Available online at www.sciencedirect.com

Resuscitation

journal homepage: www.elsevier.com/locate/resuscitation

Review

Novel technologies for heart rate assessment during neonatal resuscitation at birth– A systematic review

Peter A. Johnson[a,b], Po-Yin Cheung[a,b], Tze-Fun Lee[a,b], Megan O'Reilly[a,b], Georg M. Schmölzer[a,b,*]

[a] Centre for the Studies of Asphyxia and Resuscitation, Neonatal Research Unit, Royal Alexandra Hospital, Edmonton, Alberta, Canada
[b] Department of Pediatrics, University of Alberta, Edmonton, Alberta, Canada

Abstract

Background: 6.5–9 million newborns worldwide require resuscitation at birth annually. During neonatal resuscitation, inaccurate or slow heart rate (HR) assessments may significantly increase risk of infant mortality or morbidity. Therefore fast, accurate, and effective HR assessment tools are critical for neonatal resuscitation.

Objective: To systematically review the literature about accuracy, latency, and efficacy of technologies for HR assessment during neonatal resuscitation.

Methods: Adhering to PRISMA guidelines, PubMed, EMBASE, and Google Scholar databases were systematically searched to identify studies related to technologies for HR assessment, which could be used to guide neonatal resuscitation.

Results: Forty-six studies evaluating HR assessment technologies for neonatal resuscitation were identified. In total, 16 studies (3/16 randomized trials and 13/16 observational studies) compared two or more HR assessment technologies to measure accuracy, latency, and efficacy. Of the trials, 1/3 had a low risk of bias while 2/3 had high risks. All observational studies had high risks of bias. Most studies considered infants not requiring resuscitation, constituting indirect evidence and lower certainty in the context of neonatal resuscitation. Two trials reported faster times to HR assessment using electrocardiogram with a mean(SD) 66(20) versus 114(39) s and a median(IQR) 24(19–39) versus 48(36–69) s (both $p < 0.001$), compared to pulse oximetry.

Conclusion: While electrocardiography is faster to assess HR at birth and more reliable to detect HR changes compared to other recommended technologies, practice should not exclusively rely on ECG. While novel technologies could support HR assessment, no studies validate their clinical efficacy during neonatal resuscitation.

Keywords: Infants, Newborn, Delivery room, Heart rate assessment, Neonatal resuscitation

Introduction

The Neonatal Resuscitation Program (NRP) recommends to assess heart rate (HR) at birth if infants do not breathe or are floppy after the initial steps of newborn care.[1,2] HR is than used to decide what interventions are needed and the changes in HR are used to determine their effectiveness during resuscitation.[1,3,4] NRP and other neonatal resuscitation guidelines uses predefined HR targets at 100 beats per minute (bpm) and 60 bpm to initiate mask ventilation or chest compression, respectively.[1,2,5]

Abbreviations: NRP, Neonatal Resuscitation Program; HR, heart rate; PO, pulse oximetry; ECG, electrocardiography; PEA, pulseless electric activity; bpm, beats per minute; CI, confidence interval; SD, standard deviation; IQR, interquartile range; DS, digital stethoscope; PPG, photoplethsymography; PZT, piezoelectric transducer.

* Corresponding author at: Centre for the Studies of Asphyxia and Resuscitation, Neonatal Research Unit, Royal Alexandra Hospital, 10240 Kingsway Avenue NW, T5H 3V9 Edmonton, Alberta, Canada.
E-mail address: georg.schmoelzer@me.com (G.M. Schmölzer).

https://doi.org/10.1016/j.resuscitation.2019.07.018
Received 4 February 2019; Received in revised form 25 June 2019; Accepted 9 July 2019

Until recently, auscultation and palpation along with pulse oximetry (PO) were recommended.[6] Auscultation and palpation involve listening to the heart using a stethoscope and multiplying the number of beats heard or pulsations felt in 6 s by 10 to obtain HR; however, both auscultation and palpation underestimate a newborns' HR.[7] Factors such as noise, HR variability, and human factors such as stress during resuscitation may influence its accuracy. Instead, the use of technology such as PO, which non-invasively measures pulse rate to estimate HR have been advocated.[6] Several studies demonstrated the benefits of PO versus auscultation and palpation, however there were concerns about achieving a signal and the underestimation of HR.[8–10] Therefore, the updated neonatal resuscitation guidelines added electrocardiography (ECG) as standard monitoring for HR assessment.[1,2] However, there is ongoing debate and uncertainty regarding the optimal method to assess HR.

Technologies with longer latency to assess HR could result in delayed or prolonged intervention (e.g., in a case of pulseless electric activity (PEA), ECG HR can be displayed without any cardiac output,[11–18] resulting in delayed intervention because the clinical team is reassured of a displayed HR); alternatively, any technology which either over- or underestimates HR might result in unnecessary interventions (e.g., auscultation underestimates HR by 14 bpm,[7] which could result in the start of chest compression, which is unnecessary and potentially harmful). Therefore, any HR assessments must be fast, with minimal latency and high accuracy.

While novel technology for monitoring heart rate has been systematically reviewed previously,[19] there is a need to consolidate rapid technological advances with existing understandings. We aim to (D) systematically review existing literature on the (O) accuracy, latency, and efficacy of (I) HR assessment technologies in (P) newborn infants requiring neonatal resuscitation, (C) compared to recommended HR assessment technologies.

Methods

The study protocol was registered in the International Prospective Register of Systematic Reviews PROSPERO (https://www.crd.york.ac.uk/PROSPERO/; protocol registration number: CRD42019132794). The search strategy is summarized in Appendix A and Fig. 1 and data reporting in this review are consistent with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.

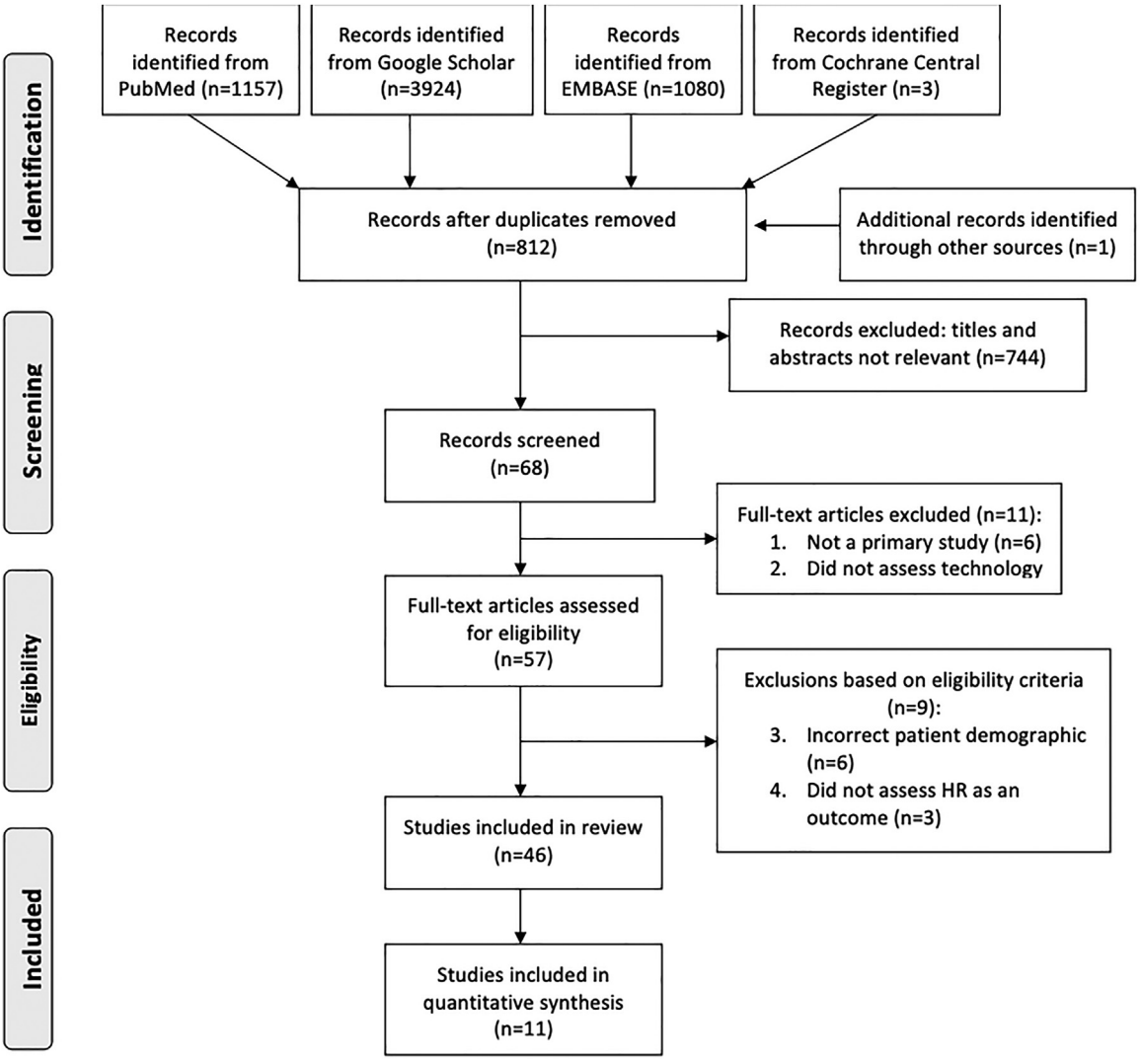

Fig. 1 – PRISMA flow chart.

Inclusion and exclusion criteria

All studies published on indexed journals or databases reporting on a HR assessment technology for newborn infants (0–28 days after birth) were considered for inclusion. All study designs evaluating these technologies during neonatal resuscitation, in the delivery room or neonatal intensive care units for term and preterm infants were included. Both in vivo and simulation studies involving recommended and novel technologies utilized for HR assessment or identified as having potential for use during neonatal resuscitation were included.

No language, setting, or publication period restrictions were applied. All studies conducted on pediatric or adult populations were excluded. Studies, which utilized the technology for a purpose other than HR assessment (e.g., oxygen saturation monitoring using PO, respiratory rate monitoring using photoplethysmography) or did not perform HR assessment using the technology, were excluded.

Search strategy and study selection

We searched PubMed, Google Scholar, EMBASE, and Cochrane Controlled Register of Trials (CENTRAL) databases from database inception to January 25, 2019 to identify studies examining HR assessment for newborns. The search term combinations, wildcards and synonyms used for the search are included in Appendix A. Additionally, the citation lists of retrieved articles were manually screened to identify other studies of interest.

Data extraction

Two investigators independently (PAJ/GMS) conducted data extraction using a standardized data extraction tool in an Excel spreadsheet (Microsoft Corporation, Redmond, WA). Extracted parameters included study design, study population, outcomes including measures of HR accuracy, latency or efficacy, and study quality. Any disagreement surrounding the selection of a manuscript or data extraction was resolved by a third author (PYC).

Risk of bias assessment

Two reviewers (PAJ/GMS) assessed risk of bias of both randomized trials and observational studies independently, using the Cochrane Collaboration risk of bias tool for randomized controlled trials and Risk Of Bias In Non-Randomized Studies-of Interventions (ROBINS-I) tool, respectively. Disagreements were resolved by a third author (PYC).

Data analysis

A narrative synthesis was performed for each heart rate assessment technology identified. We additionally performed descriptive statistics by pooling data following risk of bias assessment reporting measures of central tendency (mean or median) and variance (standard deviation or interquartile range) compared to ECG to compare HR accuracy of methods in different studies. We additionally analyzed measured time required for reliable assessment of heart rate upon application and after birth, following risk of bias assessments, using pooled data for reported central tendencies (mean or median) and variances (standard deviation or interquartile range).

Results

A total of 46 studies were identified and included using our search strategy (Fig. 1). Of the included studies 4/46 described digital stethoscope, 2/46 evaluated tap-based smartphone apps, 8/46 used PO alone, 6/46 compared PO and ECG, 9/46 examined ECG technology, 4/46 evaluated Doppler ultrasound, 5/46 used photoplethysmography, 2/46 utilized camera photoplethysmography, 4/46 were performed with piezoelectric sensors, and 2/46 used capacitance sensors. A total of 16 studies (3/16 randomized trials and 13/16 observational studies) compared two or more HR assessment technologies to assess accuracy, latency, and efficacy. Risk of bias assessments for three randomized controlled trials comparing PO and ECG and 16 observational studies and are presented in Table 1. One trials were of low risk of bias and two trials were of high risk from lack of blinding of personnel or outcome assessors. All observational studies were classified at high risk of bias. The evidence was of low quality, reflecting lack of blinding of personnel or outcome assessors and in infants not requiring resuscitation and therefore constitute an indirect form of evidence. As such, there is a lower certainty of the evidence when considering it in the context of neonatal resuscitation.

Two trials compared electrocardiogram versus pulse oximetry and reported a faster time to HR assessment electrocardiogram with a mean (SD) 66(20) versus 114(39) s and a median (IQR) 24(19–39) versus 48(36–69) s (both $p < 0.001$) (Fig. 3A–C, Table 2). Furthermore, we present a narrative synthesis of data collected.

Digital stethoscope

A digital stethoscope (DS), which converts acoustic sound into electronic signals, which can be used to assess HR (Fig. 2A, Table 2). The DS provides an amplified sound output, attenuates ambient noise and filters frequencies outside the range for heartbeats, providing greater accuracy and precision than conventional stethoscopes.[20,21] Kevat et al. compared DS with auscultation or palpation in 50 infants admitted to the neonatal intensive care unit to assess the accuracy, latency, and efficacy of HR assessments.[22] The mean difference (SD) in DS HR compared to ECG HR was 7.4 (24) bpm, which was lower than previously reported differences between ECG and standard auscultation or palpation,[22] suggesting a higher accuracy with a DS. However, Gaertner et al. compared DS utility in 37 infants and reported DS technology detected HR in only 23/37 infants within 30 s.[23] The mean difference (95% CI) was of 0.2–1(−17.6 to 18) bpm with a higher correlation with the ECG HR.[23] In the remaining 14 infants HR could not be assessed due to crying.[23] Similarly, Treston et al. compared HR assessment using DS versus handheld ultrasound versus ECG and reported successful HR assessment in 13/20, 20/20, and 20/20, respectively.[24] In addition, DS overestimated HR by a mean difference of 17 bpm compared to ECG and took the longest time from birth to obtain HR (120 s).[24] All study infants were vigorous and crying,[24] which could have affected the accuracy and time needed for assessments using the DS. While crying during assessment appears to be a limitation of this technology, it is reasonable to assume most crying babies have a HR > 120 bpm. Further studies should evaluate the DS during neonatal resuscitation to address accuracy and time needed for assessments.

Table 1 – HR assessment in newborn infants using various techniques or technologies. Studies with observational and randomized design involving comparisons between more than one technique or technology are included in this summary table. Newborn infants were randomized to intervention and comparison groups in the indicated randomized studies. Case reports/series, studies performed in animals and/or simulation studies are not reported here. Abbreviations: PA = Palpation; AU = Auscultation; ECG = Electrocardiography; PO = Pulse oximetry; DUS-Doppler ultrasound; PPG = Photoplethysmography; cPPG = Camera-Photoplethysmography; PZT, = piezoelectric transducers.

First author, year	Sample size (*n*)	Population		HR assessment technique		Study design	Outcomes
		Resuscitation required?	Gestation	Intervention	Comparison		
van Vonderen,[8] 2015	53	No	Preterm/Term	PO	ECG	Observational	Accuracy: Mean difference between ECG and PO HR was 56 bpm at 60 s ($p < 0.05$), 67 bpm at 90 s ($p < 0.01$), and 75 bpm at 120 s ($p < 0.001$) Time for initial HR assessment: 99 s for PO and 82 s for ECG ($p = 0.001$)
O' Donnell,[9] 2005	115	No	Preterm/term	PO attached to infant first, followed by sensor	PO attached to sensor first, followed by infant	Observational	Time for initial HR assessment: attaching sensor to infant first took 68 s while attaching sensor to PO first took 100 s ($p = 0.047$)
Kevat,[22] 2015	50	No	Preterm/term	DS	ECG	Observational	Accuracy: Mean difference between measured DS and ECG HR was 7.4 bpm based on Bland–Altman analysis
Gaertner,[23] 2017	37	No	Term	DS	ECG	Observational	Accuracy: DS correlated well with ECG HR during non-crying periods ($r = 0.9320$)
Treston,[24] 2018	60	No	Term	DS DUS ECG	AU	Observational	Accuracy: When compared to AU, ECG had a mean difference −10 bpm ($p = 0.024$), Doppler +5 bpm ($p = 0.4$), and DS +27 bpm ($p = 0.061$)
Murphy,[42] 2018	100	No	Term	ECG PO	ECG PO	Randomized trial	Time for initial assessment: PO took longer than ECG to first display HR (48 versus 24 s) ($p < 0.001$) Efficacy: PO displayed an initial bradycardia compared to ECG
Murphy,[43] 2018	100	No	Term	AU ECG PO	AU ECG PO	Randomized trial	Accuracy: AU underestimated ECG HR mean difference by 9 bpm and PO HR by 5 bpm (not statistically different, $p > 0.05$)
Katheria,[44] 2017	40	Yes	Preterm	ECG PO	ECG PO	Randomized trial	Time for initial HR assessment: PO HR assessment took longer than ECG (114 versus 66 s) ($p < 0.0001$). Efficacy: There were no differences between clinical interventions
Iglesias,[47] 2017	29	Yes	Preterm	ECG	PO	Observational	Accuracy: PO accuracy decreased with progressing bradycardia, compared to ECG Time for initial HR assessment: PO HR assessment took longer than ECG (60 versus 18 s) ($p < 0.0001$) Latency during resuscitation: PO was later than ECG a median time of 5 s for bradycardia start and end. Efficacy: PO did not detect bradycardia start 69% of times
Lemke,[53] 2011	16	No	Term	DUS	PA	Observational	Accuracy: HR assessed by DUS was accurate to PA of umbilical pulse (not statistically different, $p > 0.05$)
Dyson,[54] 2017	51	No	Preterm/term	DUS	ECG	Randomized study	Accuracy: Doppler had a mean difference of 0.69 bpm from ECG (not statistically different, $r = 0.99$, $p < 0.01$) Median time to assess HR: 3 s with Doppler
	92	No	Term	DUS	ECG	Observational	

(continued on next page)

Table 1 *(continued)*

First author, year	Sample size (*n*)	Population		HR assessment technique		Study design	Outcomes
		Resuscitation required?	Gestation	Intervention	Comparison		
Goenka,[55] 2013							Accuracy: Doppler HR was 3.15 bpm higher than ECG (not statistically different, $p > 0.05$)
Johansson,[57] 1999	6	No	Preterm/term	PPG	ECG	Observational	Accuracy: PPG had 1.1% false negative beat and 0.9% false positive beat compared to ECG
Olsson,[58] 2000	10	No	Preterm/term	PPG	ECG	Observational	Accuracy: ECG HR was highly associated with PPG HR in 2 ($r = 0.99$) of 3 monitoring sites
Grubb,[59] 2014	77	No	Preterm/term	PPG	ECG	Observational	Accuracy: No significant difference between PPG and ECG using Bland–Altman analysis
Aarts,[62] 2013	19	No	Preterm/term	cPPG	ECG PO	Observational	Accuracy: Bland–Altman analysis showed a stronger association for ECG versus cPPG ($r^2 = 0.0354$) than ECG versus PO ($r^2 = 0.2307$)
Sato,[67] 2010	79	No	Preterm/term	PZT	ECG	Observational	Accuracy: PZT HR was 10% lower than ECG HR ($p = 0.001$) but comparable in 70% of neonates ($p = 0.081$)

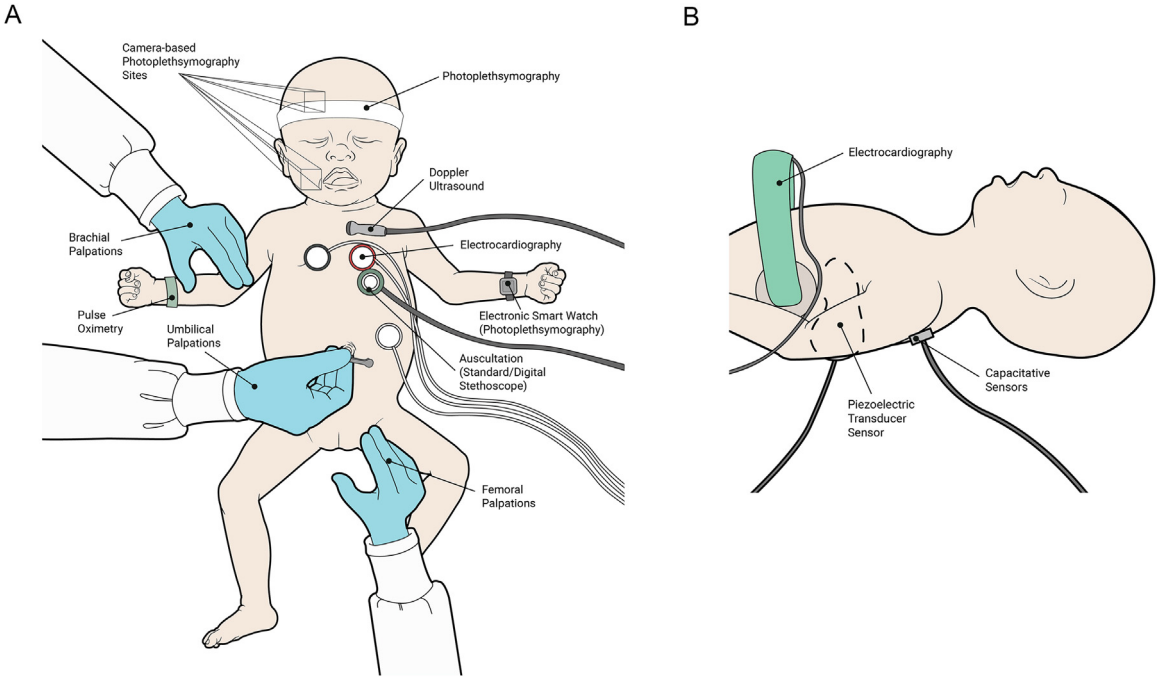

Fig. 2 – A and B: Current technologies for heart rate assessment in newborn infants.

Tap-based smartphone apps

HR assessment using auscultation and palpation has been reported to be inaccurate in 33–75% of cases, which might be due to mental computation to convert counts to HR.[1,12] Tap-based smartphone apps, which use screen tapping to estimate HR, may reduce these inaccuracies. NeoTapLifeSupport (Tap4Life, Stockholm, Sweden) is a tap-based smartphone app enabling a user to tap the screen of a smartphone or tablet in sync with HR that is auscultated or palpated. Hook et al. compared NeoTapLifeSupport plus auscultation versus NeoTapLifeSupport plus palpation to calculate heart rates of < 60 bpm, 60–90 bpm, or 100–140 bpm during simulated neonatal resuscitation.[27] Overall, the time to assess HR was similar between both groups with 15 s (95% Confidence Interval (CI) 13–16 s, $r = 0.993$) compared to 16 s (95% CI, 15–18 s, $r = 0.986$), respectively.[27] However, the time to assess HR <60 bpm was significant longer with 19 (95%CI 17–20) s compared to 15 (95%CI 13–16) s and 15 (95% CI: 13–17) s for 60–90 bpm, or 100–140 bpm, respectively ($p < 0.001$).[27] Similarily, Binotti et al. reported good accuracy and quick assessment of HR during simulated neonatal resuscitation using the NeoTapAdvancedSupport (Tap4Life, Stockholm, Sweden), an App designed for iPad devices only.[26] These data suggest tap-based

Table 2 – Reliability of heart rate assessment technology. Reliability was evaluated considering four factors: (i) applicability or user-friendliness of the device, (ii) continuous or intermittent heart rate assessments, (iii) heart rate accuracy, and (iv) time to assess reliable signal from device application.

Assessment tool/ Assistive technology	Applicability	Continuous/ Intermittent	Accuracy	Time to assess from device application
ECG	Requires attachment of three leads to infant	Continuous	Gold standard	Median acquisition time ranges from 1–24 s
Pulse oximetry	Requires attachment of sensor to infant	Continuous	Mean difference compared to ECG ranges from −5 to +0.5 bpm	Median acquisition time ranges from 12–60 s
Digital stethoscope	Requires auscultation	Continuous or Intermittent	Mean difference compared to ECG ranges from -7.4 to +27 bpm	Median acquisition time ranges from 2–45 s
Tap-based smartphone application	Requires auscultation and simultaneous screen tapping	Intermittent	Simulated and assessed values showed high correlation (r = 0.99)	Median acquisition time was 15 s
Doppler ultrasound	Requires application of gel and maintenance of transducer in position. A greater expertise is required for interpreting assessments.	Continuous or Intermittent	Mean difference compared to ECG ranges from +3.2 to +5.4 bpm	Median acquisition time ranges from 3–28 s
Photoplethysmography	Requires application of sensor on skin of infant	Continuous	A high correlation was observed when compared to ECG (r = 0.99)	Acquisition time was not described
Camera-based photoplethysmography	Requires the use of software and continuous monitoring	Continuous	Heart rate was within 2.4 bpm in only 80% of ECG recordings	Acquisition time was not described
Piezoelectric transducer	Requires placement of sensor (s) and continuous monitoring	Continuous	A high correlation was observed when compared to ECG (r = 0.92)	Acquisition time was not described
Capacitive sensor	Requires placement of sensor beneath the infant and continuous monitoring	Continuous	86% of ECG heart rate were reliable	Acquisition time was not described

applications might have the potential to improve HR assessment. However, the current available data is derived from simulation studies and studies in the delivery room are lacking. These studies are needed before this technology can be translated into routine clinical care.

Pulse oximetry

Pulse oximetry (PO) can measure both oxygen saturation and HR continuously and is routinely placed on the infant's hand or wrist (Fig. 2A, Table 1).[28,29] Two light diodes emit light at red and infrared frequencies and a photo-detector measure the changes in the transmitted light from the oxygenated and deoxygenated blood and thereby determine oxygen saturation.[30] For HR, the change in intensity of light corresponding to arterial blood volume changes associated with each pulse is detected and used by the oximeter to calculate HR.[30] However, there are several limitations including low peripheral perfusion, signal dropout, movement, arrhythmias, and presence of ambient lighting might interfere with PO measurements.[31–34]

PO is well-established and is a recommended method for HR assessment during neonatal resuscitation.[1,2,6] Kamlin et al. analyzed 5877 data pairs of ECG HR and PO HR in 55 preterm or term infants and reported a mean (2 SD) difference between ECG HR and PO HR as −2(26) bpm overall and −0.5(16) bpm in infants who received either positive-pressure ventilation and/or cardiac massage.[35] While this suggests PO could be used to monitor HR at birth, the study by Kamlin et al. did not examine the first few minutes after birth in detail.

Using PO, Toth et al. reported HR at 2, 10 and 20 min in 50 term infants with a median (range) HR of 157 (89–199) bpm, 148 (110–191) bpm, and 144 (123–178) bpm, respectively.[36] Dawson et al. also reported similar HR using either ECG or PO in 125 preterm infants receiving either 21% and 100% oxygen during resuscitation.[37] In a later study, Dawson et al. utilized PO to evaluate changes in HR over the first 10 min, determining median HR was <100 bpm at 1 min and >100 bpm at 2 min.[38] Van Vonderen et al. compared HR assessment with PO and ECG in 53 newborn infants in the delivery room and reported PO significantly underestimated HR 94(67–144) versus 150 (91–153) bpm at 60 s, 81(60–109) versus 148(83–170) bpm at 90 s and 83(67–145) versus 158(119–176) bpm at 120 s.[8] After 5 min, the PO and ECG assessments of HR were similar with no significant difference in HR.[8] Additionally, the mean (SD) time to first HR recording after birth was significantly longer with PO compared to ECG with 99(33) and 82(26) s, respectively.[8] These observations indicate ECG is faster and more reliable than PO. However, none of the presented studies were randomized trials.

Electrocardiography

Electrocardiography (ECG) is a the current gold standard to compare HR assessments in newborn infants and it involves the use of electrodes on the infant's chest to measure electrical activity of the heart[8,39,40] (Fig. 2A, Table 1). For every heartbeat, heart muscle depolarizes and repolarizes producing pulsating electrical waveforms. ECG measures HR by using the time between QRS complexes representing ventricular electrical activity.[41] With the time delay to achieve HR signal with PO and lower accuracy associated with auscultation or palpation, current resuscitation guidelines weakly recommend ECG monitoring, which enables “accurate and rapid” HR

assessments, for neonatal resuscitation.[1,2] Although, Kamlin et al. has reported similar accuracy between PO and ECG for HR monitoring,[35] van Vonderen et al. reported PO underestimates HR in the first 2 min after birth when compared to ECG.[6] Additionally, randomized trials by Murphy et al. and Katheria et al. demonstrated obtaining HR was significantly faster using ECG compared to PO [24 (19–39) s versus 48(36–69) s and 66(46–86) s versus 114(75–153) s].[42–44] Similarly, Mizumoto et al. and Katheria et al. reported a longer time to obtain HR using PO compared to ECG in both preterm and term infants.[45,46] Furthermore, during bradycardia episodes (HR $<$ 100 bpm) during stabilization immediately after birth PO has a longer detection time compared to ECG.[47] A total of 29 episodes of bradycardia were measured using ECG compared to 9/29 (31%) detected with PO having a median time delay of 5 s to display bradycardia.[47] Progressive bradycardia resulted in significantly lower PO HR measurements compared to ECG, suggesting ECG is more effective, faster, and a higher accuracy at detecting changes in HR.[47] In the context of neonatal resuscitation, this is critical information as bradycardia guide decisions about the need for interventions such as positive-pressure ventilations or chest compressions.[1,2,48]

However, the routine use of ECG for HR assessment also has some limitations. ECG-electrodes can easily become dislodged, due to wet skin (e.g., blood, mucus, vernix or amniotic fluid). In addition, extremely premature infants have more delicate, fragile skin, where the application of ECG-electrodes can result in skin injury.[46]

The *dry electrode ECG sensor* (Fig. 2B) is one solution, which could overcome these problems by using conductive textiles instead of gel electrodes to allow for loose skin contact and flexibility.[49] Linde et al. report a median (IQR) time of 3(2–5) s for application of this dry-electrode system and good-quality HR measurements within 10 s in 55 term infants.[50] However, further investigation of this technology is required before implementation in the delivery room.

More concerningly, several case reports and animal studies reported PEA, resulted in display of HR without any cardiac output.[11–18] Patel et al. and Loung et al. reported PEA is present in 40–50% of asphyxiated newborn piglets, which falsely displayed a HR on the ECG.[14,15] Similarly, case reports and case series reported a total of seven cases of PEA during neonatal resuscitation in the delivery room.[12,16–18] This is concerning as healthcare professionals rely on ECG display and PEA might delay the start resuscitation.

Moreover, a recent case report of a preterm infant with a diagnosis of non-immune hydrops fetalis, with bilateral pleural effusions, ascites, and subcutaneous edema reported ECG is not always sufficiently sensitive.[51] The ECG was unable to display QRS complexes and thus PO HR was used to guide resuscitation.[51] Once circulation and perfusion was improved ECG signal returned.[51] This suggests circumstances exist wherein healthcare professionals should not solely rely on ECG for HR monitoring alone and rather use a combination of techniques.

Doppler ultrasound

Doppler ultrasound uses high frequency sound waves to detect blood flow based on differences in the frequency of emitted and reflected sound waves (Fig. 2A, Table 1).[52] During pregnancy and fetal development Doppler ultrasound is used for prenatal screening, diagnosing congenital heart disease among others. However, its use for HR assessments in the delivery room is novel. Studies comparing Doppler ultrasound with auscultation/palpation reported faster and accurate HR acquisition using Doppler ultrasound.[40,53] Dyson et al. compared ECG with PO, audible Doppler, and Doppler display to assessed HR in a cohort of 51 term and preterm infants.[54] Audible Doppler was as accurate as ECG or PO to obtain a HR.[54] However, when audible Doppler was compared with the Doppler display, the Doppler display overestimated the HR by an average of 5(95%CI −12.8; +2.1)bpm.[54] This data suggest audible Doppler has similar reliability and accuracy compared to ECG.[54] Similar observations were reported by Goenka et al. who randomized 92 term infants to HR assessment using Doppler ultrasound, PO, or ECG HR.[55] This study also suggested Doppler ultrasound might have a greater usefulness than PO especially during the first minutes after birth, with a mean time of 18 s for Doppler ultrasound HR assessments compared with 64 s for PO measurements.[55] However, noise in real-life resuscitations might interfere with audible signals and unlike ECG and PO, Doppler ultrasound requires a dedicated operator.

Photoplethysmography

Photoplethysmography (PPG) is an optical technique that detects blood volume changes in tissues microvasculature (Fig. 2A, Table 1).[56] PPG is used to detect HR and works by emitting two wavelengths of light and using a photodiode to detect either reflected or transmitted light, which provide information about blood volume changes in the tissue.[56] Furthermore, PPG is used to measure an infant's respiratory rate and HR. While PO is a form of PPG, this paragraph focuses on forehead PPG. In a pilot study of six infants, Johannson et al. reported the forehead reflectance PPG to have 1.1% false negative heart beats and 0.9% false positive heart beats, when compared with ECG,[57] which suggests PPG has good accuracy for HR assessments. This is further supported by a recent study reporting high degree of correlation (r = 0.99) between PPG and ECG.[58] Most recently, Grubb et al. used a forehead reflectance PPG for HR assessment in 77 newborn infants admitted to the neonatal intensive care unit.[59] The reliability in infants $\geq$32 wks gestation was 97.7% with a limit of agreement between +8.39 min^{-1} and −8.39 min^{-1} between ECG and PPG.[59] For infants $<$32 wks the reliability was 94.8% with the limits of agreement between +11.53 min^{-1} and −12.01 min^{-1}.[59] These observations indicate PPG may be a useful tool to continuously monitor HR non-invasively.

PPG could also be implemented in resource-limited environments in Fitbit devices or smartphone applications. Lin and Wei recently described the possibility of detecting HR in an extremely preterm infant (24 weeks with 700 g birthweight) using a smart watch (Apple Watch 2, Apple Inc., Cupertino, CA) through a plastic bag for heat-loss protection “within a few seconds”, which was comparable to detecting the HR with the ECG.[60] As PPG uses similar mechanics to PO for detection, it is limited by the same factors including low peripheral perfusion, signal dropout, movement, arrhythmias, and ambient lighting.

Camera-based PPG

An alternative assessment technology using PPG is camera-based PPG, which uses an algorithm to calculate HR from video recordings (Fig. 2A, Table 1).[61] Aarts et al. compared camera-based PPG with PO and ECG to detect HR in a pilot study in 19 newborn infants admitted to the neonatal intensive care unit.[62] A strong association between camera-based PPG and ECG with a bias of 0.3 bpm compared with −0.6 bpm for PO versus ECG was observed,[62] suggesting its validity for clinical use. In another study with 30 preterm

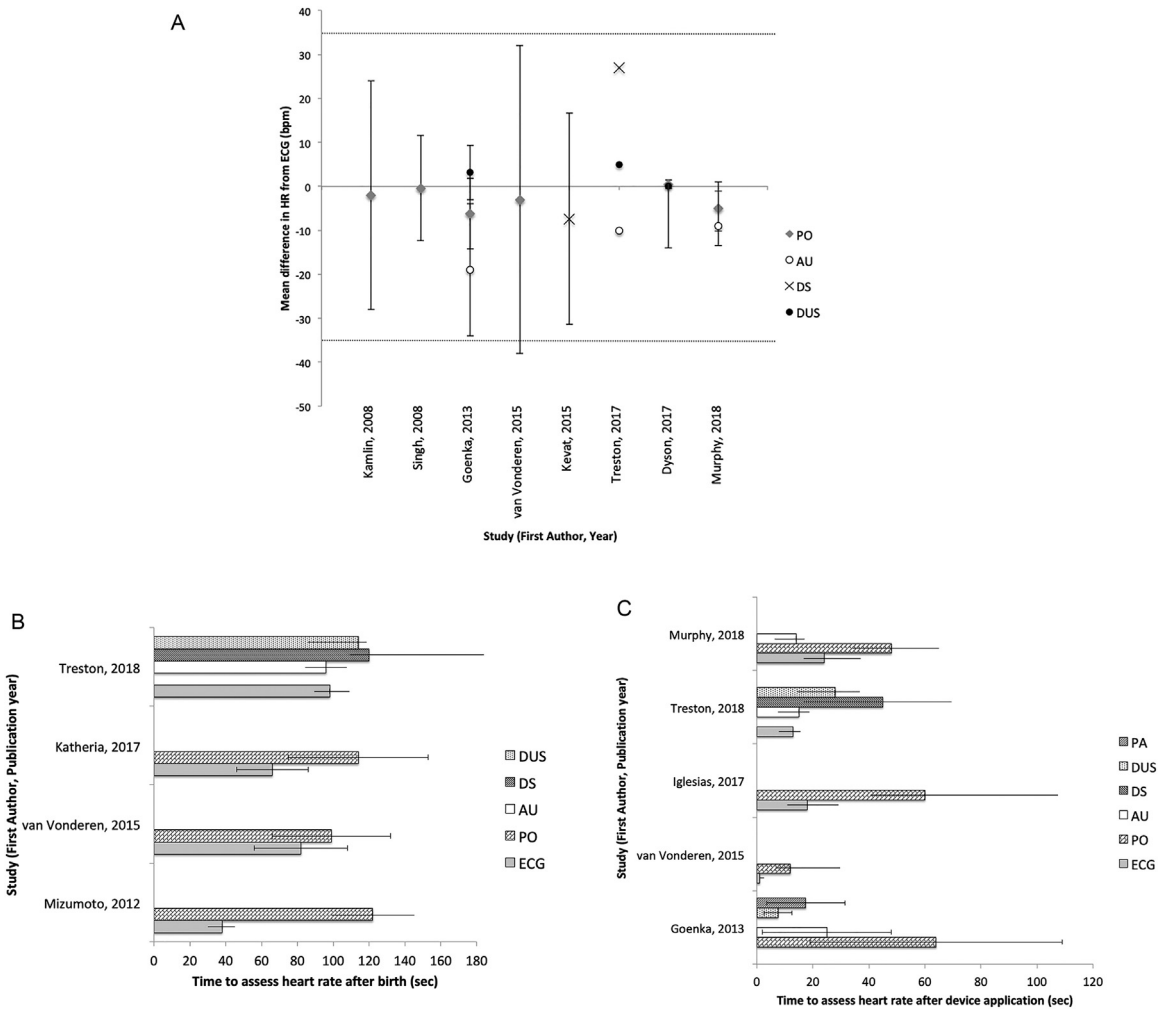

Fig. 3 – (A): Mean (SD) difference between ECG HR (Electrocardiograph heart rate) and heart rate obtained by other assessment techniques. The heart rate at 0 beats per minute (bpm) represents the comparison standard used for the other techniques. Values above 0 bpm are overestimations of heart rate while values below 0 bpm are underestimations o, with respect to ECG HR. Dotted lines represent the upper and lower limits of agreement, which were reported by van Vonderen et al.[6] The first five studies report mean with standard deviation as a measure of variance, while Treston et al. did not report a measure of variance with the mean difference. The last two presented studies report mean difference with 95% confidence interval as the measure of variance. Abbreviations: Pulse oximetry (PO); Auscultation (AU); Doppler ultrasound (DUS); Digital stethoscope (DS). (B): Total times reported for heart rate assessment from birth to heart rate signal detection for different techniques. Bars with capped error bars represent studies, which report mean heart rate with standard deviation whereas bars with uncapped error bars represent studies reporting median time with interquartile range. Abbreviations: Digital stethoscope (DS); Doppler ultrasound (DUS); Pulse oximetry (PO); Electrocardiography (ECG). (C): Times reported for application of heart rate assessment tool until signal detection. Bars with capped error bars represent studies, which report mean heart rate with standard deviation whereas bars with uncapped error bars represent studies reporting median time with interquartile range. Abbreviations: Digital stethoscope (DS); Doppler ultrasound (DUS); Palpation (PA); Auscultation (AU); Pulse oximetry (PO); Electrocardiography (ECG).

infants, accuracy between camera-based PPG HR and ECG HR was ±2.4 bpm in 80% of measurements.[63] This is concerning as this would potentially underestimate HR during resuscitation and could result in unnecessary interventions. Major limitations to detect a HR includes (i) infants movements, (ii) ambient light,[62,63] and (iii) obstruction by equipment or healthcare providers. These limitations are concerning particularly during resuscitation as movement of the resuscitator or various light sources may influence the displayed HR. Future studies should examine if PPG and camera-based PPG technology can be used during neonatal resuscitation.

Sensor-based techniques

Piezoelectric transducer sensors (PZT) detect acoustic vibrations or pressure changes produced by the heartbeat or respiratory movements, which are converted into electrical signals, which are then

translated into HR or respiratory rate (Fig. 2B, Table 1).[64] Wang et al. reported a pilot study in preterm infants with a ±8.24% error rate compared to ECG.[65] They concluded the technology was useful as a contactless assessment strategy,[66] which may be suitable for delicate and thin skin in premature infants. Similarly, Sato et al. compared PZT sensors to ECG in 38 infants and reported an average correlation coefficient of 0.92 ± 0.12 when compared with ECG.[67] Nukaya et al. reported PZT can be used for HR monitoring but identified key limitations including (i) body movements artifacts, (ii) crying, and (iii) mechanical ventilation.[62] Underestimation, noise and an overall low accuracy was associated with mechanical ventilation,[68] and as such, this technology is currently unfeasible for HR assessment, requiring further development before implementation in neonatal resuscitation.

Capacitive sensors are another form of non-contact method of HR detection, which couples an insulator (typically a garment, towel or mattress) between the infant's skin and a conductive electrode to form a capacitive electrode, which can be used to form an ECG signal by determining electrographic voltage based off capacitance (Fig. 2B).[69] Kato et al. used the described system to compare with ECG for neonatal HR detection and demonstrated comparable accuracy between the two.[69] Atallah et al. also reported capacitive sensors can reliably detect HR 86% of the time.[70] These studies are promising for neonatal resuscitation in context but further studies are needed prior to routine clinical use.

Discussion

The evidence suggests ECG is most accurate and fast technique to assess HR at birth. However, majority of studies were carried out in newborn infants, not requiring resuscitation and therefore constitute an indirect form of evidence. As such, there is a lower certainty of the evidence when considering it in the context of neonatal resuscitation. Several animal studies and case reports highlighted limitations of ECG during neonatal resuscitation. With these limitations, there is a need to identify the most efficient approach to monitor HR in the delivery room. Ideal features include continuous, non-invasive and fast acquisition of an accurate HR. Both PO and PPG device are continuous, non-invasive, and use light-emitting sensors and photo-detectors. Moreover, both techniques have similar accuracy compared to ECG HR values. However, the delay in time to display HR and poor signal quality are major limitations of these technologies.

Time to obtain signal for ECG, PO, or PPG potentially delays the start of resuscitation interventions and time needed to detect HR changes. Alternatively, auscultation with DS alongside a tap-based application or Doppler ultrasound might be the most useful technique to assess HR immediately after birth. Although these techniques have a faster time to obtain signal compared to ECG, PO, and PPG, neither can continuously monitor HR. In addition, the gel needed to obtain a Doppler ultrasound might increase hypothermia or make the chest slippery in cases where chest compressions are needed. Similarly, auscultation with a DS can provide a fast assessment of HR. However, DS are noise sensitive and might not work adequately in a stressful and noisy delivery room environment. Combining auscultation with tap-based apps might enable for faster HR detection at birth, but could also be integrated during regular assessments. Software algorithms inherent to technologies including those calculated beat-to-beat (i.e., tap-based apps) or are averaged over various intervals (i.e., ECG, PPG, PO, etc.) can differentially affect displayed HR especially when there is high HR variability.

Currently, multiple sources of information are used in practice (e.g., PO and ECG in delivery room). Furthermore any technologies must display HR in real-time during neonatal resuscitation to allow the clinical team to intervene based on the information provided. Several of the included studies used post-resuscitation analysis, which is a limitation of these techniques. Although, these new technologies are promising, future studies need to validate them against the current gold standard of HR assessment for efficacy, latency, accuracy, human factors, and ergonomics.

Conclusions

ECG is faster to assess HR at birth and more reliable to detect changes in HR compared to other recommended technologies. However, current practice should not exclusively rely on ECG. While novel technologies can support HR assessment, presently there are no studies to validate their clinical efficacy during neonatal resuscitation. Further studies are required for these technologies before they are implemented for neonatal resuscitation.

Author's contribution

Conception and design: GMS, PAJ.

Literature search: GMS, PAJ, PYC, MOR, TZF.

Drafting of the article: GMS, PAJ, PYC, MOR, TZF.

Critical revision of the article for important intellectual content: GMS, PAJ, PYC, MOR, TZF.

Final approval of the article: GMS, PAJ, PYC, MOR, TZF.

Funding sources

We would like to thank the public for donating money to our funding agencies: PAJ is a recipient of the University of Alberta Medical Sciences Graduate Program Scholarship and the Government of Alberta Graduate Citizenship Award. GMS is a recipient of the Heart and Stroke Foundation/University of Alberta Professorship of Neonatal Resuscitation, a National New Investigator of the Heart and Stroke Foundation Canada and an Alberta New Investigator of the Heart and Stroke Foundation Alberta. This research has been facilitated by the Women and Children's Health Research Institute through the generous support of the Stollery Children's Hospital Foundation.

Conflict of interest

None declared.

Appendix A

Search strategy example for one database. All databases including PubMed, Google Scholar, EMBASE and Cochrane Controlled Register of Controlled Trials (CENTRAL) followed the same search strategy and the CENTRAL database is presented. All databases were last searched on January 25, 2019, following PRISMA guidelines.

Cochrane Controlled Register of Controlled Trials (CENTRAL)
#1 Neonat* OR Newborn* OR Infant* OR OR Baby OR Babies– *n* = 71,096
#2 Asphyxia* OR Resuscitat*– *n* = 7632
#3 Delivery* OR NICU– *n* = 40,789
#4 Auscultat*– *n* = 663
#5 Palpat*– *n* = 1899
#6 Pulse oximet*– *n* = 2950
#7 Electrocardiogra* OR ECG OR EKG– *n* = 26,415
#8 Stethoscop*– *n* = 240
#9 Digital stethoscop*– *n* = 21
#10 Doppler OR ultrasound– *n* = 10,639
#11 Photoplethysmog* OR PPG– *n* = 349
#12 Piezo*– *n* = 357
#13 Capacitiv*– *n* = 72
#14 Transducer* OR Sensor*– *n* = 21,291
#15 Techn* OR Device*– *n* = 139,127
#16 App*– *n* = 337,041
#17 Method* OR Process* OR Proced*– *n* = 817,153
#18 "Heart rate" OR HR– *n* = 50,889
#19 Pulseless electric* activit* OR PEA– *n* = 544
Search strategy: #1 OR (#2 AND #3) AND #18 AND (#4 OR #5 OR #6 OR #7 OR #8 OR #9 OR #10 OR #11 OR #12 OR #13 OR #15 OR #16 OR #17)– *n* = 5

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.resuscitation.2019.07.018.

REFERENCES

1. Perlman J, Wyllie J, Kattwinkel J, et al. Part 7: Neonatal resuscitation 2015 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations. Circulation 2015;132:S204–41, doi:http://dx.doi.org/10.1161/CIR.0000000000000276.
2. Wyckoff M, Aziz K, Escobedo M, et al. Part 13: Neonatal resuscitation 2015 american heart association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation 2015, doi:http://dx.doi.org/10.1542/peds.2015-3373G.
3. Wyllie J, Bruinenberg J, Roehr CC, Rüdiger M, Trevisanuto D, Urlesberger B. European resuscitation council guidelines for resuscitation 2015. Resuscitation 2015;95:249–63, doi:http://dx.doi.org/10.1016/j.resuscitation.2015.07.029.
4. American Academy of Pediatrics, American Heart Association. Weiner GM, Zaichkin J, Kattwinkel J. Textbook of neonatal resuscitation. American Academy of Pediatrics; 2016.
5. Weiner GM, Zaichkin J, Kattwinkel J, Ades A. In: Weiner GM, Zaichkin J, Kattwinkel J, Ades A, editors. Textbook of neonatal resuscitation. 7th ed. Elk Grove Village; 2016.
6. Perlman JM, Wyllie J, Kattwinkel J, et al. Neonatal resuscitation: 2010 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations. Circulation 2010;122:S516–38, doi:http://dx.doi.org/10.1542/peds.2010-2972B.
7. Kamlin COF, O'donnell CPF, Everest NJ, Davis PG, Morley CJ. Accuracy of clinical assessment of infant heart rate in the delivery room. Resuscitation 2006;71:319–21, doi:http://dx.doi.org/10.1016/j.resuscitation.2006.04.015.
8. Van Vonderen JJ, Hooper SB, Kroese JK, et al. Pulse oximetry measures a lower heart rate at birth compared with electrocardiography. J Pediatr 2015;166:49–53, doi:http://dx.doi.org/10.1016/j.jpeds.2014.09.015.
9. O'Donnell CPF, Omar C, Kamlin F, Davis PG, Morley CJ. Feasibility of and delay in obtaining pulse oximetry during neonatal resuscitation. J Pediatr 2005;147:698–9, doi:http://dx.doi.org/10.1016/j.jpeds.2005.07.025.
10. Swenson AK, Brown D, Stevermer JJ. Pulse oximetry for newborns: should it be routine? J Fam Pract 2012;61:283–6.
11. Myerburg RJ, Halperin H, Egan DA, et al. Pulseless electric activity. Circulation 2013;128:2532–41, doi:http://dx.doi.org/10.1161/CIRCULATIONAHA.113.004490.
12. Sillers L, Handley SC, James JR, Foglia EE. Pulseless electrical activity complicating neonatal resuscitation established facts. , doi:http://dx.doi.org/10.1159/000493357.
13. Mehta C, Brady W. Pulseless electrical activity in cardiac arrest: electrocardiographic presentations and management considerations based on the electrocardiogram. Am J Emerg Med 2012;30:236–9, doi:http://dx.doi.org/10.1016/J.AJEM.2010.08.017.
14. Patel S, Cheung P-Y, Solevåg AL, et al. Pulseless electrical activity: a misdiagnosed entity during asphyxia in newborn infants? Arch Dis Child – Fetal Neonatal Ed. 2018, doi:http://dx.doi.org/10.1136/archdischild-2018-314907 fetalneonatal-2018-314907.
15. Luong DH, Cheung P-Y, O'Reilly M, Lee T-F, Schmolzer GM. Electrocardiography vs auscultation to assess heart rate during cardiac arrest with pulseless electrical activity in newborn infants. Front Pediatr 2018;6:1–4, doi:http://dx.doi.org/10.3389/fped.2018.00366.
16. Luong D, Cheung P, Barrington K, et al. Cardiac arrest with pulseless electrical activity rhythm in newborn infants– a case series [accepted]. Arch Dis Child Fetal Neonatal Ed 2019.
17. Piastra M, Cavallaro F, Genovese O, et al. Double cooling for pericardial tamponade and cardiac arrest after rewarming in neonatal asphyxia. Resuscitation 2013;84:e83–4, doi:http://dx.doi.org/10.1016/j.resuscitation.2013.03.020.
18. Hyde P, Puddy V. Pulseless electrical activity after rapid administration of fresh frozen plasma. J Paediatr Child Health 2008;44:464–6, doi:http://dx.doi.org/10.1111/j.1440-1754.2008.01345.x.
19. Kevat AC, Bullen DVR, Davis PG, Kamlin COF. A systematic review of novel technology for monitoring infant and newborn heart rate. Acta Paediatr 2017;106:710–20, doi:http://dx.doi.org/10.1111/apa.13786.
20. Swarup S, Makaryus AN. Digital stethoscope: technology update. Med Devices (Auckl) 2018;11:29–36, doi:http://dx.doi.org/10.2147/MDER.S135882.
21. Balogh ÁT, Kovács F. Application of phonocardiography on preterm infants with patent ductus arteriosus. Biomed Signal Process Control 2011;6:337–45, doi:http://dx.doi.org/10.1016/j.bspc.2011.05.009.
22. Kevat A, Dawson J, Davis P, Kamlin COF. Evaluation of a digital stethoscope and smart device technology for assessment of heart rate in the newborn infant. Arch Dis Child Fetal Neonatal Ed 2015;100:F562–3, doi:http://dx.doi.org/10.1136/archdischild-2015-308639.
23. Gaertner VD, Kevat AC, Davis PG, Kamlin COF. Evaluation of a digital stethoscope in transitioning term infants after birth. Arch Dis Child Fetal Neonatal Ed 2017;102:F370–1, doi:http://dx.doi.org/10.1136/archdischild-2016-312316.
24. Treston B, Semberova J, Kernan R. Assessment of neonatal heart rate immediately after birth using digital stethoscope, handheld ultrasound and electrocardiography: an observational cohort study. Arch Dis Child Fetal Neonatal 2018;F1.
26. Binotti M, Cavallin F, Ingrassia PL, et al. Heart rate assessment using NeoTapAdvancedSupport: a simulation study. Arch Dis Child Fetal Neonatal Ed 2018;1–3, doi:http://dx.doi.org/10.1136/archdischild-2018-315408.
27. Höök SM, Pejovic NJ, Tylleskär T, Alfvén T. Evaluation of a smartphone based application for neonatal heart rate assessment: a simulation study. Svenska Barnläkarföreningen Barnveckan. .

28. Dawson JA, Omar Kamlin CF, Vento M, et al. Defining the reference range for oxygen saturation for infants after birth. Pediatrics 2010;125:1340–7, doi:http://dx.doi.org/10.1542/peds.2009-1510.
29. Schmölzer GM, Kamlin OFOC, Dawson JA, te Pas AB, Morley CJ, Davis PG. Respiratory monitoring of neonatal resuscitation. Arch Dis Child Fetal Neonatal Ed 2010;95:295–303, doi:http://dx.doi.org/10.1136/adc.2009.165878.
30. Jahan E, Barua T, Salma U. *An Overview on Heart Rate Monitoring and Pulse Oximeter System*. Vol. 3.
31. Kopotic RJ, Lindner W. Assessing high-risk infants in the delivery room with pulse oximetry. Anesth Analg 2002;94:S31–6.
32. Workie FA, Rais-Bahrami K, Short BL. Clinical use of new-generation pulse oximeters in the neonatal intensive care unit. Am J Perinatol 2005;22:357–60, doi:http://dx.doi.org/10.1055/s-2005-872704.
33. Dawson JA, Morley CJ. Monitoring oxygen saturation and heart rate in the early neonatal period. Semin Fetal Neonatal Med 2010;15:203–7, doi:http://dx.doi.org/10.1016/J.SINY.2010.03.004.
34. Masimo Corporation. Radical signal extraction pulse oximeter operator's manual. 2006 1.1-8.2.
35. Kamlin COF, Dawson JA, O'Donnell CPF, et al. Accuracy of pulse oximetry measurement of heart rate of newborn infants in the delivery room. J Pediatr 2008;152:756–60, doi:http://dx.doi.org/10.1016/j.jpeds.2008.01.002.
36. Toth B, Becker A, Seelbach-Göbel B. Oxygen saturation in healthy newborn infants immediately after birth measured by pulse oximetry. Arch Gynecol Obs 2002;266:105–7.
37. Dawson JA, Kamlin COF, Wong C, et al. Oxygen saturation and heart rate during delivery room resuscitation of infants. Arch Dis Child Fetal Neonatal Ed 2009;94:F87–91, doi:http://dx.doi.org/10.1136/adc.2008.141341.
38. Dawson JA, Kamlin COF, Wong C, et al. Changes in heart rate in the first minutes after birth. Arch Dis Child Fetal Neonatal Ed 2010;95:F177–81, doi:http://dx.doi.org/10.1136/adc.2009.169102.
39. Di Fiore JM. Neonatal cardiorespiratory monitoring techniques. Semin Neonatol 2004;9:195–203, doi:http://dx.doi.org/10.1016/j.siny.2003.11.009.
40. Hutchon DJR. Technological developments in neonatal care at birth. J Nurs Care 2013;03:1–3, doi:http://dx.doi.org/10.4172/2167-1168.1000218.
41. Richig JW, Sleeper MM, Richig JW, Sleeper MM. Principles of electrocardiography. Electrocardiogr Lab Anim 2014;9–17, doi:http://dx.doi.org/10.1016/B978-0-12-415936-5.00002-5.
42. Murphy MC, De Angelis L, Mccarthy LK, Patrick C, O'donnell F, Finbarr O'donnell P. Randomised study comparing heart rate measurement in newly born infants using a monitor incorporating electrocardiogram and pulse oximeter versus pulse oximeter alone. Arch Dis Child Fetal Neonatal Ed 2018;1–4, doi:http://dx.doi.org/10.1136/archdischild-2017-314366.
43. Murphy MC, De Angelis L, McCarthy LK, O'Donnell CPF. Comparison of infant heart rate assessment by auscultation, ECG and oximetry in the delivery room. Arch Dis Child Fetal Neonatal Ed 2018;103:F490–2, doi:http://dx.doi.org/10.1136/archdischild-2017-314367.
44. Katheria A, Arnell K, Brown M, et al. A pilot randomized controlled trial of EKG for neonatal resuscitation. PLOS ONE 2017;12:e0187730, doi:http://dx.doi.org/10.1371/journal.pone.0187730.
45. Mizumoto H, Tomotaki S, Shibata H, et al. Electrocardiogram shows reliable heart rates much earlier than pulse oximetry during neonatal resuscitation. Pediatr Int 2012;54:205–7, doi:http://dx.doi.org/10.1111/j.1442-200X.2011.03506.x.
46. Katheria A, Rich W, Finer N. Electrocardiogram provides a continuous heart rate faster than oximetry during neonatal resuscitation. , doi:http://dx.doi.org/10.1542/peds.2012-0784.
47. Iglesias B, Rodrí Guez J, Aleo E, et al. 3-lead electrocardiogram is more reliable than pulse oximetry to detect bradycardia during stabilisation at birth of very preterm infants. Arch Dis Child Fetal Neonatal Ed 2017;1–5, doi:http://dx.doi.org/10.1136/archdischild-2016-311492.
48. Yam CH, Dawson JA, Schmölzer GM, Morley CJ, Davis PG. Heart rate changes during resuscitation of newly born infants. Arch Dis Child–Fetal Neonatal Ed 2011;96:F102–7, doi:http://dx.doi.org/10.1136/ADC.2009.180950.
49. Chen W, Bouwstra S, Oetomo SB, Feijs L. Intelligent design for neonatal monitoring with wearable sensors. In: Somerset VS, editor. Intelligent and biosensors. Vukovar: Intech; 2010. p. 1–24.
50. Linde JE, Schulz J, Perlman JM, et al. Normal newborn heart rate in the first five minutes of life assessed by dry-electrode electrocardiography. Neonatology 2016;110:231–7, doi:http://dx.doi.org/10.1159/000445930.
51. Hodgson KA, Kamlin COF, Rogerson S, Thio M. ECG monitoring in the delivery room is not reliable for all patients. Arch Dis Child Fetal Neonatal Ed 2018;103:F88, doi:http://dx.doi.org/10.1136/archdischild-2017-313928.
52. Chong SW, Peyton PJ. A meta-analysis of the accuracy and precision of the ultrasonic cardiac output monitor (USCOM). Anaesthesia 2012;67:1266–71, doi:http://dx.doi.org/10.1111/j.1365-2044.2012.07311.x.
53. Lemke RP, Farrah M, Byrne P. Use of a new doppler umbilical cord clamp to measure heart rate in newborn infants in the delivery room. EJ Neonatol Res 2011;1:83–8.
54. Dyson A, Jeffrey M, Kluckow M. Measurement of neonatal heart rate using handheld Doppler ultrasound. Arch Dis Child Fetal Neonatal Ed 2017;102:F116–9, doi:http://dx.doi.org/10.1136/archdischild-2016-310669.
55. Goenka S, Khan M, Koppel RI, Heiman HS. Precordial doppler ultrasound achieves earlier and more accurate newborn heart rates in the delivery room. Am Acad Pediatr Natl Conf Exhib 2013.
56. Moraes JL, Rocha MX, Vasconcelos GG, Vasconcelos Filho JE, de Albuquerque VHC, Alexandria AR. Advances in photopletysmography signal analysis for biomedical applications. Sensors (Basel) 201818:, doi:http://dx.doi.org/10.3390/s18061894.
57. Johansson A, Oberg PA, Sedin G. Monitoring of heart and respiratory rates in newborn infants using a new photoplethysmographic technique. J Clin Monit Comput 1999;15:461–7.
58. Olsson E, Ugnell H, Oberg PA, Sedin G. Photoplethysmography for simultaneous recording of heart and respiratory rates in newborn infants. Acta Paediatr 2000;89:853–61.
59. Grubb M, Carpenter J, Crowe JA, et al. Forehead reflectance photoplethysmography to monitor heart rate: preliminary results from neonatal patients. Physiol Meas 2014;35:881–93, doi:http://dx.doi.org/10.1088/0967-3334/35/5/881.
60. Lin Y-C, Wei K-C. An electronic smart watch monitors heart rate of an extremely preterm baby. Pediatr Neonatol 2018;59:214–5, doi:http://dx.doi.org/10.1016/j.pedneo.2017.07.010.
61. Afsar FS. Skin care for preterm and term neonates. Clin Exp Dermatol 2009;34:855–8, doi:http://dx.doi.org/10.1111/j.1365-2230.2009.03424.x.
62. Aarts LAM, Jeanne V, Cleary JP, et al. Non-contact heart rate monitoring utilizing camera photoplethysmography in the neonatal intensive care unit — a pilot study. Early Hum Dev 2013;89:943–8, doi:http://dx.doi.org/10.1016/j.earlhumdev.2013.09.016.
63. Chaichulee S, Villarroel M, Jorge J, et al. Localised photoplethysmography imaging for heart rate estimation of pre-term infants in the clinic. In: Coté GL, editor. Optical diagnostics and sensing XVIII: toward point-of-care diagnostics, vol. 10501. SPIE; 2018. p. 26, doi:http://dx.doi.org/10.1117/12.2289759.
64. Stickney RE, Jayne CP, Lank P, et al. Apparatus, software, and methods for cardiac pulse detection using a piezoelectric sensor [patent]. 2004.
65. Wang F, Tanaka M, Chonan S. Development of a PVDF piezopolymer sensor for unconstrained in-sleep cardiorespiratory monitoring. J Intell Mater Syst Struct 2003;14:185–90, doi:http://dx.doi.org/10.1177/1045389X03014003006.
66. Wang F, Zou Y, Tanaka M, Matsuda T, Chonan S. Unconstrained cardiorespiratory monitor for premature infants. Int J Appl Electromagn Mech 2007;25:469–75 IOS Press.
67. Sato S, Ishida-Nakajima W, Ishida A, et al. Assessment of a new piezoelectric transducer sensor for noninvasive cardiorespiratory

monitoring of newborn infants in the NICU. Neonatology 2010;98:179–90, doi:http://dx.doi.org/10.1159/000283994.
68. Nukaya S, Sugie M, Kurihara Y, Hiroyasu T, Watanabe K, Tanaka H. A noninvasive heartbeat, respiration, and body movement monitoring system for neonates. Artif Life Robot 2014;19:414–9, doi:http://dx.doi.org/10.1007/s10015-014-0179-4.
69. Kato T, Ueno A, Kataoka S, Hoshino H, Ishiyama Y. An application of capacitive electrode for detecting electrocardiogram of neonates and infants. 2006 International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE. p. 916–9, doi:http://dx.doi.org/10.1109/IEMBS.2006.260362.
70. Atallah L, Serteyn A, Meftah M, et al. Unobtrusive ECG monitoring in the NICU using a capacitive sensing array. Physiol Meas 2014;35:895–913, doi:http://dx.doi.org/10.1088/0967-3334/35/5/895.