Cardiology in the Young

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Evaluating the diagnostic accuracy of reduced lead paediatric electrocardiograms

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Original Article

Cite this article: Damera MC, Centanni R, Sherman A, Kline J, Follansbee CW, Chang PM, and Malloy-Walton LE (2024). Evaluating the diagnostic accuracy of reduced lead paediatric electrocardiograms. *Cardiology in the Young*, page 1 of 6. doi: 10.1017/S1047951124036023

Received: 5 March 2024
Revised: 15 August 2024
Accepted: 13 October 2024

Keywords:
Electrocardiogram; reduced lead electrocardiogram; electrophysiology; paediatric cardiology; technological advancements

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Abstract

Introduction: Alternate electrocardiogram acquisition with fewer leads lacks systematic evaluation in children. This study aims to determine if electrocardiograms with fewer leads maintain diagnostic accuracy in paediatrics. *Methods:* This is a single-centre review of 200 randomly selected standard 12-lead electrocardiograms from our hospital database (2017–2020) for patients aged 2 weeks to 21 years. An overlay technique generated 8-lead (limb + V1/V6) and 6-lead (limb only) variations of the 12-lead tracings, resulting in a total of 600 electrocardiograms, which were then interpreted by two independent paediatric electrophysiologists. *Results:* In total, 18% (35/200) of the baseline electrocardiograms were abnormal. Intervals were measured in lead II for all electrocardiograms. Comparing 12-lead to 6- and 8-lead electrocardiograms, there was almost perfect agreement for specific rhythm identification (97.5–100%, κ 0.85-1). The 8-lead showed substantial agreement with 12-lead electrocardiograms when identifying specific electrocardiogram patterns (97.5–100%, κ 0.66–1). A similar degree of agreement was not demonstrated with the 6-lead variant. Utilising the 12-lead electrocardiogram as the gold standard, sensitivity and specificity of the 8- and 6-lead electrocardiogram were > 89% for specific rhythm identification. Specificity for specific pattern recognition was > 99% while sensitivity was < 90% for certain variables for both 6- and 8-lead electrocardiogram, likely due to smaller sample size and fewer abnormal electrocardiograms. There was high percent reader agreement (92.5–100%). *Conclusions:* 8-lead electrocardiograms provide comparable diagnostic accuracy to 12-lead electrocardiograms for children. This information holds potential for future technological advancements in electrocardiogram acquisition tailored specifically for paediatrics. Additional studies are required to further refine conventional electrocardiogram acquisition.

Electrocardiograms are a very common test ordered with more than 100 million performed annually in the United States.[1] The technology for obtaining paediatric electrocardiograms has not changed in over 70 years. Normal electrocardiogram standards for infants and children utilise a 12- or 15-lead electrocardiogram, which takes several minutes to obtain and can be very challenging in certain age groups and individuals with various underlying conditions.[2] New technology has been developed in the commercial space, such as Kardia Mobile by AliveCor and Smartwatches, with application in adult rhythm and screening management using alternatively acquired electrocardiogram tracings with fewer electrodes. In paediatrics, the 12-lead recording has remained the only standardised acquisition tool. Reducing the total number of electrodes placed can have significant impact on acquisition time, resource utilisation, and patient tolerance and cooperativity during electrocardiogram acquisition.

Diagnostic criteria in electrocardiogram interpretation are derived from the application of vectorcardiography, which necessitates the use of a sufficient number of leads. Theoretically, there is a point where additional leads provide no added diagnostic value that would impact treatment or patient outcomes. Despite the challenges and delay of obtaining multiple electrode recordings in children, the minimum number of leads required to accurately analyse paediatric electrocardiograms is unknown and no such studies have been performed to specifically address these questions.

Streamlining the efficiency of electrocardiograms can have not only a significant impact on patient experience, but resource utilisation and costs. Additionally, fewer leads will aid in the reduction of electrode placement errors and reduce the incidence of inaccurate diagnoses, which could be especially advantageous in emergencies.[3] This study aims to determine if a reduced electrocardiogram with fewer leads maintains diagnostic accuracy compared to standard 12-lead tracing interpretation in children.

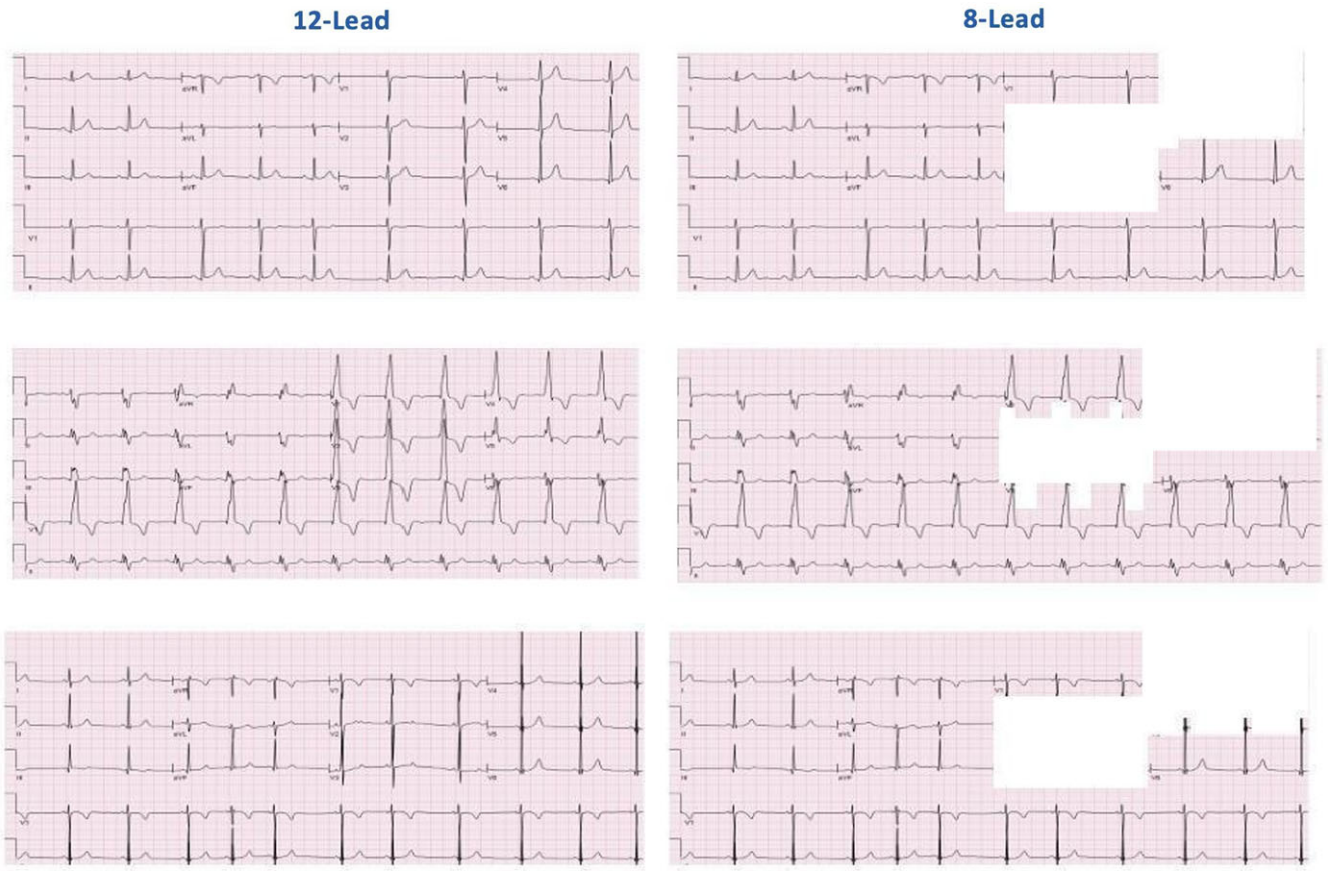

Figure 1. Sample electrocardiograms of 12 lead versus 8 lead (with overlay applied).

Methods

We performed a single-centre retrospective, case–control study involving the review of paediatric electrocardiograms. Approval for the study was obtained from our local Institutional Review Board.

A total of 200 12-lead electrocardiogram tracings with standard electrode placement were selected at random from the hospital electrocardiogram database over the original acquisition date range of January 1, 2017 through December 31, 2020 using an evenly distributed random function through the electronic medical record. Patient age among acquired tracings ranged from 2 weeks to 21 years old. Tracings were obtained using a GE machine at 500 Hz sampling frequency, with standard voltage (10mm = 1 mV) and speed (25mm/s). Tracings with missing leads were excluded. Reduced electrocardiograms were created from the original 12-lead tracings by modifying the displayed leads using an overlay technique in the Muse electrocardiogram interpretation application (General Electric, Milwaukee, WI). In this manner, the original 12-lead electrocardiogram tracing served as a control against which to compare reduced tracings. All tracings were de-identified and assigned unique ID numbers. The de-identified and reduced tracings were then reviewed by two independent paediatric electrophysiologists who provided manual interpretations on each tracing.

Lead selection

Two reduced tracings from each original 12-lead electrocardiogram were generated. The first abbreviated tracing consisted of only the 6 limb leads while a second abbreviated tracing format consisted of 6 limb leads and the V1 and V6 precordial leads (Figure 1). This translated to the theoretical practice of electrocardiogram acquisition with electrodes placed only on the extremities or with the addition of 2 electrodes on the patient's chest. Therefore, the proposed 8-lead electrocardiogram only requires 6 physical electrodes, and the 6-lead electrocardiogram only requires 4 physical electrodes.

Tracing interpretation

All electrocardiogram tracings were read using normative electrocardiogram values for paediatrics.[2] Each electrophysiologist read 100 electrocardiograms from each group (12-lead, 8-lead, 6-lead) which resulted in 300 unique reads as well as 50 randomly selected 12-lead electrocardiogram overreads to assess reader agreement. Measured variables included rhythm identification (including sinus rhythm/bradycardia/tachycardia/arrhythmia, premature atrial/ventricular complexes,), segment measurements (ST), and electrocardiogram patterns (atrial enlargement, frontal axis deviation, bundle branch block, hypertrophy, segment elevation/depression, QRS voltages).

Statistical analysis

Based on institutional historical data, it was expected that approximately 70% of the randomly selected electrocardiograms would yield normal interpretations while 30% would be abnormal.[4] Using these figures, a sample size of 181 subjects was determined to provide 80% power to detect a true kappa value of 0.60 versus a null hypothesis value of 0.40. This is based on a significance level of

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Table 1. Level of agreement of the 8-lead and 6-lead electrocardiograms in rhythm identification

	6 vs. 12 leads					8 vs. 12 leads				
	% agreement	Exact 95% CI	Kappa	95% CI	p-value	% agreement	Exact 95% CI	Kappa	95% CI	p-value
NSR	97.5	94.3–99.2	0.88	0.78–0.98	<0.001	98	95.0–99.5	0.91	0.81–1	<0.001
Sinus Arr.	100	98.2–100	1	1–1	<0.001	100	98.2–100	1	1–1	<0.001
Sinus Brady	97.5	94.3–99.2	0.85	0.72–0.98	<0.001	98	95.0–99.5	0.88	0.77–1	<0.001
PVC	100	98.2–100	1	1–1	<0.001	100	98.2–100	1	1–1	<0.001
PAC	100	98.2–100	1	1–1	<0.001	100	98.2–100	1	1–1	<0.001
Sinus Tac.	100	98.2–100	1	1–1	<0.001	100	98.2–100	1	1–1	<0.001

Slight agreement defined by K<0.2, fair agreement 0.21–0.40, moderate agreement 0.41–0.60, substantial agreement 0.61–0.80 and almost perfect agreement 0.81–1.
NSR = normal sinus rhythm; Sinus arr; = sinus arrhythmia; Sinus brady = sinus bradycardia; PVC = premature ventricular complex; PAC = premature atrial complex; Sinus tac; = sinus tachycardia.

Table 2. Level of agreement of the 8-lead and 6-lead electrocardiograms for pattern recognition

	6 vs. 12 leads					8 vs. 12 leads				
	% agreement	Exact 95% CI	Kappa	95% CI	p-value	% agreement	Exact 95% CI	Kappa	95% CI	p-value
RAE	100	98.2–100	1	1–1	<0.001	99	96.4–99.9	0.49	−0.11–1	<0.001
RVH						98.5	95.7–99.7	0.57	0.13–1	<0.001
LVH						99.5	97.3–100	0.91	0.72–1	<0.001
IVCD	98.5	95.7–99.7	0.56	0.12–1	<0.001	99.5	97.3–100	0.8	0.41–1	<0.001
RBBB						99.5	97.3–100	0.8	0.41–1	<0.001
ST Elevation	98	95.0–99.5	0.33	−0.16–0.81	<0.001	98	95.0–99.5	0.49	0.06–0.92	<0.001
LAD	100	98.2–100	1	1–1	<0.001	100	98.2–100	1	1–1	<0.001
RAD	100	98.2–100	1	1–1	<0.001	100	98.2–100	1	1–1	<0.001
Prominent Q	98.5	95.7–99.7	0.39	−0.15–0.94	<0.001	99	96.4–99.9	0.66	0.22–1	<0.001

RAE = right atrial enlargement; RVH = right ventricular hypertrophy; LVH = left ventricular hypertrophy; IVCD = intraventricular conduction delay; RBBB = right bundle branch block; ST Elevation = ST segment elevation; LAD = left axis deviation; RAD = right axis deviation.

0.05, which was determined to be sufficient to assess diagnostic accuracy. Data were analysed using both percent agreement and sensitivity/specificity. A scale was created to quantify level of agreement. When comparing agreement between the 12-lead and 6- or 8-lead electrocardiograms, we calculated overall agreement (proportion of cases where the pair of leads agreed) and kappa values along with 95% confidence intervals. The scale to quantify level of agreement included slight agreement defined by $K < 0.2$, fair agreement 0.21–0.40, moderate agreement 0.41–0.60, substantial agreement 0.61–0.80 and almost perfect agreement 0.81–1.[5] Using the 12-lead electrocardiogram as the gold standard, sensitivity and specificity were calculated with 95% confidence intervals. SAS version 9.4 (SAS Institute Inc., Cary, NC) was utilised for calculations.

Results

Of the 200 electrocardiogram tracings from patients originally acquired from the institutional database, a total of 600 unique tracings were generated with 200 12-lead, 200 6-lead, and 200 8-lead tracings. There were 5 baseline 12-lead electrocardiograms with an arrhythmia noted (2 with premature atrial beats, and 3 with premature ventricular beats), 11 with interval abnormalities (3 with PR prolongation, 6 with QRS prolongation, and 2 with QTc prolongation), and 26 with abnormal electrocardiogram patterns (2 with right atrial enlargement, 3 with right ventricular hypertrophy, 5 with left ventricular hypertrophy, 5 with prominent mid-precordial voltages, 3 with intraventricular conduction delay, 2 with right bundle branch block, 4 with left axis deviation, and 2 with right axis deviation). In total, 18% (35/200) of the baseline electrocardiograms were abnormal, with some having more than one abnormal finding. There was a high percent agreement (92.5–100%) among the two reading paediatric electrophysiologists when interpreting each measured variable (rhythm identification, and specific electrocardiogram patterns) on the baseline 12-lead electrocardiogram. Regarding rhythm identification, there was almost perfect agreement between the 6-lead versus 12-lead electrocardiogram (97.5–100%, κ 0.85–1) and between the 8-lead versus 12-lead electrocardiogram (98–100%, κ 0.88–1) (Table 1).

The 8-lead compared to the 12-lead electrocardiogram showed substantial agreement (97.5%–100%, κ 0.66–1) when identifying certain electrocardiogram patterns including atrial enlargement, axis deviation, bundle branch block, and left ventricular hypertrophy, with moderate agreement for right ventricular hypertrophy and ST elevation (98–98.5%, κ 0.49–0.57) (Table 2).

Utilising the 12-lead electrocardiogram as the gold standard, the sensitivity of the 8-lead electrocardiogram was 98.3% and specificity was 95.7% when detecting normal sinus rhythm, while

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Table 3. Sensitivity and specificity of the 8-lead and 6-lead electrocardiograms in rhythm identification

	6 vs. 12 leads				8 vs. 12 leads			
	Sensitivity	95% CI	Specificity	95% CI	Sensitivity	95% CI	Specificity	95% CI
NSR	98.3	94.7–99.6	91.3	70.5–98.5	98.3	94.7–99.6	95.7	76.0–99.8
Sinus Arr.	100	87.0–100	100	97.2–100	100	87.0–100	100	97.2–100
Sinus Brady	88.9	63.9–98.1	98.4	94.9–99.6	94.4	70.6–99.7	98.4	94.9–99.6
PVC	100	39.6–100	100	97.6–100	100	39.6–100	100	97.6–100
PAC	100	5.5–100	100	97.6–100	100	5.5–100	100	97.6–100
Sinus Tac.	100	46.3–100	100	97.6–100	100	46.3–100	100	97.6–100

Table 4. Sensitivity and specificity of the 8-lead and 6-lead electrocardiograms in interval measurement and pattern recognition

	6 vs. 12 leads				8 vs. 12 leads			
	Sensitivity	95% CI	Specificity	95% CI	Sensitivity	95% CI	Specificity	95% CI
PR	33.3	1.8–87.5	100	97.6–100	66.7	12.5–98.2	100	97.6–100
QRS	66.7	24.1–94.0	99.5	96.7–100	83.3	36.5–99.1	99.5	96.7–100
QT	100	31.0–100	100	97.6–100	66.7	12.5–98.2	99.5	96.8–100
QTc	100	5.5–100	100	97.6–100	100	0.05–100	100	97.6–100
RAE	100	19.8–100	100	97.6–100	50	2.7–97.3	99.5	96.8–100
RVH	0	0–53.7	100	97.6–100	40	7.3–83.0	100	97.6–100
LVH	0	0–53.7	100	97.6–100	100	46.3–100	99.5	96.7–100
Prominent Mid	0	0–53.7	100	97.6–100	0	0–53.7	100	97.6–100
IVCD	66.7	12.5–98.2	99	96.0–99.8	66.7	12.5–98.2	100	97.6–100
RBBB	0	0–80.2	100	97.6–100	100	19.8–100	99.5	96.8–100
ST elevation	20	1.1–70.1	100	97.6–100	40	7.3–83.0	99.5	96.7–100
LAD	100	39.6–100	100	97.6–100	100	39.6–100	100	97.6–100
RAD	100	19.8–100	100	97.6–100	100	19.8–100	100	97.6–100
Prominent Q	33.3	1.8–87.5	99.5	96.8–100	66.7	12.5–98.2	99.5	96.8–100

the sensitivity of the 6-lead electrocardiogram was 98.3% and the specificity was 91.3% (Table 3). The sensitivity and specificity of the 8-lead electrocardiogram to identify other rhythms, including PVCs and PACs, was > 94.4% and > 98.4%, respectively while the 6-lead's sensitivity and specificity were > 88.9% and > 98.4%, respectively (Table 3).

The specificity for pattern recognition and interval measurement was > 99% for both 6 and 8-lead electrocardiograms, while the sensitivity varied and was well below 90% for certain variables, such as PR interval, ST elevation, and prominent Q waves, for both 6 and 8-lead electrocardiograms (Table 4).

Discussion

Congenital and paediatric heart conditions are present in over 1% of the population in the United States and include both structural heart disease and arrhythmias.[6–7] The standard 12-lead electrocardiogram has been a longstanding tool for noninvasive cardiac rhythm assessment and screening for structural or functional cardiac abnormalities; however, new readily available handheld and wearable devices allow for rhythm screening and abnormality detection. Despite widespread use in adults, their accuracy in paediatrics lacks comprehensive evaluation.[8–10] The 12-lead recording remains the only standardised acquisition tool across a diverse paediatric population including infants, school-aged, and adolescent patients with varying body sizes, levels of development, and cooperation levels.[11–13] Furthermore, there has not been a study performed in paediatrics to assess the minimum number of leads required in electrocardiogram acquisition that does not compromise diagnostic accuracy.

Prior to validating the diagnostic usefulness of novel commercially available devices that employ alternative electrode placement, it is essential to evaluate the diagnostic accuracy of electrocardiogram tracings utilising fewer than the standard 12 leads in the paediatric population. If the diagnostic accuracy with anything less than 12 leads is significantly compromised in paediatrics, this would undermine the diagnostic accuracy of any novel electrocardiogram acquisition device also in the paediatric population. Reduced electrocardiograms were primarily based on simplification of the current conventional process of lead

https://doi.org/10.1017/S1047951124036023 Published online by Cambridge University Press

placement, theoretically needing 4 or 6 electrodes compared to the usual 10 that are placed with a 12-lead electrocardiogram.[14] The novel findings of our study indicate that (1) an 8-lead electrocardiogram composed of limb leads + V1/V6 appears to provide comparable accuracy in children, and (2) an electrocardiogram with limb leads alone is insufficient for children, potentially excluding significant electrocardiogram patterns.

The reduced 8-lead tracing simplifies electrocardiogram acquisition primarily through eliminating most of the precordial leads. In children, the precordial leads are a frequent area of incorrect electrode placement. These electrodes can also be the hardest to place and maintain in very small patients with limited chest surface area and patients who are uncooperative during tracing acquisition. In contrast, although most precordial leads were not deemed essential for diagnostic accuracy the absence of precordial leads in the 6-lead abbreviated tracing hindered the identification of more common patterns including ventricular hypertrophy, where precordial amplitudes are typically relied on for determination, and more specific designations of right or left bundle branch block in situations where nonspecific conduction delay was present on limb lead assessment. This was also a limitation of the 8-lead electrocardiogram for rare specific mid-precordial dependent diagnosis.

Overall, our data suggest that the standard 12-lead electrocardiogram model could potentially be reduced to an 8-lead version (only requiring 6 electrode sites on the patient's body) in the clinical setting without adversely impacting diagnostic accuracy. Reducing the total number of electrodes placed can have significant impact on acquisition time, resource utilisation, patient tolerance, and cooperativity during electrocardiogram acquisition.[15–16] The simplification of electrode placement demonstrated in this study serves as a foundation for developing innovative, paediatric-specific electrocardiogram technology, streamlining acquisition without compromising interpretive integrity and allowing for the use of standard electrocardiograms if needed.

Alternative electrocardiogram acquisition methods, such as a reduced lead electrocardiogram, can serve as an effective screening tool for patients without known arrhythmias or CHD, as these were listed as exclusion criteria of the study. As discussed, this method offers a quicker and less invasive option for initial rhythm screening, making it particularly useful in settings where efficiency and patient comfort are priorities. It is crucial, however, for physicians to remain empowered to pursue a standard 12-lead electrocardiogram if abnormalities are detected during the initial screening. The 12 and 15-lead electrocardiograms remain the gold standard for comprehensive cardiac evaluation, providing detailed insights that alternative methods may not capture. These standard models are capable of providing a more comprehensive evaluation to identify critical conditions such as specific cardiomyopathies and arrhythmia syndromes which might be missed with an 8-lead electrocardiogram given the lack of mid-precordial leads. The data presented demonstrates high sensitivity and specificity for the 8-lead as compared to the 12-lead electrocardiogram in evaluating QTc interval and patterns such as left ventricular hypertrophy, underscoring its use as a screening tool for initial assessment. While alternative electrocardiogram methods can streamline the screening process and reduce patient burden, they should complement rather than replace the 12-lead electrocardiogram, ensuring that any detected abnormalities can be thoroughly investigated with the most accurate and detailed diagnostic tool available.

While the 8-lead reduced electrocardiogram retains all limb leads and V1/V6, there is potential for additional abbreviation. Future studies can be directed to further condense conventional electrocardiogram acquisition. In this study, the augmented limb leads were already incorporated into the acquisition process using standard limb lead placement, but their necessity for diagnostic interpretation can be further investigated to identify which ones could be omitted without compromising screening accuracy. It is worth assessing in a more rigorous manner the possibility of reducing the number of limb leads, while carefully evaluating the impact on specific diagnostic criteria.

Limitations

The limitation of this study stems from its single-centre retrospective design and small sample size. In general, the specificity was adequately high (> 75% for most variables); however, the sensitivity varied and was low for certain analysed variables. Given the relatively small sample size, there was underrepresentation of certain arrhythmia conditions, which limited the ability to fully assess diagnostic accuracy in true arrhythmia states. The study did not assess certain rare conditions, such as Brugada syndrome or arrhythmogenic cardiomyopathy, where precordial leads may be crucial for diagnosis. Therefore, it is unclear whether alternate electrocardiogram acquisition methods maintain diagnostic accuracy for these specific rare disorders. This design bias limits the study to identifying abnormalities that do not require mid-precordial lead assessment. To determine the equivalence of the 8-lead electrocardiogram, a statistically adequate subset of electrocardiograms where mid-precordial lead information is crucial would be necessary; however, this may be challenging. As most tracings were normal, there were fewer tracings from the randomly selected sample to be able to assess the diagnostic accuracy of the reduced tracings for potential structural abnormalities. There was a limited representation of the true population and a higher chance of random variation.

While the study demonstrated interpretive consistency among the two reading physicians, it was not designed to evaluate interpretive accuracy and consistency among general cardiologists and non-cardiology-trained professionals. Finally, it should be noted that although the reduced electrocardiograms were compared to the original 12-lead tracings, there was no confirmation of the diagnostic accuracy of abnormal electrocardiogram tracings through imaging studies.

Conclusion

The data suggest that a reduced 8-lead electrocardiogram demonstrated nearly perfect agreement for specific rhythm identification and substantial agreement for specific electrocardiogram pattern recognition when compared to a 12-lead electrocardiogram. These findings serve as a foundation for the development of novel technology for paediatric electrocardiogram acquisition. Although this acquisition approach shows promise, it is not an immediate replacement of the existing 12-lead standard of care. The 8-lead electrocardiogram may not maintain diagnostic accuracy for mid-precordial dependent diagnoses. Additionally, the reduced lead model is not intended for those with known arrhythmias or congenital heart disease, as it may exclude important components of a comprehensive assessment. Future research should also consider the clinical efficacy and reliability of

https://doi.org/10.1017/S1047951124036023 Published online by Cambridge University Press

the reduced lead model in various patient populations and the economic impact of alternative electrocardiogram acquisition methods.

Competing interests. None.

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