EBT performance is highly context-dependent, influenced by neonatal physiology and therapeutic interventions [6,9], and available evidence is largely restricted to research settings [32]. Of note, the use of different EBT techniques and methodological differences in the study design and population intrinsically reflect the variability of neonatal care; however, methodological standardization is imperative for appropriate data comparison. Importantly, validation against TTE is constrained by the variability of the reference standard itself, with reported MPE approaching 30% compared with thermodilution [33].

Critically, reported LOA frequently exceeded clinically meaningful changes reported for CO—12–35 mL/kg/min in preterm infants with IVH or NEC, 56 mL/kg/min in PPHN, and approximately 10% change in physiological studies, thereby limiting the utility of EBT for absolute

Table 1
Comparison of technological differences between bioimpedance and bioreactance.

	Thoracic EBT		Whole body EBT
	Bioimpedance	Bioreactance	
Assumptions regarding blood flow	Related to the change in body's resistance only	Related to change in body's resistance, capacitance, and inductance	Related to impedance changes across the entire arterial tree reflects global pulsatile blood volume changes during the cardiac cycle
Anatomical assumption regarding thorax	Fluid-filled cylinder or truncated cone	Thorax is an electrical circuit with resistor and capacitor	NA
SV estimation	Calculated from estimated changes in resistance/impedance (Z0) – electrical current flow over time due to aortic blood flow changes	Calculated from phase shift, determined from resistance and capacitance [amplitude (magnitude of impedance)]and phase (direction of impedance (Z0)]	Calculated the magnitude of impedance change during systole (ΔZ), the timing of systolic ejection
SV calculation	Instantaneous rate of change in Z0 is related to aortic blood flow and SV is proportional to the maximal rate of change of Z0 ($dZ0/dt_{max}$) and the ventricular ejection time (VET)	Peak rate of change of the phase shift ($d\varphi/dt_{max}$) is proportional to the peak aortic flow from which SV is calculated	Sramek–Bernstein stroke volume equation
Electrode placement	Four electrodes –placement dependent on technology used Measurements stated not to be sensitive to placement 	Applied at the base of the neck and costal margins on both sides. Measurements are sensitive to electrode placement 	Radial artery of wrist and posterior tibial artery of ankle 
Commercially available devices	ICON & Aesculon – Osypka Medical, Germany 	Starling, Baxter Medical, UK 	NiCaS, NI medical, Israel 

dZ0/dt – impedance change over time; VET – ventricular ejection time; Z0 – impedance; $d\varphi/dt_{max}$ -peak rate of change od change of phase shift.

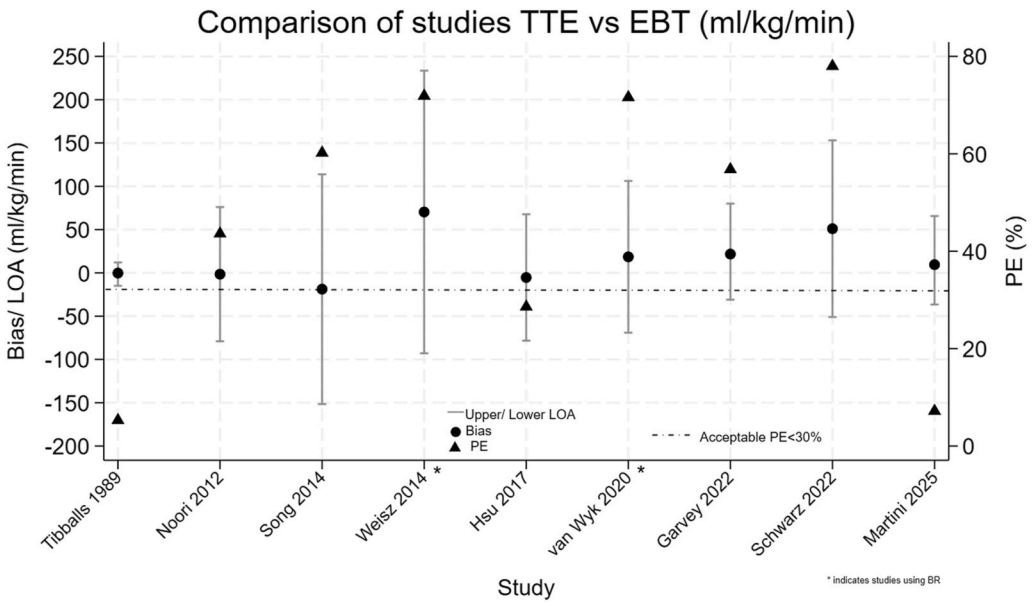


Fig. 1. Comparison of EBT vs TTE CO weight indexed studies.

CO–based decision-making [34–36].

4. Beyond comparative accuracy: EBT in the neonatal clinical context

Beyond validation studies, a growing body of literature shows the use of EBT for real-time hemodynamic monitoring and assessment. Recent studies (Table 2) demonstrate findings largely consistent with neonatal pathophysiology, supporting the usefulness of EBT as a research tool for advancing precision hemodynamic assessment in neonatal care.

EBT may detect intra-patient hemodynamic changes across multiple clinical contexts [18,47–49,51–55]: postnatal transition [50,56], PDA management (prediction [26,31,38,41,43,44,46], medical therapy [40, 45], surgical management [37,39,42,79]), pharmacological [57,58] and ventilatory interventions [34,68–73], and sepsis [21,77]. It has also been used to assess responses to cardiorespiratory events, red blood cell transfusions [61–64], cord clamping strategies [47,55], and postural changes [35,59,60]. In hypoxic–ischaemic encephalopathy, preliminary studies suggest EBT can track CO changes during therapeutic hypothermia and identify associations with outcomes [65–67] (Table 2). However, many studies report contradictory limiting clinial usefulness on a population level [6,9,32].

Emerging data further suggest a role in inter-patient phenotyping. EBT has differentiated hemodynamic profiles based on gestational age, mode of delivery, and antenatal Doppler findings during transition [18, 36,54,56,80,81]. Similarly, hemodynamic profiles differ may differ in the presence of septic shock, [77,78], hemodynamically significant PDA, and NEC [74], but associations with IVH remain inconsistent [75].

5. Should the core question shift?

A substantial body of physiological monitoring literature suggests that devices with imperfect accuracy may retain clinical value if they reliably detect longitudinal changes [82]. Accordingly, the key question shifts from “Do these devices match TTE?” to “When does imperfect information retain clinical utility?”

This paradigm reflects established methodological principles: method-comparison studies are limited by reference variability, clinical utility depends on detecting change rather than agreement, and monitoring is only valuable when embedded within a therapeutic framework [82]. In neonates, EBT performance is constrained by the inherent inaccuracy and variability of TTE and the non-stationary nature of neonatal physiology [9]. Importantly, precision—rather than bias alone—determines reliability [83].

While absolute CO measurement may remain relevant in selected contexts, EBT offers continuous longitudinal data, which is unavailable with intermittent TTE, enabling assessment of trends from baseline [84]. However, evidence for trending ability remains inconsistent, with studies reporting both poor and acceptable performance [10,17,24].

In this context, “imperfect but useful” monitoring may be particularly relevant. EBT may support earlier recognition of instability, guide timing of echocardiography, and assist in evaluating therapeutic response between TTE assessments [8]. However, monitoring alone does not improve outcomes [82]. Clinical benefit depends on integration into structured, multimodal hemodynamic management strategies. Accordingly, the value of EBT should be judged by its impact on clinically meaningful outcomes rather than agreement metrics alone—an area where evidence remains limited and warrants further investigation.

6. Potential clinical applications of EBT for neonatal hemodynamic assessment

Based on technical principles and the available neonatal literature, several potential clinical applications of EBT can be delineated.

1) Recognition of hemodynamic deterioration and profiling:

EBT enables continuous, multiparameter assessment of cardiovascular physiology, including CO, SV, SVR, contractility indices, and TFC. Low systemic blood flow (SBF) remains clinically important yet frequently under-recognised when relying on clinical or pressure-based surrogates alone [3]. Compared to intermittent TTE, continuous monitoring with EBT may facilitate earlier detection of evolving hemodynamic compromise [3,8]. Simultaneous evaluation of flow and resistance parameters may also support identification of different hemodynamic phenotypes, as suggested in conditions such as sepsis, intrauterine growth restriction, and PDA [18,21,34,43,67,77,79].

2) Monitoring responses to therapies and interventions:

Given limitations in absolute accuracy, the principal application of EBT lies in trend monitoring. Continuous data may allow assessment of

Table 2
Studies using EBT in different neonatal clinical contexts.

Author (year)	Condition/Intervention	N	Population	Monitoring period	Results
PDA and other cardiac disorders					
Lien 2015 [37]	PDA ligation	30	Preterm VLBW infants	During and after PDA ligation	Decreased CO and SV, increased SVR after PDA ligation
Katheria 2018 [38]	hsPDA prediction	292	Preterm infants <32 weeks	First 24h	PDA requiring treatment had lower CO and SV, not confirmed after GA adjustment
Rodriguez Sanchez de la Blanca 2018 [39]	Pharmacological and surgical PDA closure	18	Preterm infants < 28 weeks	72h after treatment initiation	CI & contractility decreased and SVRI increased within 72h from successful closure (either pharmacological or surgical)
Hsu 2019 [40]	PDA treatment	18	Preterm VLBW infants	24h after ibuprofen treatment	Higher CI but not HR or SVI in non-responders
Gatelli 2020 [41]	Hypoplastic left heart syndrome (HLHS)	2	Term infants with HLHS	During prostaglandin (PGE) therapy	CO trending showed ability to track therapies (fluid, PGE, ventilation)
Rafaeli Rabin 2020 [26]	hsPDA prediction	36	Preterm infants < 35 weeks, <1750g	Not available	Increasing SVI, CI and decreasing TPRI with increasing PDA size
Gatelli 2022 [42]	Percutaneous PDA closure	5	Preterm ELBW infants	Before, 15min & 24h after percutaneous closure	Increased SV, CO, and contractility post percutaneous closure
Martini 2023 [43]	hsPDA prediction	46	Preterm infants <32 weeks/VLBW	First 72h of life	Higher CO and TFC in the presence of a hsPDA compared with a restrictive or closed duct
Eid 2024 [44]	PDA in infants on invasive ventilation	25	Preterm infants <37 weeks	Day 0,1,3,5,7 of ventilation with PDA	Decreasing CO, SV during first week of life compared to day 0 of life
Gad, 2024 [45]	PDA treatment	40	Preterm infants <35 weeks	Enrolment & day 5	EBT did not track CO changes with PDA treatment, inotropes, mechanical ventilation
Chen 2025 [31]	hsPDA prediction	98	Preterm infants <32 weeks and/or VLBW	First 7 days	WBEBT-measured CO predictive of hsPDA
El-Farrash 2025 [46]	Early PDA detection	75	Preterm infants ≤ 35 weeks	First 48 h	CO and SV lower at admission & 12 h
Postnatal transition					
Katheria 2016 [47]	Delayed cord clamping (DCC), positive pressure ventilation	150	Preterm <32 weeks	After resuscitation, first 24h of life	No difference in hemodynamic parameters between DCC with/without positive pressure ventilation at birth
Freidl 2016 [48]	Early transition	100	Term	First 15min of life	HR & CO increased in first minutes & decreased after 3 min. No effect of SV
Cappelleri 2019 [49]	Transition	29	Preterm infants 30-34 weeks	First 48h of life	CO increased by 34% - due to 29% increase in SV and 5% increase in HR over 1st 48 h. SVR decreased by 14%
Author (year)	**Condition/Intervention**	**N**	**Population**	**Monitoring period**	**Results**
Martini 2020 [50]	Transition, cardiorespiratory events	40	Preterm infants < 32 weeks, VLBW	First 72h of life	SV increases, CO decreases, contractility decreases, SVR increases during desaturations with or without bradycardia but not isolated bradycardia
Baik-Schneditz, 2021 [51]	Early transition, sex differences	99	Term	First 15min of life	Higher CI in males than females at 15 min but not at 5 or 10min No difference in HR at any time point
Baik-Schneditz, 2021 [52]	Early transition	99	Term	First 15min of life	CO decreased from 5 to 10 min and increased from 10 to 15 min
McCarthy, 2021 [53]	Early transition	49	Term	10min after delivery and 2h after birth	Decreased CI and HR but no change in SV between birth and 2h of life
Metwalli, 2022 [54]	Early transition	200	Term & Late preterm (34-36 weeks)	First 60min of life	SVV, TFC differed between term and late preterm in 1st 15 min. SVV and TFC differed between NVD and CS delivery
Soliman 2024 [55]	30s vs. 120s DCC	68	Term infants	First 24h of life	Improved SV and contractility following 120s vs. 30s DCC
Martini 2025 [18]	Transition, IUGR with abnormal fetal Doppler	92	VLBW infants	First 72h of life	CO, SV, contractility, and SVR patterns differed between AGA and IUGR infants as well as between different antenatal Doppler phenotypes in IUGR infants
Soliman 2025 [56]	Early transition, mode of delivery	200	Preterm and term infants	First 60min of life	CI increase between 5 and 10 min and decrease between 15 and 60 min. SI, CI, and contractility differed between NVD and CS born preterm and term infants
Drug administration					
Katheria 2017 [57]	Sodium bicarbonate administration	36	Preterm infants <32 weeks	80 min after administration	No change in CO, HR
Parladori 2024 [58]	Caffeine effect on CVS and CNS during transition	77	Preterm infants <32 week/VLBW	First week of life	No difference in CO, ICON, HR; slight but significant SVR increase
Body positioning					
Ma 2015 [59]	Positioning	30	Late preterm & term	During position changes	Decreased SV, CO & SVR in prone position; return to baseline in supine position
Paviotti 2017 [60]	Positioning	32	Late preterm	During position changes	CO and SV decreased and SVRI increased in left lateral position; return to baseline in supine position
Wu 2017 [35]	Positioning	34	Term	During position changes	CO SV decreased in prone position; return to baseline in supine position
Red blood cell transfusion (RBCT)					
Weaver 2018 [61]	RBCT	75	Preterm infants < 37 weeks	30 min prior & during transfusion	Increased SV & CO post-transfusion, no change in TFC

(*continued on next page*)

Table 2 (*continued*)

Author (year)	Condition/Intervention	N	Population	Monitoring period	Results
Jain 2019 [62]	RBCT	30	Preterm infants <32 weeks	1 h pre & 1-h post-RBCT	No difference in CO pre and post transfusion
Author (year)	**Condition/Intervention**	**N**	**Population**	**Monitoring period**	**Results**
Chakkarapani 2023 [63,64]	RBCT	20	Preterm infants ≤ 28 weeks	4 h prior, 3 h during, 24 h after RBCT	Contractility and TFC changed significantly during and after RBCT
Hypoxic-ischemic encephalopathy (HIE) and therapeutic hypothermia (TH)					
Wu 2018 [65]	TH (rewarming phase)	20	Term HIE infants	4h pre- to 1h post-rewarming	Increased CO, related to HR but not SV increase during rewarming
Eriksen 2019 [66]	HIE, TH	25	Term HIE infants	Before and during TH	Impaired CO related to HR decrease and SV increase, in HIE infants compared to healthy term infants.
Balog 2023 [67]	HIE	26	Term HIE infants	During TH and rewarming	Significant SV and HR differences at rewarming and 6h post-rewarming between infants with favourable and adverse outcome
Respiratory support					
Buguiera 2020 [68]	Different CMV modalities	20	Preterm infants <28 weeks	During cross over between PC and VT ventilation	No change in hemodynamic parameters (CI, CO, SV, HR)
Weaver, 2021 [69]	Ventilation	800	Preterm infants <36 weeks	During ventilation	No difference in hemodynamic parameters for infants 29-36 weeks died vs survived. Lower SV, CO in infants 25-28 weeks who died. Lower SV, CO and higher SVR &TFC in infants <25 weeks who died vs survived
Mullaly, 2022 [70]	Extubation from CMV	10	Preterm and term infants	2hrs pre and 2 h post-extubation	Significant CO and SV post extubation
Elmazzahy 2023 [71]	RD	30	Term	1st 2 h of life	No difference in hemodynamic parameters between infants who developed RD and those who did not within 1st 2 h of life. Significant differences in CI/SV between infants with RD who required NICU and those who did not
Koura 2025 [34]	PPHN on HFV vs CMV	58	Term	First 7 days	CO, SV, and contractility lower in HFV group compared to the CMV group at all time points. PAP remained unchanged and SVR showed no significant changes at any time point in either group
Nissen 2025 [72]	ETT suctioning during CMV	7	Preterm and term infants	Variable	HR decrease during suctioning; SV and CO increase after suctioning
Zuiki 2025 [73]	Effect of PEEP during CMV	36	Preterm and term infants	During incremental increases in PEEP	SV and CO decreased if PEEP increased (>7cmH2O)
Neonatal outcome prediction					
Miletin 2020 [74]	IVH and/or NEC	39	Preterm infants <1250g	6-48h of life	Low CI on day 1, followed by an increased CI on day 2, associated with IVH and/or NEC
Schwarz 2024 [36]	Mortality and/or IVH/PVL	53	Preterm infants <32 weeks	First 48h of life	Time trajectories of CO (i.e. daily CO increase ≥35 ml/kg/min) were associated with the development of IVH ≥ grade 2. No association with CO absolute values after adjusting for GA.
Author (year)	**Condition/Intervention**	**N**	**Population**	**Monitoring period**	**Results**
Hibner 2025 [75]	Mortality and/or IVH	482	Preterm infants <32 weeks	First 24h of life	No predictive hemodynamic parameters after correcting for GA
Hsu, 2025 [76]	Any brain injury at neuroimaging	30	Preterm infants <28 weeks/ELBW	First 72h of life and weekly up to term age	No difference in hemodynamic parameters in infants who developed brain injury vs intact survivors.
Sepsis					
Gatelli, 2022 [77]	Sepsis	1	Preterm infant	During sepsis	Early SVR and CO modifications following institution of antibiotic therapy; response to cardiovascular drugs
Abdou 2025 [21]	Sepsis	70	34-36 weeks	Day 2 of sepsis	Higher CO, CI and SV and lower SVR and SVRI in septic vs. non-septic infants
Fang 2025 [78]	Sepsis with and without cardiocirculatory shock	113	Term and preterm infants	Not available	Term infants: lower SV, SVI, CO, CI, and higher SVR and SVRI in the septic shock group compared to sepsis without shock group and controls. Preterm infants: lower SV, SVI, CO, and CI in the septic shock group compared to controls; no difference in SVR and SVRI

AGA – appropriate for gestational age; CNS – central nervous system; CI – cardiac index; CO – cardiac output; CMV – conventional mechanical ventilation; CS – cesarean section; CVS – cardiovascular system; ELBW – extremely low birth weight; EBT – electrical biosensing technology; ETT – endotracheal tube; GA – gestational age; hsPDA – hemodynamically significant PDA; IUGR – intra-uterine growth restriction; NICU – neonatal intensive care unit; NVD – normal vertex delivery; PC – pressure control; PAP – peak airway pressure; PDA – patent ductus arteriosus; PEEP – positive end expiratory pressure; PPHN – persistent pulmonary hypertension; RD respiratory distress; SV – stroke volume; SVI – stroke volume index; SVR – systemic vascular resistance; SVRI – systemic vascular resistance index; SVV – stroke volume variation; TFC – thoracic fluid content; TPRI – total peripheral resistance index; VLBW – very low birth weight; VT –volume targeted.

hemodynamic responses to interventions—including fluid therapy, vasoactive support, PDA treatment, and ventilatory adjustments—particularly when TTE is unavailable or cannot be repeated frequently. While studies demonstrate the ability of EBT to capture such changes (Table 2), evidence that EBT-guided management improves clinical outcomes is still lacking.

3) Workflow integration and resource optimization:

Limited access to TTE in many settings constrains timely hemodynamic assessment. EBT may provide continuous surveillance and support prioritisation of TTE. In high-resource settings, it may complement multimodal monitoring frameworks alongside TTE and near-infrared spectroscopy, enabling contextual interpretation and cross-validation

[58,72]. In resource-limited environments, despite limited agreement with TTE, the ability of EBT to detect directional change may retain clinical utility, if interpreted cautiously.

7. From diagnosis to monitoring: a pragmatic integration framework

A pragmatic role for EBT is best conceptualised not as a replacement for TTE, but as an adjunct within a staged, multimodal hemodynamic assessment strategy. Targeted neonatal echocardiography remains the cornerstone for defining cardiac anatomy, shunt physiology, ventricular performance, and the underlying hemodynamic phenotype in unstable infants [5]. This diagnostic step is essential, as management depends not only on the presence of low flow, but on its mechanism and physiological context. Current recommendations emphasise that EBT should not be used for absolute CO or SV measurement, but may support

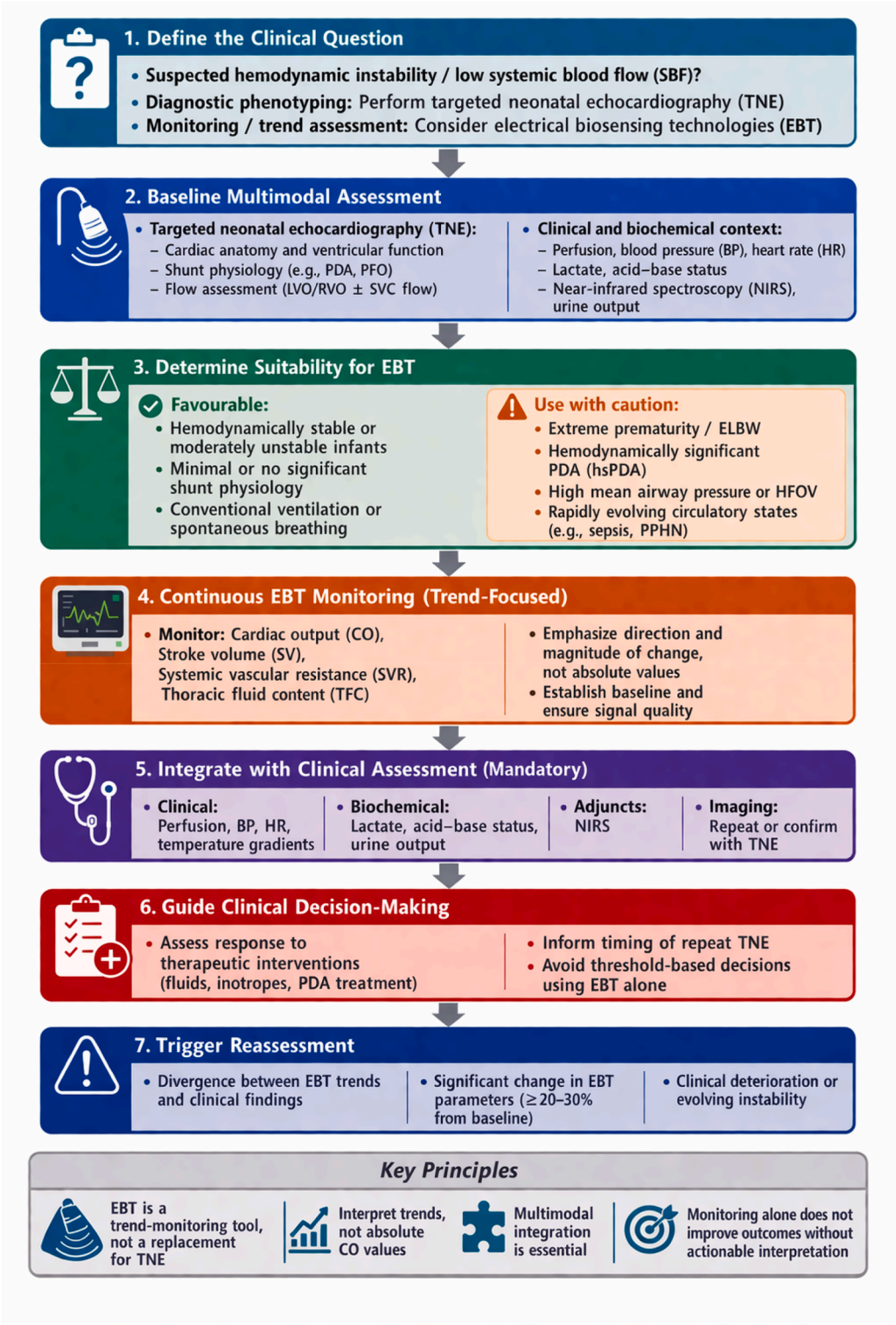


Fig. 2. Pragmatic approach to integrating EBT into hemodynamic monitoring in clinical scenarios.

within-patient trend monitoring [32].

Within this framework, EBT is best applied after initial echocardiographic diagnosis. TTE provides a high-information "snapshot," whereas EBT offers continuous longitudinal surveillance. A pragmatic approach may be to establish diagnosis and hemodynamic phenotype using TTE, followed by EBT for continuous trending. Deviations from expected trends or discordance with clinical findings should prompt reassessment with echocardiography (Fig. 2).

This approach aligns with the broader shift toward multimodal hemodynamic monitoring. Rather than replacing existing tools, EBT may contribute to integrated assessment alongside TTE and other modalities, improving temporal resolution and contextual interpretation. Importantly, this model remains provisional. Routine implementation requires outcome-based trials, improved methodological standardisation (e.g., COMPARE guidelines), and evaluation of human factors influencing interpretation and decision-making. Until such evidence is available, TTE should remain the diagnostic anchor, with EBT used cautiously as a trend-based adjunct within clearly defined clinical and analytical boundaries.

Integration of EBT, with TTE, and within a multimodal model, may allow precision care, aligning intervention with individual physiology rather than with population-derived thresholds [85]. Continuous EBT monitoring may therefore function as an early-warning adjunct, prompting timely TTE and therapeutic review, particularly where access to expert imaging is limited.

However, care needs to be taken on the over-reliance on high-resolution numerical displays, including continuous physiologic monitors, such as EBT, which may convey an appearance of objectivity and precision that may exceed the evidentiary basis supporting their use [86]. This phenomenon—described as automation bias or data reification—is well recognised in critical care, where clinicians may over-trust numerical outputs despite uncertainty in signal validity or contextual relevance [86]. In the neonatal intensive care unit (NICU), this risk is amplified by time pressure, emotional burden, and clinical uncertainty [86].

Ethically, the clinical value of EBT lies not in numerical outputs but in their influence on clinician judgement and action. Embedding EBT within explicit analytical boundaries—trend-focused interpretation, mandatory clinical correlation, and predefined triggers for TTE confirmation—may mitigate bias and reduce harm. Such restrictions would ensure that monitoring augments, rather than replaces, expert clinical judgement in vulnerable neonates.

8. From promise to responsibility: the future of EBT

Neonatology operates at the limits of measurement, where clinical decisions are made amid incomplete data and rapidly evolving physiology. In this context, EBT challenges not only technical boundaries but also the definition of clinically meaningful hemodynamic information. A dual reality persists: EBT offers the promise of continuous bedside hemodynamic surveillance, earlier recognition of circulatory compromise, and improved temporal decision-making regarding TTE assessments, particularly where access to expert imaging is limited. Yet, current evidence demonstrates insufficient accuracy for independent decision-making, wide LOA, and physiology-dependent performance, with limited robust data on trending ability [9].

Rather than abandonment of EBT, progress requires recalibration. Future development should prioritise neonatal-specific technological refinement, including sensor adaptation and algorithms that account for transitional physiology, ventilation, and signal interference. Research should also shift from method-comparison studies to therapy-focused and outcome-driven studies, evaluating whether EBT-informed management improves clinically meaningful endpoints, such as survival and neurodevelopment. Importantly, EBT technologies should be evaluated separately given fundamental technical differences [9].

Equity-focused evaluation is essential, particularly in low-resource settings where potential benefit is greatest. Ultimately, responsible adoption will depend on integrating technological innovation with clinician training, human-factors research, and ethical governance, ensuring that EBT augments—rather than distorts—clinical decision-making.

9. Conclusion

Non-invasive cardiac output monitoring using electrical biosensing technologies (EBT) represents a significant conceptual advance in neonatal hemodynamic care, shifting the field toward continuous, physiology-informed assessment. However, current evidence underscores a critical distinction between technological promise and clinical readiness. EBT does not yet demonstrate sufficient accuracy or precision to guide independent clinical decision-making, and its performance remains highly context dependent.

The emerging value of EBT lies not in absolute measurement, but in its potential to provide continuous, trend-based insight into dynamic cardiovascular physiology. When integrated within a multimodal framework—including clinical assessment, biochemical markers, near-infrared spectroscopy, and transthoracic echocardiography (TTE)—EBT may support earlier recognition of hemodynamic instability, enhance temporal decision-making, and contribute to individualized, response-guided care.

Future progress requires a shift from validation against imperfect reference standards toward outcome-based evaluation within structured clinical algorithms. Equally important is the need for ethical restraint: continuous numerical data must not displace clinical reasoning or introduce harm through misclassification or automation bias. The responsible evolution of EBT will depend on aligning technological innovation with methodological rigor, clinician training, and patient-centered outcomes. In this context, EBT should be viewed not as a replacement for echocardiography, but as a complementary tool with potential to advance precision hemodynamic care in neonatology.

10. Practice points

- Use EBT as a trending tool, not a diagnostic replacement
- Integrate EBT within a multimodal assessment framework
- Apply explicit clinical and analytical boundaries.

11. Research directions

- Outcome-based, algorithm-driven trials
- Technology-specific and physiology-aware validation
- Equity-focused and implementation research

CRediT authorship contribution statement

Lizelle van Wyk: Conceptualization, Writing – original draft, Writing – review & editing. **Silvia Martini:** Writing – original draft, Writing – review & editing.

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The authors have no conflicts of interest to declare.

Data availability

No data was used for the research described in the article.

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