Heart Rate Monitoring in Newborn Babies: A Systematic Review

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Key Points

- At the time of a baby's birth, midwives or neonatal staff are keen to listen to the baby's heart to determine the heart rate (HR) and to make sure the baby adapts well to a life outside the uterus. Listening to the baby's heart beat and detecting it can be quite difficult, especially if the rate is low and the baby is unwell and in need of breathing support. This review aims to establish which methods are currently in use to detect HR in babies, and also explore novel technologies.

What Is Known on the Subject?

- There are multiple established methods as well as novel technologies to determine HR in newborn babies. Electrocardiography and pulse oximetry are both more precise than palpation and auscultation, but multiple studies have shown that the time elapsed from birth to successful establishment of HR display often exceeds 1–2 min. Novel technologies have their own limitations.

What This Study Adds?

- This study describes each available method and determines obstacles in use for each of them. It focuses on three areas: difficulties related to the application of sensors and interfaces, time to display, and user or observer feedback. Our review informs further studies and potentially improves outcomes by establishing methods to overcome the obstacles in use.

Keywords

Neonates · Heart rate · Monitoring

Review registration: PROSPERO registration CRD42018091024.

Abstract

Background: Around 10% of newborn infants require assistance during transition after birth. Heart rate (HR) is the most important clinical indicator to evaluate the clinical status of a newborn. **Aim:** Our study aimed to review all established

and novel methods to detect HR in babies giving special consideration to non-invasive techniques. **Methods:** We performed a systematic literature search on the following databases: MEDLINE, Embase, Cochrane Central Register of Controlled Trials (CENTRAL), and CINAHL. The inclusion criteria were studies on methods to detect HR in both term and pre-term infants in comparison to one of the current gold standards: pulse oximetry (PO) or electrocardiography (ECG) published in the last 15 years. Two independent reviewers screened titles and abstracts for eligibility. Data extracted in an Excel table were analysed to produce a narrative review structured around the type of monitoring, identified obstacles in use, as well as methods to overcome these limitations. **Results:** The search revealed 649 studies after duplicates were removed. Full article analysis was performed on 26 studies of which 25 met the inclusion criteria. Well established methods such as auscultation and palpation, although rapid and easily available, have been shown to be inaccurate. ECG and PO were both more precise but the delay in obtaining a reliable HR signal from birth often exceeded 1–2 min. Novel sensors offered the advantages of minimally obtrusive technologies but have limitations mainly due to movement artefact, bad sensor coupling, intermittent measurement, and poor-quality recordings. **Conclusions:** The limitations of existing methods have a potential impact on short- and long-term morbidity and mortality outcomes. The development of a technological solution to determine HR accurately and quickly in babies at birth has immense implications for further research and can guide interventions, such as placental transfusion and resuscitation.

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Background

The majority of newborn infants make the transition from the intrauterine to extrauterine environment successfully; however, approximately 10% of newborn infants require assistance during this transition. Heart rate (HR) is the most important clinical indicator to evaluate the clinical status of a newborn [1, 2].

HR during the first minutes of life in infants needing resuscitation may be a predictor of early neonatal mortality and moderate to severe brain injury in those who survive [3]. HR at birth has to be assessed as quickly and accurately as possible to guide further interventions [1, 2] such as placental transfusion and effective resuscitation efforts.

There are several established methods of palpation and auscultation to determine HR at birth as recommended

by international guidelines [2]: feeling for pulsations at the base of the umbilical cord, feeling the brachial or femoral pulses, and listening to the precordium with a stethoscope. Other methods mentioned in the literature include: electrocardiography (ECG), pulse oximetry (PO), Doppler ultrasound, and forehead reflectance photoplethysmography (PPG) [4].

A review by Phillipos et al. [4] concluded that auscultation is superior to palpation, although neither technique provides an accurate assessment of current HR and both are intermittent.

ECG remains the gold standard to continuously monitor an infant's HR in the neonatal intensive care unit (NICU) [4]. Potential limitations of ECG include: delay in signal acquisition due to skin cleaning (all infants are wet at delivery) and lead placement as well as skin fragility in extremely premature infants. There is also the potential of pulseless electric activity, which could be interpreted as HR on an ECG, thus potentially delaying resuscitation efforts [5]. Although it is continuous and visible to the whole team, PO has its limitations, including delay in HR display sometimes up to 2 min, which could potentially delay resuscitation efforts [6], and inaccuracy of HR measurements due to motion artefacts or poor tissue perfusion (e.g., hypothermia) [7].

Kevat et al. [8] recognised that even though ECG and PO are both precise, multiple studies have shown that the time elapsed from birth to successful establishment of HR display using these devices often exceeds 1–2 min [7, 9]. Nevertheless, rapid, reliable, and accurate HR detection and monitoring is a critical indicator of the clinical status of a newborn at delivery or in the NICU.

Aims

Considering the limitations of the currently established methods our study aimed to determine and review all established and novel methods that have been developed to date to quickly detect HR in babies giving special consideration to non-invasive techniques as they have the advantage of minimising noxious stimuli and infection [8]. Our main objectives were to identify barriers and facilitators for these devices in obtaining a reliable HR measurement by giving details about difficulties related to the application of sensors and interfaces, time to display, and user or observer feedback.

Fig. 1. PRISMA flowchart of the identification and selection of studies.

Methods

We developed a protocol prior to commencing the literature search. This was registered on Prospero and can be accessed under the following registration number: CRD42018091024.

The systematic literature search was performed on the following databases: MEDLINE, Embase, Cochrane Central Register of Controlled Trials (CENTRAL), and CINAHL. The terms searched for were: term and preterm neonates, vital signs, HR, pulse rate determination, monitoring devices, birth. There were no restrictions on the type of studies or the language. Duplicates were removed using EndNote. Two independent reviewers screened titles and abstracts for eligibility. Any discrepancies were resolved by discussion with a 3rd reviewer.

The inclusion criteria were studies published in the last 15 years reviewing the method to detect HR in both term and preterm infants in comparison to one of the current gold standards: PO or ECG. We included studies based on experiments, as well as feasibility studies in different health care settings: NICU, high-dependency unit (HDU), postnatal ward, delivery room, and community birthing centre. We also reviewed studies that have been registered on respective databases and are ongoing. Studies were excluded if there was no comparison with the gold standard in monitoring ECG or PO. A PRISMA flow diagram detailing the selection process is provided in Figure 1. Risk of bias in individual studies was assessed according to the QUADAS-2 method [10] (online suppl. e-Table 1; for all online suppl. material, see www.karger.com/doi/10.1159/000499675). The full search strategy is available in the online supplementary material.

Data on country, publication year, study setting, study type, population (gestational age and sample size), intervention (methods to detect HR, type of interface and placement for sensors), limitations or barriers as well as advantages in comparison to the

gold standard were extracted into a descriptive Excel table, producing a summary of review studies. The table was analysed, and a narrative review was structured around type of monitoring, identified obstacles in use, as well as methods to overcome these limitations. Due to heterogeneity of data and the variation in reporting, a statistical analysis of the results was not possible.

Results

The search identified 649 studies after duplicates were removed. Full article analysis was performed on 26 studies meeting the inclusion criteria; 1 study was excluded after full text review because it did not include a comparison with a gold standard. Twelve were observational studies, out of which 11 were prospective [6, 7, 9, 11–18] and 1 was retrospective [19]. Eleven studies were based on experiments [20–30]. We also included 2 randomised controlled studies [31, 32] (Fig. 1).

Looking at population characteristics, 13 studies included term and preterm, 6 only preterm, and 5 only term neonates; 1 study did not mention gestational age. The preferred location of the studies was NICU (15 studies) followed by delivery room (6 studies) and a combination of the above (2 studies). One study was conducted on the postnatal ward and NICU, and one on both the neonatal HDU and NICU.

Table 1. Summary of results comparing different techniques of PO

Author	Study type (ST) Location (L) Population (P) Sample size (n)	Technique for PO	Results		Limitations
			time to display	time to apply	
Louis et al. [32], 2014	ST: randomized controlled trial L: NICU, India P: term and pre-term n: 150	STIF vs. STOF	STIF vs. STOF: 16 (15–17) s vs. 10 (6–18) s, $p = 0.001$	STIF longer than STOF	Single investigator Only one type of oximeter Challenges in the delivery room: wet infant
O'Donnell et al. [9], 2005	S: prospective observational study L: delivery room, Australia P: term and pre-term n: 115	STIF vs. STOF	STIF produced data display by 92 s in 90% of cases	STIF shorter than STOF	No randomization for sensor application Only one type of oximeter

PO, pulse oximetry; STIF, sensor to infant first; STOF, sensor to oximeter first.

Fig. 2. Summary of methods to detect and monitor HR.

The methods to detect HR included in our review can be categorised into well-established methods and novel methods. We have also divided them into continuous contact, intermittent contact, and non-contact methods (see Fig. 2 for details).

Established Methods to Detect and Monitor HR in Neonates

The well-established methods to detect HR in neonates are: auscultation and palpation, PO, and ECG. The latter is considered the gold standard for monitoring in NICU [4].

Auscultation and Palpation

One of the studies included in our review compared the clinical assessment to detect HR by auscultation and palpation to HR by ECG [13]. This was an observational study conducted in the delivery room on vigorous term babies. It concluded that clinical assessment underestimated HR compared to ECG. The mean difference between HR assessed by auscultation or palpation and ECG HR was 14 and 22 bpm, respectively. Although the limitations of the clinical assessment were clearly identified the advantages were that it was cost effective and easily available in the delivery room compared with ECG. In reality the cost and limited access to ECG on a global scale, as well as time for data acquisition, precluded the routine use of ECG to detect HR at birth [13].

PO to Detect HR in Neonates

International guidelines recommend the use of PO during resuscitation of the newborn baby, especially when there is a need for providing positive pressure ventilation

Table 2. Comparison between HR by ECG and HR by PO

Author	Study type (ST) Location (L) Population (P) Sample size (n)	Results			Advantages	Limitations	Suggestions to overcome limitations
		time to connect (ECG vs. PO)	time to display (ECG vs. PO)	accuracy and precision			
Iglesias et al. [19], 2016	ST: retrospective observational study L: hospital DR, Spain P: preterm n: 39	26.64±3.01 vs. 17.10±1.28 s, $p < 0.05$	26.38±3.41 vs. 87.28±12.11 s, $p < 0.05$	PO had a lower availability of HR readings at initiation of different resuscitation manoeuvres PO displayed lower HR values during the first 6 min after birth	ECG placement faster by 30% (10 s) Reliable ECG HR 70% faster than PO HR at 1 min	In first 30 s of life reliable HR readings could not be obtained by either method in any of the patients	Recommend studies in babies <32 weeks and <1,500 g
Kamlin et al. [6], 2008	ST: prospective observational study L: DR, Australia P: term and preterm n: 55	not mentioned	not mentioned	Sensitivity and specificity of PO HR for detecting HR <100 bpm: 89 and 99% Mean difference (2 SD) between ECG HR and PO HR: 2 (26) bpm overall 0.5 (16) bpm in infants with positive-pressure ventilation and/or cardiac massage	ECG HR has higher sensitivity and specificity	PO HR may be inaccurate in vigorous infants Inaccurate PO HR readings may lead to unnecessary interventions	Recommend studies in extreme preterm babies to determine accuracy and precision of these technologies as well as improvements in important patient outcomes in the DR
Katheria et al. [31], 2017	ST: randomized controlled trial L: NICU, USA P: preterm n: 40	not mentioned	114 vs. 66 s	ECG HR non-significantly lower than PO HR in the first 2 min of life ECG HR faster and more accurate than during stabilization of preterm infants at birth	ECG HR faster	PO placed first causing delay in ECG lead placement ECG HR available around 60 s	Recommend earlier ECG lead placement for future studies as well as routine clinical use
Mizumoto et al. [7], 2012	ST: prospective observational study L: DR, Japan P: term and preterm n: 20	not mentioned	38 (34–43) vs. 122 (101–146) s, $p < 0.001$	ECG HR reliable throughout resuscitation and consistent with clinical observation	ECG HR faster	Delay in sensor attachment by 60 s due to meconium ECG HR not reflecting cardiac output Risk of hypothermia with ECG HR in low birth weight babies	not mentioned
van Vonderen et al. [16], 2015	ST: prospective observational study L: DR, the Netherlands P: term and preterm n: 48	82±26 vs. 99±33 s, $p = 0.001$	1 (1–2) vs. 12 (9–30) s, $p = 0.001$	Frequent occurrence of poor-quality signal during PO measurement PO HR underestimates HR in 1st min Stable ECG HR throughout Steep increase in PO HR from 60 to 180 s after birth	ECG HR faster ECG HR more stable	ECG and PO sensor placement dependent on availability of staff	Recommend the use of auscultation or palpation when in doubt about PO measurements

HR, heart rate; ECG, electrocardiography; PO, pulse oximetry; DR, delivery room.

or supplemental oxygen [2]. PO offers accurate continuous measurement of HR and oxygen saturation, and it is available for all members of the team compared to clinical assessment by auscultation and palpation, which is subjective and intermittent and available only to the assessor [4].

However, obtaining pulse oximeter signals quickly and reliably in the delivery room can be challenging due to various factors (e.g., the effect of vernix, skin oedema, transitional circulation, low-volume state, acrocyanosis, and motion artefacts), all of which could delay the signal acquisition process [32].

There are two studies in our review comparing different techniques of PO: sensor to infant first (STIF) versus sensor to oximeter first (STOF) [9, 32]. Their conclusions were contradictory. Table 1 provides a summary of studies comparing different techniques of PO.

Comparison of PO versus ECG in Detecting Neonatal HR

There are 5 studies included in our review that compare PO HR with ECG HR. Four studies measured the time from birth until a reliable HR was displayed, comparing PO versus ECG during neonatal resuscitation in either preterm or term infants [7, 16, 19, 31]. All studies concluded that ECG was more reliable and the time to display HR was at least halved compared to PO. For example, Mizumoto et al. [7] obtained the fastest HR by ECG in 38 s after birth. In addition, ECG leads were placed more quickly onto the infant compared to a PO sensor [16, 31].

There are 3 studies suggesting that pulse rate PO underestimates HR compared with ECG in the first minutes after birth [16, 19, 31]. False positive HR by PO readings was a concern, as it may have led to interventions that were not indicated [6]. In addition to this, the availability of reliable HR readings at initiation of different resuscitation manoeuvres was lower, with the PO accompanied by a frequent occurrence of poor quality signal [16, 19]. Table 2 gives a summary of those studies comparing HR by ECG with HR by PO.

Novel Technology to Detect HR on Neonates

Although rapid and easily available, chest auscultation and pulse palpation have been shown to be inaccurate, affecting the resuscitation processes [13, 33]. ECG and PO are both more precise compared to clinical assessment alone, but multiple studies have shown that the delay in obtaining a reliable HR from birth often exceeds 1–2 min [7, 9]. Current methods for monitoring HR also require the use of adhesive electrodes or sensors. These can damage the fragile skin of preterm infants, and cause

stress and pain [17]. These limitations have driven the development of novel technologies to assess newborn and infant HR, especially with regard to non-contact measurement methods for HR assessment.

Novel technology development is aimed to minimize patient contact and produce non-obtrusive measurements of vital signs. Our review identified 5 non-contact devices: camera PPG, capacitive sensors/electrodes, piezo-ceramic sensors, piezo-electric sensors, and laser Doppler vibrometer. In addition, we reviewed other minimally invasive devices that use skin contact either continuously or intermittently, but are not attached to the babies: reflectance PPG, a handheld Doppler device, and digital stethoscope.

Photoplethysmography

PPG is an optical measurement technique that can be used to detect blood volume change in the vascular bed of a selected skin area. The basic concept of video plethysmography (VPG) is similar to backscattered reflectance PPG, in which a light source illuminates an exposed skin area, and the backscattered light is measured with a photodetector array (i.e., a camera) [27]. For VPG, recorded images are stored using a computer software and then analyzed with the help of different algorithms to extract a waveform measurement of the HR.

There were 4 small, observational, and experimental studies on both term and preterm infants in the NICU that evaluated the accuracy of camera PPG to detect and monitor HR in neonates [17, 20, 27, 30]. Table 3 offers a detailed summary of studies looking into camera or reflectance PPG. The video cameras were placed at a distance ranging from 7.9 inches to 3 feet away. All studies reported a high correlation between the VPG HR and ECG or PO HR, with limits of agreement as high as 95% [27]. Differences were reported close to medical standards with values from ± 4 beats per minute (bpm) to ± 5.48 bpm.

The advantages of VPG include greatly improved comfort in prolonged observation periods [27], that it can be used on dark skin, high frequency oscillation ventilation and gentle rock movements (in mum's arms), it is pain free, there is no interference with other equipment (X-ray machine), and no impact on parent-child bonding [20]. VPG has the potential for remote healthcare monitoring allowed by reduced costs and an easy to deploy system [27, 30]. The limitations and barriers to the use of VPG were loss of data due to motion artefacts [20, 27, 30], poor illumination (all 4 studies), and regular interaction between clinical staff and the baby [17]. The authors suggested strategies to overcome these barriers by improving extraction algorithms, using higher-definition cameras

Table 3. Summary of studies comparing HR by camera and reflectance PPG with HR by ECG

Author	Study type (ST) Location (L) Population (P) Sample size (n)	Method	Results	Advantages	Limitations	Suggestions to overcome limitations
Aarts et al. [20], 2013	ST: experiment-based study L: NICU, USA and the Netherlands P: term and preterm n: 19	Camera PPG	PPG HR vs. ECG HR: no significant difference	No discomfort, stress, pain or epidermal stripping with the sensors Not affected by dark or damaged skin Not affected by high-frequency oscillation ventilation or gentle rocking movement No interference with X-rays or parent-child bonding	Movement artefacts Poor illumination	Improved extraction algorithms Higher resolution cameras Improvement of accuracy with regard to light conditions
Mestha et al. [27], 2014	ST: experiment-based study L: NICU, India P: term n: 8	VPG using commercial HD camera	VPG HR vs. ECG HR: 95% within ± 5.48 bpm of each other, mean deviation 2.52 bpm	Improved comfort Potential applications for remote healthcare	Movement artefacts Not tested in a low-light environment	Validation in large trial Improvement of accuracy with regard to light conditions
Scalise et al. [30], 2012	ST: experiment-based study L: NICU, Italy P: term and preterm n: 7	Camera PPG	PPG HR vs. ECG HR: average difference 4.5 bpm, Pearson's $r = 0.94$	Non-contact Potential applications for remote healthcare Portable device Reduced cost	Movement artefacts Environment conditions stable – no variation in light intensity	Improvement of accuracy with regard to movement artefacts and light conditions
Villarroel et al. [17], 2014	ST: observational study L: NICU, HDU, UK P: preterm n: 4	Camera PPG	PPG HR vs. ECG HR: 94% within ± 4 bpm of each other	Non-contact	Movement artefacts Major changes in lighting conditions Lack of visible skin areas Regular handling required	Not mentioned
Grubb et al. [23], 2014	ST: experiment-based study L: NICU, UK P: term and preterm n: 77	Forehead reflectance PPG	PPG HR vs. ECG HR: 97.7% within 10 bpm of each other in >32 weeks 94.8% within 10 bpm of each other in <32 weeks	Easy placement of sensors Forehead perfusion better than peripheries Less interference with resuscitation	Movement artefacts	Improvement of accuracy with regard to movement artefacts through better sensor fixation on forehead Use of suitable low pass filter
Mann et al. [25], 2011	ST: experiment-based study L: NICU, UK P: term and preterm n: 50	Reflectance PPG	PPG HR vs. ECG HR: $\geq 88\%$ within ± 5 bpm of each other Median agreement of 88% (IQR 79–95%)	Not mentioned	Movement artefacts	Improvement of accuracy with regard to movement artefacts through better sensor fixation
Ward et al. [18], 2010	ST: prospective observational study, L: NICU, UK P: term and preterm n: 30	Reflectance PPG	PPG HR obtained quickly and in 95% of duration	Easy placement of sensors No interference with care Improved quality of signal by using green light	not mentioned	Qualitative studies with staff midwives, nurses and clinicians to optimise the device Incorporate sensor in hat

HR, heart rate; PPG, photoplethysmography; VPG, video plethysmography; ECG, electrocardiography.

Table 4. Summary of studies comparing HR by handheld Doppler with HR by ECG

Author	Study type (ST) Location (L) Population (P) Sample size (n)	Method	Results	Advantages	Limitations	Suggestions to overcome limitations
Dyson et al. [22], 2017	ST: prospective observational study L: NICU and post-natal ward, Australia P: term and preterm n: 51	Handheld Doppler, AD over 10 s and DD	AD and DD HR vs. ECG HR: AD time to reliable HR 3 (0–45) s Average difference 0.69 bpm, Pearson's $r = 0.94$, $p < 0.001$ (counting audible beats)	Fast (3 s) Whole team can hear HR ECG HR does not always imply cardiac output is present whereas AD sounds do Reduced variability between methods in small babies	Study only on stable babies Higher variability in AD HR vs. ECG HR compared to PO HR vs. ECG HR AD HR and DD HR difficult to record	Enhanced training Development of handheld Doppler probe for newborns
Goenka et al. [12], 2013	ST: prospective observational study L: NICU+DR, USA P: not specified n: 92	PDU	PDU HR vs. ECG HR: Average difference 3.15 ± 6.2 bpm, Pearson's $r = 0.95$ PDU HR vs. PO HR: Good correlation PDU faster PDU HR vs. auscultation and palpation: More accurate PDU faster	PDU HR is faster than palpation, auscultation and PO HR PDU HR is more accurate than auscultation and palpation HR	Not mentioned	Not mentioned
Shimabukuro et al. [15], 2017	ST: prospective cross-sectional study L: DR, Japan P: term n: 33	Handheld FDD	FDD HR vs. ECG HR: Average difference 2.5 bpm, Pearson's $r = 0.98$ Median time to display 5.6 vs. 5.2 s	Equipment readily available in childbirth facilities in primary care Midwives familiar with FDD Information readily shared with team members as can hear the HR No risk of mistaking pulseless electrical activity for output Gives you an idea of cerebral blood flow No financial implications	Study only on term stable babies All measurements were performed by the same examiner Needs an extra staff member Can interfere with resuscitation efforts in terms of crowding	Not mentioned

HR, heart rate; ECG, electrocardiography; DR, delivery room; AD, audible Doppler; DD, display Doppler; PDU, precordial Doppler ultrasound; FDD, foetal Doppler device; PO, pulse oximetry.

[20], improving light conditions [20, 27], and developing robust systems to eliminate movement artefact [30].

Reflectance PPG

There were 3 studies reviewing the advantages and limitations of using reflectance PPG. The preferred area to place a PPG sensor was the forehead. This was the most suitable measurement site and should not interfere with any of the care or resuscitation procedures [23]. All stud-

ies used green light (525 nm), where most of the cameras have peak detection sensitivity, in preference to the more usual red or infrared wavelengths, where the sensitivity of cameras starts dropping, to optimize the amplitude of the pulsatile signal acquisition [18, 23, 25].

In order to determine reliability, Grubb et al. [23] determined the positive percentage agreement with HR by ECG and obtained values of 97.7% in the >32 weeks gestational age group and 94.8% in <32 weeks gestational age.

Table 5. Summary of the studies comparing non-contact and other novel HR sensors with HR by ECG

Author	Study type (ST) Location (L) Population (P) Sample size (n)	Method	Results	Advantages	Limitations	Suggestions to overcome limitations
Atallah et al. [21], 2014	ST: observational study based on experiments L: NICU, the Netherlands P: preterm n: 15	8 capacitive sensors	Capacitive sensors HR vs. ECG HR: High positive predictive value, but low sensitivity Better time coverage results if baby lying on chest Better sensor alignment if reduced number of layers	No skin damage Increased comfort	Bad sensor coupling Movement artefacts Worse if baby supine	Better design of sensor matrix Embedding the sensors in a support system close to neonate Reduce number of layers
Kato et al. [24], 2006	ST: observational study based on experiments L: NICU, Japan P: term n: 4	Capacitive electrode	Capacitive sensor HR vs. ECG: Synchronized to the simultaneously recorded ECG even when cotton underwear was inserted High-frequency component was attenuated	Reduced likelihood of irritation, allergy or discomfort Possible introduction to bedding	Detected waveform was distorted at high frequency	Not mentioned
Nukaya et al. [28], 2014	ST: observational study based on experiments L: NICU, Japan P: preterm n: 1	Non-invasive Piezo-ceramic	Piezoceramic sensor HR vs. ECG HR: high correlation, Pearson's $r = 0.91$	Reduced risk of skin damage No restriction of movement Decreased mechanical and painful stimuli	Movement artefacts	Not mentioned
Sato et al. [29], 2010	ST: observational study based on experiments L: NICU, Japan P: term and preterm n: 70	Piezoelectric transducer	Piezoelectric transducer HR vs. ECG HR: High HR detection rate, 90% high correlation Pearson's $r = 0.92$ Bland-Altman correlation 96.8 and 95.2% within 2 SD of mean values	No skin damage No conflict with other tubes or catheters Ability to analyse HR variability Strong durability for repetitive use of over 12 months	Movement artefacts Sensor interfered with ECG signal	Advanced signal-processing algorithms such as: Pattern recognition Wavelet transforming Independent component analysis
Freidl et al. [11], 2017	ST: prospective observational study L: NICU, Austria P: term n: 100	EV non-invasive cardiac output monitoring	Electrical velocimeter HR vs. ECG HR: Limited comparison data Information regarding stroke volume and cardiac output HR by EV decreased significantly from min 3 to 12 of life	Continuous monitoring of cardiac output, stroke volume and HR Accuracy comparable to echocardiography	Study only on term babies delivered by C-section Movement artefacts Only validated SQI (signal quality index) >80%	Recommend using high SQI over certain time as quality control
Kevat et al. [14], 2015	ST: prospective observational study L: NICU, Austria P: term and preterm n: 50	DS and smart device technology	DS HR vs. ECG HR: Average difference 7.4 bpm Median time to first DS HR display was 2 (1–7) s	Accuracy of DS HR greater than chest auscultation and umbilical cord palpation	Poor performance Accidental loss of stethoscope contact DS imprecise due to software algorithm flaw Unacceptable for clinical use	not mentioned
Marchionni et al. [26], 2013	ST: observational study based on experiments L: NICU, Italy P: preterm n: 55	LDVI	LDVI HR vs. ECG HR: High correlation Pearson's $r = 0.96$	No skin contact Continuous monitoring Can be used for prolonged monitoring and in MRI Reports HR and respiratory rate simultaneously Reduced contamination and skin infection risk	Large size Large complexity High costs	Recommend reducing: Physical dimensions Complexity Costs

HR, heart rate; ECG, electrocardiography; EV, electrical velocimetry; DS, digital stethoscope; LDVI, laser Doppler vibrometer.

Sensor placing on the forehead was considered an advantage of PPG as perfusion was better maintained in comparison with the peripheries and it was easy to access. It also caused less interference with the resuscitation of the extreme preterm babies at risk of hypothermia (delivered into polythene bags) [23].

Barriers to the use of forehead PPG were mainly due to motion artefacts causing sensor displacement [23, 25]. The authors suggested methods to overcome these limitations by improving sensor fixation, using a low-pass filter applied to the HR data, and making adjustments in the averaging windows [23]. Ward et al. [18] recognized the role of qualitative studies with staff to optimize the device and the possibility of incorporating the PPG sensor in a hat.

Handheld Doppler

Handheld Doppler ultrasound (HDU) to detect HR in babies at birth was described by 3 of the studies included in our review. Overall HDU HR correlated well with HR by ECG and is a quick solution to determine HR at birth. Table 4 provides a summary of these studies.

Other Non-Contact and Novel Sensor-Based Methods

Other non-contact sensors used to detect HR in babies identified by the review were: capacitive electrodes [21, 24], piezo-ceramic [28], and piezo-electric sensors [29]. There were 3 other novel sensors identified in our review: electrical velocimetry by non-invasive cardiac output monitoring [11], a digital stethoscope and smart device technology [14], and the laser Doppler vibrometer [26].

Electrical velocimetry using non-invasive cardiac output monitoring has the advantage of continuously monitoring cardiac output, stroke volume, and HR, and was comparable in accuracy to echocardiography. It required the attachment of 4 electrodes. The authors only used a signal quality index more than 80% for further analysis. Its limitations came from the alteration in position or skin contact due to activity and movement [11].

The digital stethoscope and smart device technology was easy to use and offered intermittent light-contact HR monitoring. It was more accurate than auscultation and umbilical cord palpation, but had its own limitations. These were due to a high proportion of recording being excluded due to poor performance. There was accidental loss of contact with the precordium and loose wiring connection leading to imprecision with differences >20 bpm compared with HR by ECG. The software algorithm flaws rendered the device unacceptable for clinical use [14].

The laser Doppler vibrometer is a non-contact method with the laser pointing towards a thoracic site near the nip-

ple area offering continuous monitoring of both HR and respiratory rate. It has all the advantages of the other non-contact devices, reducing biohazards and the risk of skin contamination. It offers information simultaneously on HR and respiratory rate. It has a high correlation to HR by ECG, but its limitations are related to large size, complexity, and costs [26]. Table 5 provides a detailed summary of the studies looking into non-contact and other novel sensors.

Discussion

This review summarizes both the well-established methods to detect HR in babies at birth and also the novel technologies with potential for clinical use. The bias assessment is summarised in online supplementary e-Table 1 using the QUADAS-2 structure [10]. This accounts for the limitations of the studies by reviewing the population's methods of selection, the way the authors performed the index test, whether they compared it with the reference test, and the impact they have on generalization. The studies included in our review were small studies which impact on generalizability either due to a limited population, lack of robust statistical analysis, and little consideration given to context (limited to a specific NICU setting, obstetric theatre, or use of a certain clinical status, such as only stable babies or only high-risk delivery).

In reality, the most commonly used methods in practice, as recommended by the International Resuscitation Liaison Committee on Resuscitation (ILCOR), were auscultation, palpation, and PO. Although rapid and easily available, chest auscultation and pulse palpation have been shown to be inaccurate, affecting the resuscitation processes [13, 33]. ECG and PO were both more precise compared to clinical assessment alone, but multiple studies have shown that the delay in obtaining a reliable HR from birth often exceeds 1–2 min [5, 9].

ECG was the gold standard for HR monitoring in the NICU [4]. When used at delivery, ECG was more reliable and the time to display HR was at least halved compared to PO. In addition, ECG leads were placed more quickly onto the infant compared to a PO sensor [16, 31]. In reality the cost and limited access to ECG on a global scale, as well as time for data acquisition, precluded the routine use of ECG to detect HR at birth [13]. Apart from the costs, ECG had other limitations: the skin had to be dry for electrodes to be placed, which increased the risk of hypothermia, especially in preterm babies. The use of adhesive electrodes could cause stress and painful stimuli [17].

Novel technology development is aimed at minimizing patient contact and producing non-obtrusive measurements of vital signs. These novel sensors offered the advantages of minimally obtrusive technologies. They did not compromise the natural skin barrier and therefore reduced skin damage and susceptibility to infection. In addition, they offered increased comfort by reducing mechanical and painful stimuli [21, 24, 26, 28, 29]. They did not interfere with other equipment or with the routine work of nurses and doctors [29].

The limitations of these novel sensors were mainly due to movement artefact, bad sensor coupling, intermittent measurement, and poor-quality recordings. For either camera or reflectance PPG, reliability was affected by motion and changes in the lighting conditions [17, 23, 27, 30].

Strengths and Limitations

One of the strengths of our review was the comprehensive literature search that included non-medical resources such as engineering journals. It gives an overview of both well-established methods and novel technologies, outlining the limitations in use and offering solutions to overcome these barriers. The limitations were due to high levels of bias and heterogeneity of reporting, which rendered it unsuitable for a statistical analysis.

Conclusions

Our review looks into the advantages and disadvantages of current and novel methods to detect HR in babies. All these methods have limitations with potential impact on short-term and long-term morbidity and mortality outcomes. For a novel sensor to be accepted it has to over-

come the practical barriers for use and prove its accuracy, reliability, and speed, but also have advantages in use and cost compared to the current methods. The development of a technological solution to determine accurately and quickly the HR on babies at birth has immense implications for clinical practice. Apart from offering a more reliable and faster alternative for monitoring, further studies can guide interventions, such as placental transfusion, and determine its role in the cardiovascular adaptation after birth. Larger studies are required to determine the advantages of a novel sensor and overcome the barriers to use.

Acknowledgements

The authors thank Igor Brbre, Clinical Librarian, Royal Sussex County Hospital Library, for his valuable help with the systematic literature search. The study was partially funded by Rockinghorse Appeal and The Early Birth Association charities.

Disclosure Statement

The authors have no conflicts of interest relevant to this article to disclose.

Author Contributions

Oana Anton designed the study, coordinated and supervised data collection, carried out elements of data analysis and wrote parts of the manuscript. Heike Rabe and Ramon Fernandez conceptualized and designed the study and reviewed and revised the manuscript. Elizabeth Rendon-Morales and Rodrigo Aviles-Espinosa provided technical advice and reviewed and revised the manuscript. Harriet Jordan assisted the data collection. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

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