Indian Pacing and Electrophysiology Journal 22 (2022) 131–136

Contents lists available at ScienceDirect

Indian Pacing and Electrophysiology Journal

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

Use of the Apple Watch iECG in adult congenital heart disease patients

Stephan Striepe [a, *], Anna Michaelis [a], Franziska Markel [a], Philipp Kalden [a], Florian Löffelbein [a], Andreas Bollmann [b], Alireza Sepehri Shamloo [b], Ingo Dähnert [a], Roman Antonin Gebauer [a], Christian Paech [a]

[a] Department for Pediatric Cardiology, University of Leipzig - Heart Center, Strümpellstr. 39, 04289, Leipzig, Germany
[b] Department of Electrophysiology, University of Leipzig - Heart Center, Leipzig Heart Institut, Strümpellstr. 39, 04289, Leipzig, Germany

A R T I C L E I N F O

Article history:
Received 27 October 2021
Received in revised form
19 January 2022
Accepted 27 January 2022
Available online 1 February 2022

Keywords:
Apple watch
iECG
ECG
Pediatric cardiology
Telemedicine

A B S T R A C T

Introduction: This study evaluates the accuracy of iECGs in comparison to the gold standard ECG in adult patients with congenital heart disease and recommends the appropriate iECG derivation based on the patient's characteristics.
Methods: In 106 adults (51 female, 55 male) with congenital heart disease, a gold standard 12-lead ECG was recorded, followed by three iECGs with the Apple Watch series 4, which correspond to Einthoven leads I, II, and III. Two experienced and independent cardiologists analyzed the time intervals, amplitudes, and polarities of the ECG parameters as well as the rhythm type and correlated the patient characteristics with the iECG parameters.
Results: The iECG parameters of all three iECG leads correlate strongly with those of the gold standard ECG, with exception of the P and T wave durations. We demonstrated that the informative value of the individual iECGs was independent of the patient's characteristics, in particular the heart axis, anatomy, and situs, even if the quality of the Einthoven III-like derivation was partially inadequate. The automatic rhythm analysis of the Apple Watch and the heart rhythm classification of a standard ECG analyzed manually by a cardiologist corresponded in 77%.
Conclusion: iECG recordings of adults with congenital heart disease provide comparable results with Einthoven recordings I, II, and III of the 12-lead ECG and current data encourage the use of the Apple Watch not only in patients with structurally normal hearts but also in patients with congenital heart disease.
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1. Introduction

Adult patients with congenital heart disease are at increased risk for atrial and ventricular arrhythmias [1] due to intense scarring after cardiac surgery that results in macro-reentry tachycardia [2]. In addition, there is often an early connective tissue disease due to stretching or chronic pressure or volume load in the presence of residual lesions [2]. The presence of arrhythmias has been reported with increased morbidity and mortality in congenital heart disease patients [3,4].

Current guidelines recommend regular cardiac follow-up for these patients [5] including: an assessment of the patient's hemodynamic status, an electrocardiogram (ECG), and a regular 24-h Holter ECG [6]. Since these patients are particularly susceptible to the development of supraventricular arrhythmias and also suffer from significant morbidity in their presence, early detection and treatment of these arrhythmias seem to be of particular importance [7].

The Apple Watch offers a single-channel iECG function in adults with structurally normal hearts [8–10]. With the increasing spread

* Corresponding authorDepartment for Pediatric Cardiology, University of Leipzig - Heart Center, Strümpellstr. 39, 04289, Leipzig, Germany.;
E-mail addresses: Striepe7@web.de, Stephan.Striepe@helios-gesundheit.de (S. Striepe), Anna.Michaelis@helios-gesundheit.de (A. Michaelis), Franziska.Wagner@helios-gesundheit.de (F. Markel), Philipp.Kalden@helios-gesundheit.de (P. Kalden), Florian.Loeffelbein@helios-gesundheit.de (F. Löffelbein), Andreas.Bollmann@helios-gesundheit.de (A. Bollmann), Alireza.Sepehri-Shamloo@helios-gesundheit.de (A. Sepehri Shamloo), Ingo.Daehnert@helios-gesundheit.de (I. Dähnert), Roman.Gebauer@helios-gesundheit.de (R.A. Gebauer), Christian.Paech@med.uni-leipzig.de (C. Paech).
Peer review under responsibility of Indian Heart Rhythm Society.

https://doi.org/10.1016/j.ipej.2022.01.007
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of smartwatches such as the Apple Watch [12], recording an Apple Watch ECG (iECG) in the event of suspected arrhythmia or palpitations can help to provide the doctor with information; the patient avoids hospital contact and the treatment can be promptly adjusted.

While the Apple Watch iECG has FDA approval (Food and Drug Administration) for healthy adults [8–10], there is no data on its use in patients with congenital heart disease although there are case reports of cardiac patients who have used their Apple Watches as an out-of-hospital monitoring facility for cardiac events [5,11]. Adult patients with congenital heart disease represent a very heterogeneous patient population in terms of cardiac anatomy (including single ventricle hearts, right or left heart predominance, and various degrees of cardiac axis or thoracic situs anomalies) and the standard recording of an iECG, which is similar to an Einthoven lead I recording, may not present the optimal recording lead in some of these patients. In addition, bundle branch block is also commonly seen in these patients and aggravates the ECG analysis [13,14].

This study aimed to evaluate if the Apple Watch iECG is interpretable in this patient group and to identify the optimal recording position with regard to the individual patient's anatomy. A high-quality iECG would enable adult patients with congenital heart disease to use such a smartwatch as an event recorder.

2. Methods

This prospective, single-armed study included 106 adult patients with congenital heart disease, who had presented themselves to the outpatient clinic of the Leipzig Heart Center Department for Congenital Heart Defects for their routine examination, were eligible to participate and had to give their informed consent. Patients' privacy was fully respected throughout the study and their data were treated and analyzed in anonymized coded form. The ethics committee of the University of Leipzig fully approved the research project. Patients with mental or motor impairments that would limit their cooperation in the ECG recording were excluded from the study.

The patient characteristics including age, gender, body mass index, medical history, and medication were recorded. Medical staff took a conventional 12-lead ECG of at least 8 s with the GE MAC 5500 HD device (recording speed of 50 mm/s, low-pass filtering of 0.32 Hz, and high-pass filtering of 150 Hz) and immediately afterward three iECGs with the Apple Watch 4.1 (WatchOS 5.2.1).

Starting with the Einthoven I-like iECG measurement, the Apple Watch was placed on the patient's left wrist and the index finger of the patient's right hand was placed on the button of the Apple Watch for 30 s, as described in Ref. [10] and shown in Fig. 1. For the Einthoven II-like iECG measurement, the patient placed the smartwatch on the lower left quadrant of the abdomen and again touched the Apple Watch button with the right index finger for 30 s; for the Einthoven III-like recordings the patient placed the smartwatch in the lower left abdomen area again and this time placed the left index finger on the button of the Apple Watch for 30 s, as shown in Fig. 1. All iECGs were saved as PDF files and printed on A4 size paper for analysis with a recording speed of 25 mm/s.

In all three iECGs and the Einthoven leads I, II, and III of the 12-lead, two cardiologists from the Department of Pediatric Cardiology, who are trained in the analysis and interpretation of ECGs of congenital heart diseases, classified the heart rhythm and analyzed the specific parameters of an ECG as shown in Fig. 2.

While the heart rhythm analysis of the iECG was based merely on the one lead position the strip was recorded, the classification of heart rhythm from 12-lead ECG was based on all 12 leads. The heart rates were measured manually in the 12-channel ECG and the three iECG printouts by averaging the cycle length of 5 RR intervals. This manual determination of the heart rate was chosen for all patients including three patients who presented with atrial fibrillation. ECG and iECG recordings were presented to the investigators in a randomized order. The aim was to analyze the amplitude and polarity of the P wave, the QRS complex and the T wave as well as the individual times of the P wave, PR interval, QRS complex, QT interval, and the T wave.

These measurements were made blind from the patient's data. After the ECG interpretation, demographic data and the medical history were evaluated.

Statistics: The statistical analysis was carried out with R 4.0.3 including the BlandAltmanLeh 0.3.1 package, IBM SPSS Statistics (Version 27 für Mac, IBM Corporation, Somers, NY, USA). Mean, standard deviation, and range were calculated for continuous variables. The individual times, amplitudes, and polarities of the three iECGs were compared with the respective Einthoven I, II, and III leads of the 12-lead ECG and analyzed using Bland-Altman analysis, two-sided paired t-tests, and Pearson's r (with 95% confidence interval using Pearson's product-moment relationship). *P*-values of <0.05 were considered significant in two-tailed significance tests. Pearson correlation coefficients between 0.4 and 0.69 were classified as “moderate”, between 0.7 and 0.89 as “strong” and between 0.9 and 1 as “very strong correlation” (see Table 1).

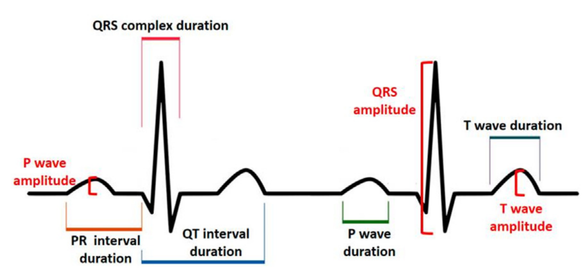


Fig. 2. Principles of electrocardiogram assessment [15].

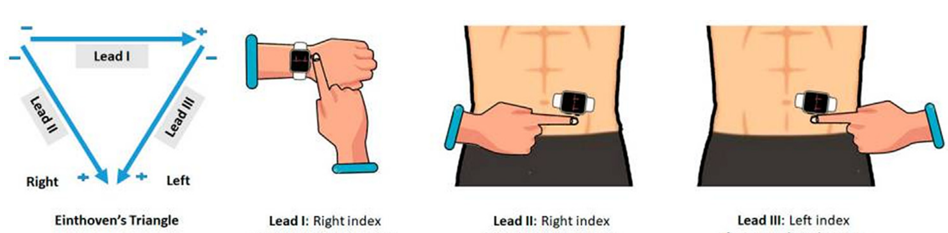


Fig. 1. The positioning of the Apple Watch Series 4 for obtaining leads I, II, and III using the Einthoven triangle. In the Apple Watch, the negative electrode is placed in the digital crown and the positive electrode is on the back crystal of the watch [15].

Table 1
Patient characteristics: Absolute number of patients (valid, missing), mean, standard deviation (SD), minimum, maximum based on age, height in meter, weight in kilograms and BMI.

	Age	Height in m	Weight in kg	BMI
Mean	34	1,72	74,32	25,2
SD	13,22	0,10	17,06	5,00
Minimum	18	1,51	43,8	14,9
Maximum	75	2,04	133,0	39,3

3. Results

Patient Characteristics: 106 adults aged 18–75 years were included. Of these, 51 were female and 55 were male. Their features are listed in Tables 2 and 3.

Table 4 shows the analysis of the 12-lead-ECGs and iECGs.

It is noticeable that the iECG lead, corresponding to the Einthoven III lead, could not be evaluated in 12 cases. For comparison: In the two iECG leads, which are similar to Einthoven leads I and II, there were only 2 recordings each that could not be analyzed. As a result, the number of pairs of the respective ECG parameters is overall smaller for lead III, while those for leads I and II are approximately the same. If one considers the individual correlations of leads I and II, they show comparably similar values except for T1 amplitude.

Multiple regressions could not reveal any causalities between patient characteristics (such as age, gender, BMI, type of heart position, heart anatomy, etc.) and ECG parameters of the individual leads (such as intervals, amplitudes, polarities). Thus, the ECG parameters seem to be independent of the patient's characteristics, especially anatomy, electrical axis, or situs. In addition, there was basically no relevant interobserver variability in the sense of measurement deviations > 5–7 ms in duration measurements or 0.2–0.3 mV in amplitude measurements.

Interpretability and classification of heart rhythm: All 106 12-lead ECGs and 105 iECGs were of sufficient quality for assessment. Due to rapid change between sinus and ventricular escape rhythm, one iECG could not be classified.

Graphic 1 and Graphic 2 show the distribution of the rhythm types within the group of manually measured 12-channel ECGs and automatically diagnosed iECGs.

Comparing the classification of the heart rhythm between manually defined heart rhythm in 12-lead ECGs and previously diagnosed heart rhythm in iECGs, the same rhythm was diagnosed in 82 of 106 (77,4%) pairs, when analyzed by a cardiologist.

The match and mismatch are shown in Table 5.

However, the weakness of the frequency analysis of the Apple Watch must be addressed here. Because the Apple Watch cannot recognize an escape rhythm, pacemaker rhythm or VT due to a lack of algorithms. The smartwatch can only display sinus rhythm, atrial fibrillation or inconclusive. Therefore, seven pacemaker rhythms were automatically diagnosed as sinus rhythms. In addition, nine sinus rhythms were recognized as unclassifiable. To mention is also that one sinus rhythm was defined as atrial fibrillation.

Table 2
Patient characteristics: Absolute numbers and percentage division of gender, type of operation, situs, devices and anatomy.

	n (%)		n (%)
Gender		**Devices**	
Female	51 (48,1)	None	91 (85,8)
Male	55 (51,9)	Pacemaker	11 (10,4)
Type of operation		ICD	4 (3,8)
Surgical correction	87 (82,1)	**Anatomy**	
Surgical palliation	19 (17,9)	Biventricular	96 (90,6)
Situs		Single left	7 (6,6)
Levocardy	103 (97,2)	Single right	3 (2,8)
Mesocardy	2 (1,9)		
Dextrocardy	1 (0,9)		

Table 3
Patient characteristics: Absolute numbers and percentage division of congenital heart disease.

	n (%)
Tetralogy of Fallout	24 (22,6)
dextro-Transposition der großen Arterien (d-TGA)	5 (4,7)
levo-Transposition of the Great Arteries (l-TGA)	4 (3,8)
Truncus arteriosus communis (TAC)	2 (1,9)
Univentricular heart	10 (9,4)
Aortic stenosis	18 (17,0)
Atrial septal defect	8 (7,5)
Ventricular septal defect	13 (12,3)
Structural normal heart	22 (20,8)

4. Discussion

This study aimed to evaluate the accuracy of Apple Watch-generated iECGs in different positions in adult congenital heart disease patients compared to conventional ECGs and evaluate possibly influencing factors like anatomy, electrical axis, or situs anomalies. This study demonstrated that the quality of the iECG recordings of adults with congenital heart disease resembles that of the 12-lead ECG without showing any influence on patient characteristics.

The similarity of the iECGs with the Einthoven I, II, and III leads was shown in studies by Samol et al. This research group compared the similarity of iECGs from an Apple Watch Series 4 from 50 healthy probands with the same Einthoven leads from a gold standard recorded ECG [13]. Further studies with a larger pool of test persons followed and were able to show that the iECGs recorded with an Apple Watch Series 4 were very similar to those of conventional Einthoven recordings [14].

In contrast to the studies by Samol et al. our study was the first to quantitatively and qualitatively assess the similarity of the Einthoven leads I, II, and III recorded by the Apple Watch with those of the conventional ECG in patients with congenital heart disease and showed a strong correlation for all three leads.

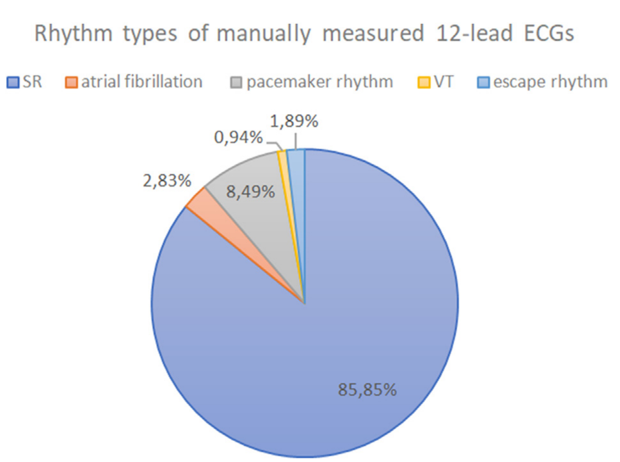
Neither heart rate, ECG timing intervals nor amplitudes differed significantly between the 12-lead ECGs and the iECGs. This is shown by strong correlations between heart rate, PR interval, QRS duration, QRS amplitude as well as QT interval and T wave amplitude. The weakest correlations were seen in the P and T waves. One explanation could be the recording speed of the iECG of 25 mm/s and ECG filter settings that are unknown to the doctors as these are a company secret of Apple. The faster recording speed hampers the assessment of small and shallow deflections such as the P wave. This observation in particular of the *P*-wave has also been reported from other studies with other wireless devices [16–18].

It was also noticeable that the Einthoven III-like iECG could not be evaluated in 12 cases. The reason for this was simple, as several patients were not able to physically perform the measure due to obesity and abdominal circumference.

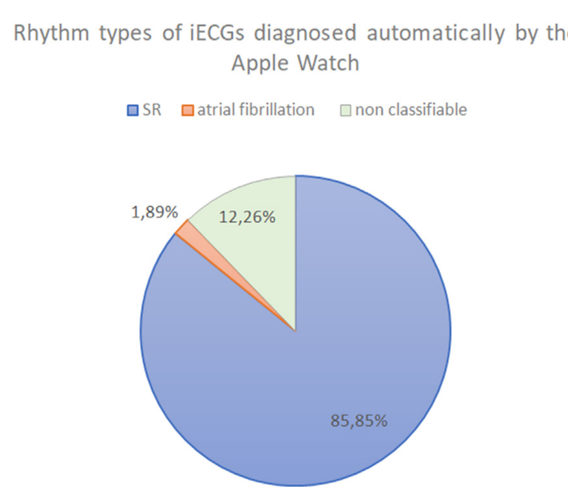
In contrast, position 1 of the iECG recordings (standard positioning as advised by the manufacturer) and Einthoven II-like iECG showed overall good quality and interpretability and they were independent of influencing factors. This is of particular importance as one of the main topics of this study was to evaluate the most suitable positioning of the Apple Watch in adult congenital heart disease patients.

Table 4
Timing intervals and amplitudes: Table 4 shows the comparison of heart rate, timing intervals and amplitudes in 12 ECG and iECG. SD = standard deviation; green = lead I; yellow = lead II; red = lead III..

	Pairs [N]	12 ECG Mean ± SD	Apple ECG Mean ± SD	Pearson's r [95 CI]	P-Value
Heart rate given (bpm)	104	72,00 ± 15,25	77,74 ± 14,72	0,84	<0.01
Heart rate computed (bpm)	106	71,85 ± 14,93	77,49 ± 15,13	0,80	<0.01
P1 wave duration (ms)	95	89,80 ± 17,20	109,59 ± 19,10	0,20	<0.05
P2 wave duration (ms)	96	97,10 ± 17,99	108,14 ± 18,50	0,24	<0.02
P3 wave duration (ms)	82	93,54 ± 19,66	112,41 ± 19,91	0,39	<0.01
PR1 interval (ms)	94	166,22 ± 33,78	170,62 ± 29,33	0,63	<0.01
PR 2 interval (ms)	95	168,28 ± 36,62	168,54 ± 29,09	0,64	<0.01
PR 3 interval (ms)	81	166,94 ± 37,32	175,24 ± 36,35	0,82	<0.01
QRS 1 duration (ms)	105	113,58 ± 33,16	118,95 ± 31,25	0,80	<0.01
QRS 2 duration (ms)	104	118,87 ± 33,16	122,40 ± 32,07	0,80	<0.01
QRS 3 duration (ms)	93	116,79 ± 29,91	120,11 ± 28,69	0,78	<0.01
QT 1 interval (ms)	101	377,48 ± 49,14	377,77 ± 49,49	0,81	<0.01
QT 2 interval (ms)	102	387,98 ± 42,25	382,52 ± 45,26	0,72	<0.01
QT 3 interval (ms)	93	387,31 ± 42,89	375,70 ± 45,74	0,74	<0.01
T 1 wave duration (ms)	101	140,00 ± 26,08	149,32 ± 18,80	0,28	<0.01
T 2 wave duration (ms)	102	151,44 ± 24,75	153,11 ± 19,95	0,37	<0.01
T 3 wave duration (ms)	91	146,06 ± 28,57	146,24 ± 22,11	0,37	<0.01
P 1 amplitude (mV)	95	0,08 ± 0,04	0,08 ± 0,04	0,56	<0.01
P 2 amplitude (mV)	96	0,15± 0,08	0,13 ± 0,06	0,59	<0.01
P 3 amplitude (mV)	82	0,09 ± 0,13	0,08 ± 0,12	0,89	<0.01
QRS 1 amplitude (mV)	100	0,37 ± 0,69	0,45 ± 0,74	0,96	<0.01
QRS 2 amplitude (mV)	89	0,66 ± 1,19	0,82 ± 0,84	0,84	<0.01
QRS 3 amplitude (mV)	82	0,26 ± 1,28	0,36 ± 0,78	0,86	<0.01
T 1 amplitude (mV)	101	0,11± 0,16	0,13 ± 0,16	0,90	<0.01
T 2 amplitude (mV)	102	0,32 ± 0,24	0,27 ± 0,23	0,63	<0.01
T 3 amplitude (mV)	91	0,22± 0,28	0,12 ± 0,25	0,80	<0,01



Graphic 1. Percentage distribution of rhythm types of manually measured 12-lead ECGs
(SR = sinus rhythm; VT = ventricular tachycardia).



Graphic 2. Percentage distribution of rhythm types of iECGs diagnosed automatically by the Apple Watch
(SR = sinus rhythm).

Table 5
Match and mismatch between the automatically diagnosed rhythm type of iECGs and the manually measured 12-lead ECG “gold standard”. The matches are marked with red circles..

iECG / *12 lead ECG*	*SR*	*atrial fibrillation*	*not classifiable*	*Total*
SR	81	1	9	91
escape rhythm	2	0	0	2
pacemaker rhythm	7	0	2	9
VT	0	0	1	1
atrial fibrillation	1	1	1	3
Total	91	2	13	106

In this study, 77,36% of the iECG rhythms automatically analyzed by the Apple Watch could be correctly assessed compared to the heart rhythm classified by a cardiologist from the corresponding 12-lead ECG.

As seen in an earlier study by our group, the automatic iECG diagnosis by the Apple Watch algorithm is limited to the detection of sinus rhythm and atrial fibrillation [15]. Currently, the Apple Watch software is unable to diagnose pacemaker or ectopic rhythms due to the lack of a suitable algorithm. Therefore, the use of rhythm analysis should be restricted to patients with spontaneous rhythm. Apart from the automatic heart rhythm analysis, it has to be said that only unipolar stimulation artifacts are visible in the iECG. Artifacts of bipolar cardiac stimulation cannot safely be identified even by an experienced cardiologist.

It should also be mentioned that only 3 patients with atrial fibrillation could be included in the patient cohort. Further studies are therefore necessary to investigate the question of whether atrial fibrillation can be reliably detected by an Apple Watch in patients with congenital heart disease.

With the spread of smartwatches, an easily accessible source of information on heart health became available. We consider the smartwatch valuable as an additional diagnostic instrument for adult patients with congenital heart disease, to document symptomatic arrhythmias by the patient himself. The data can be transmitted to the attending physician via cell phone for quick medical advice. Adult congenital heart disease patients should perform a recording either in the standard position as advised by the manufacturer or position II as shown above.

In summary, it can be said that the Apple Watch can record reliable iECGs not only in adults with structurally normal hearts but also in those with congenital heart disease of any type.

Recognizably, the iECGs cannot replace a gold standard ECG and therefore patients must be encouraged to attend their follow-up intervals with their cardiologist.

5. Conclusion

Apple Watch iECG recordings of adults with congenital heart disease provide comparable results with Einthoven recordings I, II, and III of the 12-lead ECG and current data encourage the use of the Apple Watch not only in patients with structurally normal hearts but also in patients with congenital heart disease.

Limitations

The main limitation of the current study is the low percentage of arrhythmias compared to normal sinus rhythm. Therefore, the current data are limited with regard to the quality of heart rhythm classification. Furthermore, there is a limitation that iECGs were recorded at a paper speed of 25 mm/s, while standard 12-lead ECGs were recorded at a paper speed of 50 mm/s, which especially could have influenced the difference in the interval duration of the P and T wave between the iECGs and the 12-lead standard ECG. Moreover, there is a time gap in the recording between the ECG and the iECG, which in particular could influence the correlation of the heart rate.

Disclosure statement

The authors declare no disclosure.

Declaration of competing interest

The authors declare no conflict of interest.

References

[1] Houck CA, Chandler SF, Bogers AJJC, et al. Arrhythmia mechanisms and outcomes of ablation in pediatric patients with congenital heart disease. Circ Arrhythm Electrophysiol 2019;12(11):e007663. https://doi.org/10.1161/CIRCEP.119.007663.
[2] Namboodiri N. Ablation of ventricular arrhythmias in GUCH: the surgical scar and the second substrate. Indian Pacing Electrophysiol J 2012;12(1):1–3. https://doi.org/10.1016/s0972-6292(16)30457-0.
[3] Heijman J, Guichard JB, Dobrev D, Nattel S. Translational challenges in atrial fibrillation. Circ Res 2018;122(5):752–73. https://doi.org/10.1161/CIRCRESAHA.117.311081.
[4] Raina A, Meeran T. Right ventricular dysfunction and its contribution to morbidity and mortality in left ventricular heart failure. Curr Heart Fail Rep 2018;15(2):94–105. https://doi.org/10.1007/s11897-018-0378-8.
[5] Siddeek H, Fisher K, McMakin S, Bass JL, Cortez D. AVNRT captured by Apple Watch Series 4: can the Apple watch be used as an event monitor? Ann Noninvasive Electrocardiol 2020;25(5):e12742. https://doi.org/10.1111/anec.12742.
[6] Moons P, Bratt EL, De Backer J, et al. Transition to adulthood and transfer to adult care of adolescents with congenital heart disease: a global consensus statement of the ESC association of cardiovascular nursing and allied professions (ACNAP), the ESC working group on adult congenital heart disease (WG ACHD), the association for European paediatric and congenital cardiology (AEPC), the pan-african society of cardiology (PASCAR), the asia-pacific pediatric cardiac society (APPCS), the inter-American society of cardiology (IASC), the cardiac society of Australia and New Zealand (CSANZ), the international society for adult congenital heart disease (ISACHD), the world heart federation (WHF), the European congenital heart disease organisation (ECHDO), and the global alliance for rheumatic and congenital hearts (global ARCH) [published online ahead of print, 2021 Jul 1] Eur Heart J 2021. https://doi.org/10.1093/eurheartj/ehab388. ehab388.
[7] Baumgartner H, De Backer J. The ESC clinical practice guidelines for the management of adult congenital heart disease 2020. Eur Heart J 2020;41(43):4153–4. https://doi.org/10.1093/eurheartj/ehaa701.
[8] https://www.accessdata.fda.gov/cdrh_docs/pdf18/DEN180044.pdf. [Accessed 12 December 2020].
[9] Samol A, Bischof K, Luani B, Pascut D, Wiemer M, Kaese S. Single-lead ECG recordings including einthoven and wilson leads by a smartwatch: a new era of patient directed early ECG differential diagnosis of cardiac diseases? Sensors 2019;19(20):4377. https://doi.org/10.3390/s19204377. Published 2019 Oct 10.
[10] https://support.apple.com/en-us/HT208955. [Accessed 12 December 2020].
[11] Yerasi C, O'Donoghue S, Satler LF, Waksman R. Apple Watch detecting high-grade block after transcatheter aortic valve implantation. Eur Heart J 2020;41(10):1096. https://doi.org/10.1093/eurheartj/ehz854.
[12] https://www.statista.com/statistics/381696/wearables-unit-sales-forecast-

united-states-by-category. Nov 15th, 2019).
[13] Samol A, Bischof K, Luani B, Pascut D, Wiemer M, Kaese S. Recording of bipolar multichannel ECGs by a smartwatch: modern ECG diagnostic 100 Years after einthoven. Sensors 2019;19(13):2894. https://doi.org/10.3390/s19132894. Published 2019 Jun 30.
[14] Samol A, Bischof K, Luani B, Pascut D, Wiemer M, Kaese S. Patient directed recording of a bipolar three-lead electrocardiogram using a smartwatch with ECG function. JoVE 2019;154. https://doi.org/10.3791/60715. Published 2019 Dec 11. doi:10.3791/60715.
[15] Behzadi A, Sepehri Shamloo A, Mouratis K, Hindricks G, Arya A, Bollmann A. Feasibility and reliability of SmartWatch to obtain 3-lead electrocardiogram recordings. Sensors 2020;20(18):5074. https://doi.org/10.3390/s20185074. Published 2020 Sep. 7.
[16] Desteghe L, Raymaekers Z, Lutin M, et al. Performance of handheld electrocardiogram devices to detect atrial fibrillation in a cardiology and geriatric ward setting. Europace 2017;19(1):29–39. https://doi.org/10.1093/europace/euw025.
[17] Lau JK, Lowres N, Neubeck L, et al. iPhone ECG application for community screening to detect silent atrial fibrillation: a novel technology to prevent stroke. Int J Cardiol 2013;165(1):193–4. https://doi.org/10.1016/j.ijcard.2013.01.220.
[18] Kobel M, Kalden P, Michaelis A, et al. Accuracy of the Apple watch iECG in children with and without congenital heart disease [published online ahead of print, 2021 Sep 1] Pediatr Cardiol 2021. https://doi.org/10.1007/s00246-021-02715-w. 10.1007/s00246-021-02715-w.