Andreas Holzinger · Alan Pope ·
Hugo Plácido da Silva (Eds.)

Physiological Computing Systems

International Conferences
PhyCS 2016, Lisbon, Portugal, July 27–28, 2016
PhyCS 2017, Madrid, Spain, July 27–28, 2017
PhyCS 2018, Seville, Spain, September 19–21, 2018
Revised and Extended Selected Papers

Springer

Editors
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Medical University of Graz
Graz, Austria

Alan Pope
NASA Langley Research Center
Hampton, VA, USA

Hugo Plácido da Silva
IT - Instituto de Telecomunicações
Lisbon, Portugal

ISSN 0302-9743 ISSN 1611-3349 (electronic)
Lecture Notes in Computer Science
ISBN 978-3-030-27949-3 ISBN 978-3-030-27950-9 (eBook)
https://doi.org/10.1007/978-3-030-27950-9

LNCS Sublibrary: SL3 – Information Systems and Applications, incl. Internet/Web, and HCI

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Physiological data in its different dimensions, either bioelectrical, biomechanical, biochemical or biophysical, collected through specialized biomedical devices (video and image capture or other sources) is opening new boundaries in the field of human-computer interaction into what can be defined as Physiological Computing. The International Conference on Physiological Computing Systems (PhyCS) is a series of annual meetings of the physiological interaction and computing community, and serves as the main international forum for engineers, computer scientists, and health professionals, interested in outstanding research and development that bridges the gap between physiological data handling and human-computer interaction.

Given the topical nature of this subject, the present book includes extended and revised versions of a set of selected papers from the Third International Conference on Physiological Computing Systems (PhyCS 2016), 4th International Conference on Physiological Computing Systems (PhyCS 2017), and the 5th International Conference on Physiological Computing Systems (PhyCS 2018), which brought together people interested in creating novel interaction devices, adaptable interfaces, algorithms, and tools, through the study, planning, and design of interfaces between people and computers that are supported by multimodal biosignals.

This volume is a collection of the best papers, resulting in a final acceptance rate of approximately 20%, selected by the event chairs and their selection is based on a number of criteria that include the classifications and comments provided by the Program Committee members, the Session Chairs' assessment and also the Program Chairs' global view of all papers included in the technical program. The authors of selected papers were then invited to submit a revised and extended version of their papers having at least 30% innovative material.

The papers selected to be included in this book contribute to the understanding of relevant trends of current research on physiological computing systems, including brain-computer interfaces, virtual reality, psychophysiological load assessment in unconstrained scenarios, body tracking and movement pattern recognition, emotion recognition, machine learning applied to diabetes and hypertension, tangible biofeedback technologies, multimodal sensor data fusion, and deep learning for hand gesture recognition.

We would like to express our gratitude, first of all, to the contributing authors of the technical papers, whose work and dedication made it possible to put together an exciting program of high technical quality. We would also like to thank all the members of the international Program Committee and auxiliary reviewers, who provided a comprehensive set of thoughtful reviews, helping us with their expertise and

time. We would also like to thank the invited speakers for their invaluable contribution and for sharing their vision in their talks. We are especially grateful to the INSTICC Steering Committee whose invaluable work made this event possible.

September 2018

Andreas Holzinger
Alan Pope
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Contents

Heart Rhythm Qualitative Analysis Using Low-Cost and Open Source Electrocardiography: A Study Based on Atrial Fibrillation Detection

Hélio B. M. Lourenço[1(✉)], Víctor Sanfins[3], Fernando Torgal[3], Sílvia Ala[4,5,6], Manuel J. C. S. Reis[2,9], Hugo P. Silva[7,8], and Francisco Barros[2,5]

[1] Ace Centre, Oxford OX14 1RG, UK
helourenco@outlook.pt
[2] University of Trás-os-Montes and Alto Douro, Quinta de Prados, 5000-801 Vila Real, Portugal
{mcabral,flbarros}@utad.pt
[3] Laboratório de Arritmologia, Pacing e Electrofisiologia, Hospital de Guimarães, Serviço de Cardiologia, Guimarães, Portugal
vsanfins@hotmail.com, fernandotorgal64@gmail.com
[4] Departamento de Ciências Sociais e Gerontologia, Instituto Politécnico de Bragança, Bragança, Portugal
silvia.ala@ipb.pt
[5] Instituto de Investigación Sanitaria Galicia Sur—Grupo de Investigación en Neurociencia y Enfermedades Psiquiátricas, Vigo, Spain
[6] Neurosciences and Clinical Psychology, University of Vigo, Vigo, Spain
[7] IT—Instituto de Telecomunicações, Lisbon, Portugal
hsilva@lx.it.pt
[8] Escola Superior de Tecnologia do Instituto Politécnico de Setúbal, Setúbal, Portugal
[9] Department of Engineering, IEETA—The Institute of Electronics and Informatics Engineering of Aveiro, Aveiro, Portugal

Abstract. In the current digital era, cardiovascular activity analysis is becoming ubiquitous with the increasing availability of embedded systems, and, in some cases, these systems are even endowed with the capabilities of detecting health risk factors identified through electrocardiographic (ECG) markers. Aligned with this trend, and inspired by the results from our pilot study, we focus this research on exploring the potential of a low-cost and open source device for heart rhythm analysis, with emphasis on Atrial Fibrillation (AF). AF is the most common cardiac arrhythmia, defined as a complex cardiac disease which is highly correlated to stroke and heart failure, and its prevalence is especially high in elderly population. Given the importance and impact of such cardiovascular disease, we performed ECG acquisitions in a hospital setting to evaluate the potential of this device to identify heart rhythms. These ECG acquisitions were performed in 10 patients, accomplished simultaneously with the low-cost

A. Holzinger et al. (Eds.): PhyCS 2016–2018, LNCS 10057, pp. 198–217, 2019.
https://doi.org/10.1007/978-3-030-27950-9_11

device and the gold standard devices used in the clinical routine of the hospital. The data collected from the low-cost device was analysed by the cardiologist specialized in rhythmology, along with the conventional ECG exam analysis, whom suggested 100% accuracy of the low-cost device in differentiating a sinus rhythm from AF. The results also present great accuracy in the detection of atypical cardiac events through ECG analysis, as well as a good agreement for the corroboration of the numerical data from the devices used for this study, as the RR intervals and QTc intervals values suggest.

Keywords: Electrocardiography · Atrial fibrillation · Low-cost · Open source · Cardiovascular disease · Heart rhythm · QTc

1 Introduction

Bio-signal analysis with open source and low-cost devices has increasingly gained popularity in the past decade, as its applications are being recognized and extensively explored by research and industrial engineering fields. The convergence of synergies between diverse communities has allowed significant advances in research and development activities, due to the opportunity for experimentation given by the low-cost, versatility and accuracy of the current Do-it-Yourself (DIY) devices. More importantly, the development of proof of concept methodologies or prototypes for bio-signal applications can represent significant cost and development time reduction when compared to more standardized medical devices. They can even be further enhanced when allied with other areas sharing the same philosophy (i.e., spreading the opportunity to gain knowledge and experiment), such as 3D printing.

Within DIY and open source devices for biomedical applications, BITalino[1] has been described as a viable choice [2]. This platform presents a wide range of sensors, as well as a high level of hardware configurability, due to its developmental ideological nature. There are a comprehensive range of software resources allowing deeper physiological data exploitation, within which particular attention has been given to the ECG [10,13,15].

In our previous research [7], we have presented an empirical corroboration of the data acquired with BITalino and a medical-grade ECG device, acquired at rest from a control group of 21 subjects, by analysing the QTc interval for the heart rate and the segmented heartbeat waveform. The results have shown a good agreement between the numerical data acquired from the gold standard and the low-cost device. We have also included the results of the Heart Rate Variability (HRV) numerical data analysis for this control group. Beyond this main control group, we have also tested ECG acquisition with the low-cost device in static and dynamic conditions, as well as further HRV analysis for both acquisition conditions, which revealed a great performance for rhythmical ECG analysis. Also, by analysing the data from our preliminary study and the control group, promising

[1] http://bitalino.com/en/.

results regarding BITalino's potentiality for cardiomyopathy pre-screening were found. In particular, ECG abnormalities in two volunteers were detected by BITalino and confirmed with the results from the gold standard devices.

Inspired by the results from our previous research, we focused this study on exploring BITalino's reliability for cardiomyopathy pre-screening with real patients, in a hospital setting – mostly in the Cardiology Department. In this case study-based article, we are exploring the low-cost device's accuracy in detecting arrhythmias, namely, Atrial Fibrillation (AF). The main gold standard device used was an ELI^{TM} 280 12-lead Resting ECG, hereinafter referred to as ELI. In case study 10, a different gold standard device was used – Philips PageWriter Trim III – as this patient was monitored in the Emergency Department, where this is the device available. For this study, we were able to record the ECG signal with both devices recording simultaneously. The ECG acquisition was performed by the medical team with the hospital patients, along with their conventional ECG diagnostic exams.

The data collected from the low-cost device was analysed by the cardiologist specialized in rhythmology, along with the conventional ECG exam analysis. With this analysis we aimed to verify BITalino's reliability in detecting pathologic cardiac rhythms. The enrolled patients are usually referred for ECG analysis by routine hospital appointments as, usually, they present typical symptoms of cardiac disease. A total of 10 patients were monitored: two of them have shown sinus rhythm, and the remaining patients were diagnosed with AF. In addition to the rhythmic analysis, we performed the waveform morphology analysis, as well as the numerical data analysis – corrected QT interval for the heart rate (QTc). The QTc interval is an important marker for the rhythmic disease, as it represents the depolarization and repolarization of the ventricles and it can give important information in situations where there is the risk of sudden death. The finding of this study suggests that BITalino demonstrated precise signal quality for rhythmical analysis and ECG waveform segments analysis, and it was possible to detect healthy and pathological rhythms with 100% accuracy. The results also show great accuracy for abnormal events detection (i.e., extrasystoles), as well as heart's electrical conduction blocks. Also, the corroborated numerical data obtained from BITalino and the medical grade devices present good agreement.

2 Motivation

The current digital era is surrounding us with technology that has vastly increased its capabilities on tracking vital signs, specifically, cardiovascular markers. Such devices allow proactive monitoring and can be present in daily wearables that are evolving in the direction of diagnostic supporting tools. Apple Watch is an example of such technology. However, this device is still in working progress to achieve accurate cardiac disease detection [19]. Such devices are also being deftly empowered through Artificial Intelligence (i.e., Heartsense[2]), improving their ability to detect cardiac pathology. The portability of such devices can make the difference in their ease of use and range of applications, being the e-textile applications an example of such portability and ubiquitous use [14,17].

These technologies have been paving the way for continuous and more pervasive ECG data acquisition, which can become crucial in supporting patients with cardiovascular diseases to track their health status or benefit from preventive interventions. However, such technology is still yet to be accessible for a wide range of users due to its cost. For example, due to the limited infrastructures, access to technology, as well as access to health services, developing countries and remote communities can face insufficient primary care; and DIY and low-cost devices have been used to develop solutions for ECG acquisition, in an attempt to promote access to health in such cases [4,12,21].

The World Health Organization reported, in 2017, that cardiovascular diseases continue to be the main cause of death globally.[3] Within cardiovascular diseases, AF is the most common cardiac arrhythmia and its prevalence in developed countries range from 1.5% to 2% of the general population [18]. A study conducted by Marini et al. revealed that, in the United States (US) only, 17% of the deaths from their cohort were attributed to the presence of AF in patients with ischemic stroke [8]. The US population projections by the US Census Bureau estimates that the cases of AF will increase to 12 million until 2050 [9].

The prevalence of AF increases with ageing, and its episodes increase in frequency and duration, which makes its early detection pivotal to increase the possibility of using reversible and less invasive interventions. AF can be a chronic condition where electrocardiographic diagnosis is easy, it can be paroxysmal, which makes its electrocardiographic documentation more difficult and dependent on prolonged electrocardiographic monitoring techniques.

In the presence of AF, the myocardium shows uncoordinated and ineffective atrial contractions, which can result in hemodynamic instability. Such disorganized atrial activity consequently causes irregular ventricular rate, and it can be detected through ECG analysis, once its main characteristics are the irregularity of RR intervals and the absence of P-waves [6,18,20].

This work aims at finding the potential of using a low-cost device for arrhythmias pre-screening, in particular AF, due to its importance and prevalence in the general elderly population. We aim to take a step further in expanding the evidence that can sustain the use of BITalino for a broader range of applications, and to influence the research and educational communities to direct their attention to such significant matter in public health.

Previous researches found that BITalino presents high similarity on the results for ECG acquisition by benchmarking with gold standard devices. Multiple studies, with non-pathologic volunteers, have explored the potentiality of this low-cost device through the analysis of Signal-to-Noise Ratio (SNR), Root Mean Square Error (RMSE), morphological analysis and R-peak detection for

[2] http://www.cambridgeheartwear.com.

[3] https://www.who.int/en/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds).

segmentation [1,2,16]. Silva et al. [16] presented a correlation of ECG data, acquired from 38 volunteers at rest, between a medical device (Philips PageWriter Trim III series) and the first version of BITalino, aiming to validate the signal acquisition accuracy for "off-the-person" applications. The medical device used a setup that included the classical 12-lead ECG placement system, whilst BITalino used a single lead, in a setup with two dry electrodes placed at the index fingers. The comparative tests showed that the "off-the-person" ECG data had a precision for R-peak detection above 98% when compared to the corresponding lead in the gold standard device. Additionally, the segmentation performance and morphological waveform analysis showed a strong correlation between the real-world empirical data assessed for both devices, reinforcing the potential of low-cost devices.

3 Materials and Methods

3.1 Volunteers

The data was collected in a hospital setting from 10 patients aged 80.5 ± 6.06 years old where 4 are male and 6 are female. These patients were referred for the 12-lead ECG, at rest, for evaluation of palpitations, a symptom that suggests the presence of arrhythmias.

The medical team accomplished the ECG acquisitions with BITalino along with the conventional 12-lead ECG acquisition, following the same clinical procedures for ECG acquisition.

In order to proceed with the experimental part of the study, we had the approval of the hospital to conduct the ECG acquisition with BITalino as well as to use the data collected from the medical ECG devices. The consent of the volunteers who have participated in this study was also obtained. Data acquisition was performed in accordance with the existing institutional rules and regulations.

3.2 Methodology

Building upon our previous work [7], we performed an empirical corroboration of the ECG data acquired from BITalino and with the gold standard devices, focusing on determining the accuracy of the low-cost device to detect arrhythmias, specifically, AF. In addition to the traditional ECG screening exam using the conventional 12-lead ECG, acquired at rest and supine position, the medical team of the Cardiology Department added the modified bipolar leads CM_5 and Lead II, suggested by [3,5], to be used with BITalino.

In relation to our previous study, we have modified the experimental protocol by changing the previously used Conventional Lead (CL) for the Modified Lead II, both suggested by the same author [3], as these leads have an approximate configuration and electrical vector, as well as similar signal output. Also, the modified Lead II can give us an approximate waveform pattern to the standard Lead II used in the conventional 12-lead ECG. Although the signal output from the bipolar Modified Lead II and the conventional Lead II have the best waveform pattern similarity, within the leads that were used, it is still differentiated due to the characteristic electrode placement configuration of each lead.

The ECG data acquisition carried out with the ELI device was recorded with 25 mm/s of speed and 10 mm/mV in amplitude. The ECG machine automatically selects the 10 best seconds of recording to obtain the ECG tracings. The data obtained with BITalino was made correspondent to the data obtained with the gold standard devices. The devices features for ECG acquisition are described in Table 1.

The data from the conventional 12-lead ECGs were provided in portable document format (PDF), and we were able to further perform the signal synchronization between this data and BITalino's data, through ECG traces observation. To support the synchronization process, the ECG acquisitions performed with the low-cost device had a time frame ranging from 0:41 to 2:36 min, and the ECG acquisitions using the medical devices were performed simultaneously, so the moment of the data collected by the medical devices could be contained in the former acquisition. The initial and final moment of the ECG acquisition with the gold standard device was recorded on BITalino, by triggering an input signal to mark the recording instant, using a pushbutton.

Once the data was collected, BITalino's raw data was post-processed so the signal filtering and feature extraction could be performed (see Sect. 3.4). Therefore, once the post-processing was accomplished, BITalino's ECG tracings resulting from the synchronization with the 12-lead ECGs were analysed by the cardiologist. The data analysed is presented in Sect. 4.

3.3 Acquisition Setup

Hardware. Adding to the hardware used in our previous work [7], where we used the BITalino (r)evolution Core BT with two ECG sensors, and respective 3-lead cables, we included the pushbutton sensor for event annotation. To house each of the components we used 3D printed enclosures. Another modification developed for this study was reducing the number of cable connections by removing the UC-E6 connectors and soldering the cables directly on the sensors in order to improve usability, which also resulted in a *poka-yoke* procedure for the medical team when handling the BITalino hardware system (see Fig. 1).

The BITalino main board was powered by a 500 mAh capacity and 3.7 V output LiPo battery and data transmission performed by Bluetooth to our base station—a laptop with Windows operating system. Pre-gelled Ag/AgCl electrodes were used to interface the electrode leads with the subject body.

Table 1 presents the BITalino ECG sensors and the ELI^{TM} 280[4] hardware specifications. Note that the features from the ELI device presented are the same used for this study, as this device presents different features.

[4] https://www.welchallyn.com/content/dam/welchallyn/documents/sap-documents/MRC/80022/80022538MRCPDF.pdf.

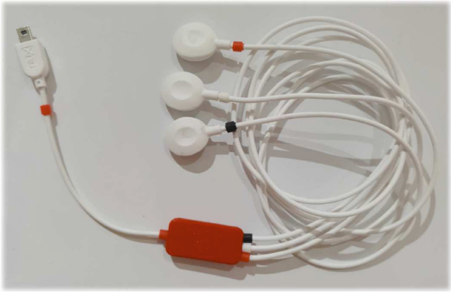

Fig. 1. BITalino ECG sensor adapted with the UC-E6 cable connector and 3-lead cable soldered.

Table 1. BITalino (r)evolution ECG and ELI^{TM} 280 specifications.

Feature	BITalino	ELI
Sampling rate	1000 Hz	1000 Hz
ADC resolution	10 bit	20 bit
Gain	1100	n.a.
Range	±1.5 mV (VCC = 3.3 V)	Meets or exceeds the requirements of ANSI/AAMI EC11
Bandwidth	0.5–40 Hz	0.05–300 Hz
Input voltage range	±1.65 V	Universal AC power supply (100–240 VAC at 50/60 Hz) 110 VA
Input impedance	7.5 GΩ	Meets or exceeds the requirements of ANSI/AAMI EC11
CMRR	86 dB	Meets or exceeds the requirements of ANSI/AAMI EC11

Software. For data acquisition with BITalino we used the OpenSignals software; the recorded data was acquired using 1000 Hz sampling rate. The ELI device was set up for 1000 Hz and had digital filters incorporated in the hardware, namely high-performance baseline filter, AC interference filter 50/60 Hz, band-pass filter [0,05–40] Hz.

The feature extraction and automatic ECG analysis for ELI^{TM} 280 are integrated into the ECG device hardware.

3.4 Data Post-processing

Although the ELI^{TM} 280 already provides the ECG signal filtered, BITalino mostly performs raw data acquisition, reason why data post-processing was needed. For raw data conversion to the correct physical units - millivolt -, the transfer functions suggested in BITalino's manuals[5] were implemented. Equation 1 converts the raw data into Volts units, and Eq. 2 converts the data obtained from the former equation into millivolts.

$$ECG(V) = \frac{\left(\frac{ADC}{2^n} - \frac{1}{2}\right) \cdot VCC}{G_{ECG}} \tag{1}$$

$$ECG(mV) = ECG(V) \cdot 1000 \tag{2}$$

Further feature extraction was performed using the BioSPPy[6] toolbox, a set of open source and Python-based routines for biomedical signal analysis, that includes modules for ECG filtering, R-peak detection, HR plot, waveform template.

The BioSPPy toolbox original band-pass filter of [3–45] Hz was modified to [0.05–40] Hz so it could correspond to the filter used by the ELI device. The toolbox was adapted to obtain the standard ECG trace grid for 25 mm/s recording speed and 10 mm/mV amplitude for our previous study and improved for this work. This grid allows rhythmical and morphological ECG trace analysis by observation. For each subject, we have extracted ECG traces for 10 s, for both ECG bipolar leads.

Once accomplished the signal post-processing procedure, the corrected QT interval was collected. The values for the classic 12-lead ECG were obtained through the automatic extraction features from the gold standard devices, whilst the values for BITalino were obtained through ECG trace scalar measurement (QT interval and QTc interval). QT interval variation is inverse to the heart rate, and, for this reason, multiple expressions were suggested to adjust it to the heart rate. Bazett formulae [11] is one of the most popular calculation methods and it was the selected method for this study. The data for the classic 12-lead ECG was obtained through the feature extraction provided by the ELI, whereas the values for BITalino were obtained through ECG trace scalar measurement (QT and QTc intervals).

The statistical parameters of RR intervals were extracted through the OpenSignals's Heart Rate Variability (HRV) add-on, from the raw data.

4 Results

4.1 General Considerations

The results are presented in a case study structure and are individually analysed. There are a total of 10 case studies, where the case studies 1 and 2 represent

[5] http://bitalino.com/datasheets/REVOLUTION_ECG_Sensor_Datasheet.pdf.
[6] http://biosppy.readthedocs.io/en/stable/.

sinus rhythm and the remaining were diagnosed with AF. The AF case studies share two distinctive characteristics: irregular RR intervals and P wave absence. The ECG acquisitions for subjects 1 to 9 were synchronized by visual observation.

Even though this analysis consists in a rhythmical analysis, some morphological aspects of the ECG tracings were further analysed and described on the results. For this reason, the case studies are presented individually. Case studies (CS) 3, 4 and 5 are presented altogether as they exhibit similar characteristics.

The RR intervals, QT interval and QTc interval were obtained for all volunteers, through the ECG traces obtained from both devices. Table 2 presents these values.

The OpenSignals add-on used to obtain the RR intervals is restricted by the minimum number intervals needed to extract these parameters, which corresponds to 11 QRS complexes. For this reason, we used the RR intervals average duration within the whole monitoring. Case studies 4 and 9 are exceptions, as they present a higher heart rate, and it complies with the minimum number of RR peaks needed.

4.2 Case Study 1—Sinus Rhythm with Extrasystoles

The subject presented in CS1, designated as S1, is a 73 years old male and presents a sinus rhythm. However, during the screening exam, two supraventricular extrasystoles were detected. These events were detected by both the ELI and BITalino, as represented in Figs. 2 and 3, respectively.

Table 2. QTc values obtained for the 10 subjects, with respective QT and RR intervals, as well as the average and standard deviation for the overall values for both devices. AVG - Average; STD - Standard Deviation.

Subject	BITalino (r)evolution					ELI^{TM} 280		
	Min RR (ms)	Max RR (ms)	AVG RR (ms)	QT (ms)	QTc (ms)	AVG RR (ms)	QT (ms)	QTc (ms)
S1	555	2157	1075	440	424	1021	409	404
S2	406	1814	925	520	540	964	416	423
S3	657	1788	954	420	430	1023	411	406
S4	484	1184	775 (787*)	440	499	786	362	408
S5	914	1804	1008	520	500	1182	426	391
S6	684	1732	1057	500	486	1007	475	473
S7	713	1445	944	540	555	954	447	457
S8	455	2028	994	520	521	1027	431	425
S9	253	1149	757 (770*)	480	551	770	439	500
S10	564	1171	740	540	627	659	368	453
AVG	559	1760	949	510	511	986	421	424
SD	184.871	366.778	131.064	44.422	60.373	155.068	34.209	35.242

∗ Shows the values extracted automatically through OpenSignals add-on

Fig. 2. CS1 – ECG trace from Lead II extracted with ELI, representing the sinus rhythm with two supraventricular extrasystoles during the signal acquisition.

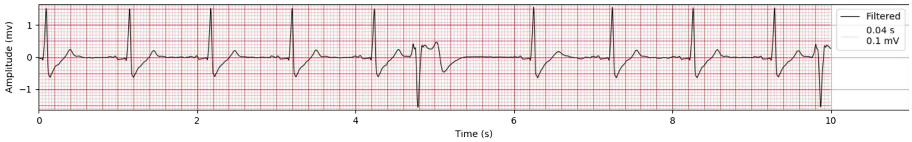

Fig. 3. CS1 – ECG trace from Modified Lead II extracted with BITalino, representing the sinus rhythm with two supraventricular extrasystoles.

4.3 Case Study 2—Sinus Rhythm with Supraventricular Extrasystole

In this case study, an ECG tracing from an 83 years old female, who presents a sinus rhythm, is analysed. Although this subject presents a non-pathological cardiac rhythm, this subject presents a supraventricular extrasystole that was detected by both devices, represented in Figs. 4 and 5.

Fig. 4. CS2 – ECG trace from Lead II extracted with the ELI, showing the sinus rhythm and the supraventricular extrasystole.

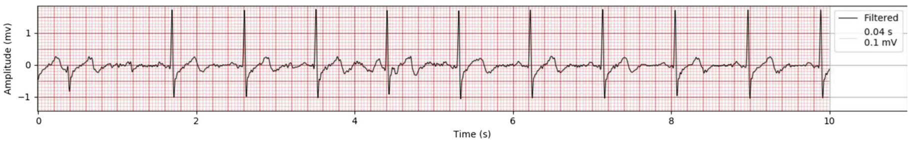

Fig. 5. CS2 – ECG trace recorded from Modified Lead II with BITalino, showing the sinus rhythm and the supraventricular extrasystole.

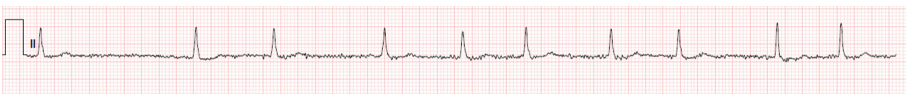

Fig. 6. CS3 – 12-lead ECG trace extracted with ELI device. The irregular RR intervals and P wave absence are the only factors that can be observed during this ECG acquisition.

Fig. 7. CS3 – ECG trace from the bipolar Modified Lead II obtained with BITalino. The irregular RR intervals and P wave absence can be observed.

Fig. 8. CS4 – ECG trace from Lead II extracted with the ELI device. The RR intervals irregularity and P waves absence present on this cardiac rhythm can be observed.

Fig. 9. CS4 – ECG acquisition from the bipolar Modified Lead II obtained with BITalino. Irregular RR intervals and the absence of P waves can be observed.

4.4 Case Studies 3, 4, 5 and 6—Atrial Fibrillation

The AF case studies presented in this section refer to: subjects S3 (81 years old female), represented in Figs. 6 and 7; S4 (77 years old female) is represented in Figs. 8 and 9 – these ECG tracings recorded with BITalino show high morphological similarity to the classic Lead II from the 12-lead ECG; S5 (87 years old male) is represented in Figs. 10 and 11; and S6 (76 years old female), results refer to Figs. 12 and 13. Even though this ECG traces morphology maintains a homogeneous pattern during the signal acquisition, it is clear that all of them show the characteristics that distinguish AF from another heart rhythm: all RR intervals are different and no P waves are observed.

Fig. 10. CS5 – ECG acquisition accomplished with the ELI device, recorded from Lead II. This ECG trace shows the typical AF rhythmic pattern and the absence of P waves.

Fig. 11. CS5 – ECG acquisition accomplished with BITalino from Modified Lead II. The arrythmic AF rhythm can be recognized, as well as the absence of P waves.

Fig. 12. CS6 – This ECG trace was generated by the ELI device, recorded from Lead II. The typical characteristics of AF are recognised.

Fig. 13. CS6 – This ECG acquisition was recorded with BITalino, from Modified Lead II. The IBIs irregularity and P waves absence can be observed on this ECG trace.

4.5 Case Study 7—AF with Undulated Baseline

CS7 is a 67 years old female and presents AF. This arrhythmia was detected by the medical device (Fig. 14) and by BITalino (Fig. 15). Beyond the classic AF characteristics shown, this ECG presents undulated baseline that can be recognized in Lead V_1, and also V_2, on the 12-lead ECG obtained with the ELI device. This chaotic baseline is also present in the signal extracted with BITalino, particularly in Modified Lead II. The Lead CM_5 also shows these events in the waveform morphology (Fig. 16), although they are clearer in Modified Lead II.

During the analysis of BITalino's complete monitoring, wide and bizarre QRS complexes were detected in multiple moments of the acquisition, on both leads. Figure 16 shows one of those moments.

4.6 Case Study 8—AF with Atypical QRS Complex

CS8 is based on the rhythmic analysis of an ECG record from an 81 years old female, who was diagnosed with AF. This 10 s ECG trace present the RR intervals irregularly, and the P wave absence is detected. The synchronization of both ECG acquisitions was possible to accomplish by visual observation, due to the extrasystole found in the 12-Lead ECG (Fig. 17) – Lead II, and also affecting the morphology of the QRS complex on Lead V_1 –, as well as in both bipolar leads acquired with BITalino (Fig. 18).

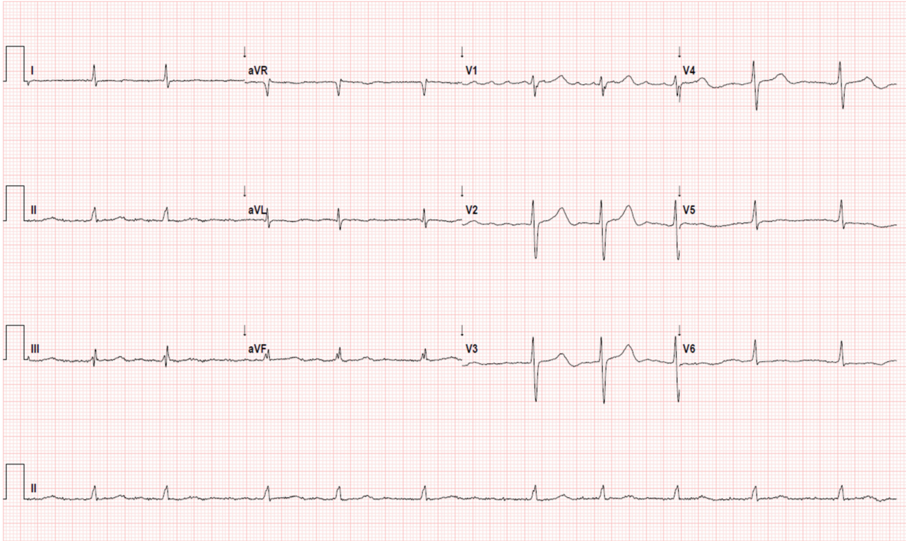

Fig. 14. CS7 – ECG trace from Lead II obtained with the ELI device. The results show the AF and the undulated baseline in Lead V_1, as well as in Lead V_2.

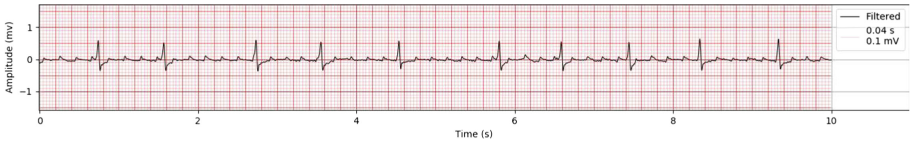

Fig. 15. CS7 – ECG trace recorded from Modified Lead II with BITalino, synchronized with the ECG trace obtained from the ELI device. The irregular cardiac rhythm and undulated baseline can be recognised.

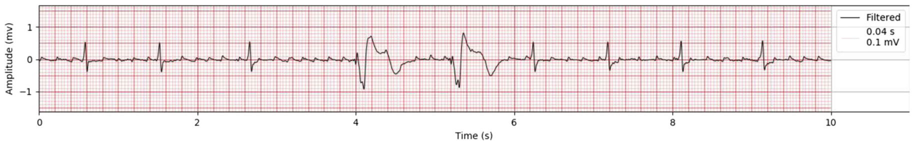

Fig. 16. CS7 – ECG trace recorded from Modified Lead II with BITalino. The AF characteristics are explicit, as well as the two wide QRS complexes. This ECG trace was obtained during the long signal acquisition performed with BITalino.

4.7 Case Study 9—AF with Atypical QRS-T

Case study 9 is made from the ECG acquisition from a 86 years old male. This person was diagnosed with AF by the medical team as the ECG traces clearly shows the irregular RR intervals and absence of P waves.

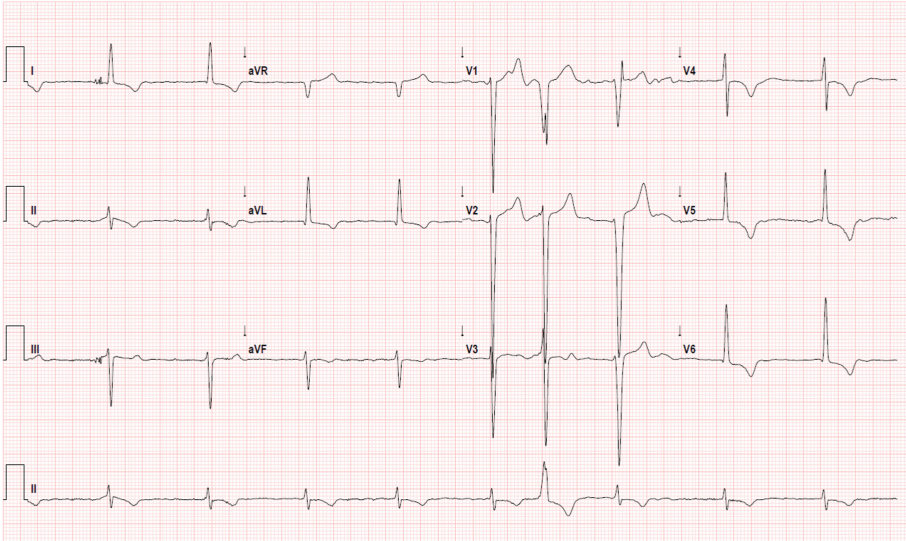

Fig. 17. CS8 – 12-lead ECG representing the extrasystole in Lead II and atypical QRS complex in Lead V_1 at the same instant, as well as the T wave inverted polarity. The RR intervals irregularity and P wave absence that characterize AF can be observed.

Fig. 18. CS8 – ECG tracing recorded from Modified Lead II using BITalino. AF can be detected in this strip, as well as the extrasystole that yields a peculiar QRS complex morphology.

In terms of morphological analysis, an extrasystole was detected during the ECG acquisition, through which the ECG tracing from BITalino (Figs. 20 and 21) were synchronized with the ECG tracing recorded with the gold standard (Fig. 19). This event was detected with all the leads that have recorded that moment. Looking at the ECG tracings recorded with BITalino, this event is more pronounced in Lead CM_5, as in Modified Lead II this change in wave morphology is subtle, even though the amplitude in S wave is higher, and its duration is shorter than the pattern of the remaining S waves.

4.8 Case Study 10—AF, Anterior Fascicular Block and Right Bundle Branch Block

This case study consists of an analysis of an ECG exam from an 80 years old male. This subject's ECG strip reveals that this person has AF. Beyond the

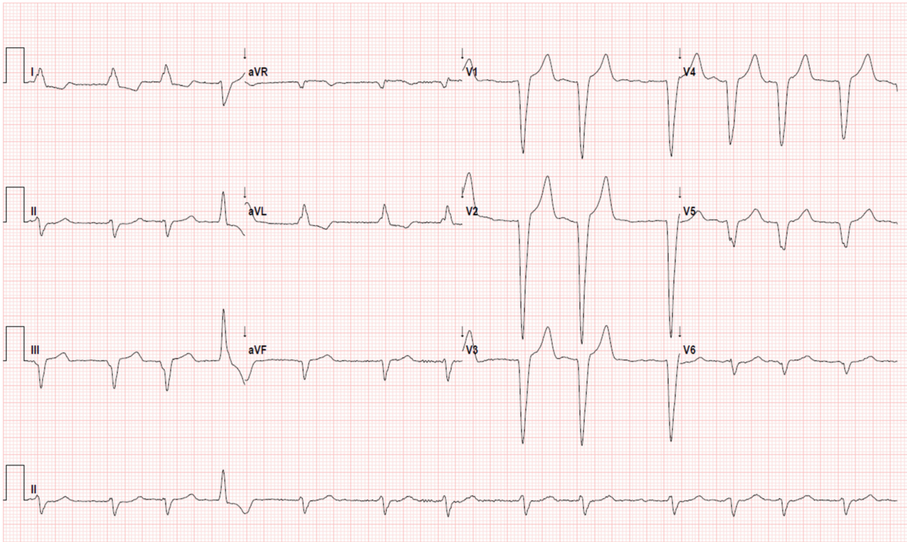

Fig. 19. CS9 – 12-lead ECG obtained with ELI. This ECG represents the IBIs irregularity, as well as the P wave absence. The extrasystole can be observed in Leads I, II and III, which were recorded at the same moment.

Fig. 20. CS9 – ECG tracing from Lead CM_5, obtained with BITalino. The extrasystole is detected, as well as the AF characteristics.

Fig. 21. CS9 – ECG trace obtained from Modified Lead II, recorded with BITalino. This ECG tracing shows the RR intervals irregularly and absence of P waves. However, the extrasystole is less evident than in Lead CM_5.

arrhythmia, the ECG shows evidences that suggests left anterior fascicle block, and right bundle branch block – the effects of these conduction blocks on the 12-lead ECG are represented by markers such as tall R waves, wide QRS complexes, left axis deviation and ST depression in Leads V_1 and V_2.

The 12-lead ECG is represented in Fig. 22. Note that this ECG was recorded with a different ECG machine than the one used with the remaining case studies presented, as this patient was monitored in the Emergency Department, while the remaining patients were monitored in the Cardiology Department. The medical device used with this patient was a Philips PageWriter Trim III – the recording speed and signal amplitude represented was accomplished at the same standards used with ELI, but different filters are applied by this ECG machine: baseline correction filter 35 Hz and AC interference filter 50 Hz.

The markers found with the medical grade device were also detected on the ECG traces recorded with BITalino, as Fig. 23 represents.

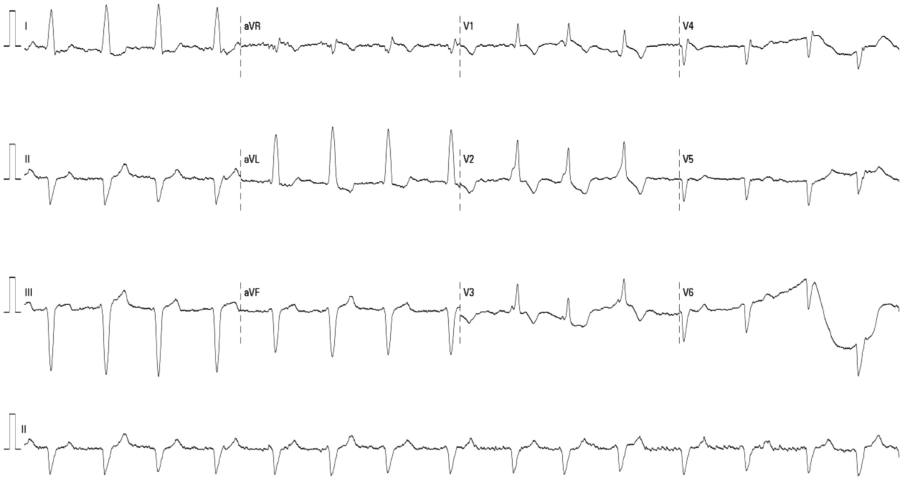

Fig. 22. CS10 – complete 12-lead ECG obtained with Philips PageWriter Trim III that represents AF, left anterior fascicle block, and right bundle branch block.

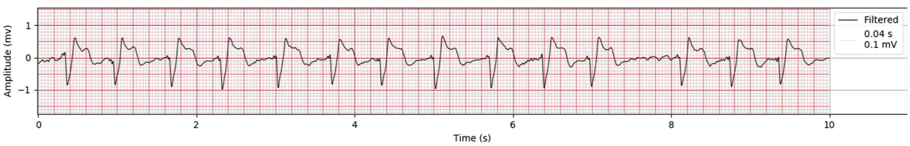

Fig. 23. Subject 10 – ECG trace from Modified Lead II, obtained with BITalino. This ECG represents the evidences for AF, left anterior fascicle block, and right bundle branch block for this subject.

5 Discussion

Since this study is focused on the detection of AF, the case studies presented were selected from a broader sample of volunteers. A requirement for this selection was the fact that the ECG traces could be synchronized by observation so the ECG recordings could be properly matched up. Case study 10 was an exception, as the process of synchronization by observation has limited this action. The fact that the gold standard devices automatically select the best 10 s of the recording, where the signal is less affected by noise, causes some disparity on the recording moment registered in each device. The selected case studies have evident morphology patterns that can be recognized by observation, which highly contributed to their selection.

Even though the main objective of this work is to determine BITalino's reliability for arrythmia detection, we have also analysed morphological aspects of the ECG waveform, as well as the comparison of the RR intervals and QTc interval between both devices. Similarly to our previous work [7], the results from the comparison of RR intervals and QTc intervals show comparable results. However, the QTc intervals for BITalino's traces present higher values, due to the output waveform signal produced by the bipolar ECG leads used. Also, the QTc intervals from BITalino were obtained by scalar measurement through observation of the longer QT interval, while the QTc interval from the medical device was automatically calculated.

The RR intervals automatically extracted from both devices exhibit identical results for subject S4 and S9. The remaining ones show approximate results even though BITalino's RR intervals were obtained from the whole ECG monitoring.

The results suggest that BITalino has a precise signal quality that allows reliable rhythmic and morphological analysis, as the events detected by the medical grade device were all found on the ECG tracings acquired with BITalino. The case studies presented represent 100% accuracy by a human expert in detecting sinus rhythm and AF. Besides the differentiated detection of sinus rhythm and AF, atypical events such as extrasystoles, ventricular escape beats, inverted P waves were also detected by BITalino, demonstrating that the signal quality allows correct identification of each event and the origin of these events in the heart's electrical conductive system and myocardium.

The results presented show the morphological difference between the bipolar modified leads used with BITalino and the conventional 12-lead ECG. However, the rhythmical analysis from both devices have a great correlation, as Table 2 shows. This morphological difference is affected by the lead configuration, which confer on a characteristic waveform morphology, although there is a high similarity in some cases (i.e., CS4 and CS5).

CS9 reveals that some atypical morphological events can be masked to some ECG leads, as the atypical QRS-T segment detected by both BITalino's ECG leads shows (Figs. 20 and 21). CS8 represents a similar situation, but in this case, the extrasystole is masked in some of the leads of the conventional ECG trace (Fig. 17).

The fact that we only had access to the data in PDF format has limited the feature extraction from the 12-lead ECGs. We have selected a group of case studies, from a broader sample, which allowed us to synchronize the ECG strips from both devices for rhythmic and morphological analysis. Case study 10 was the exception, as the task of synchronizing the ECG strips by observation needs clear reference points (i.e., IBIs clear pattern; extrasystoles; among others). Even without a synchronized ECG tracing, and considering the fact that this subject was monitored with a different ECG machine, which slightly differs from our experimental protocol, we decided to include this case study as it presents a range of cardiac pathologies that were detected by both devices, even considering that there are only two leads available from BITalino.

6 Conclusions and Future Work

In the sequence of our previous study, we present an evaluation of the potential of a low-cost and DIY device for detection of cardiac disease, namely, Atrial Fibrillation, in an empirical corroboration of the data with gold standard devices. The results from the 10 case studies described have demonstrated that the signal quality allows reliable ECG acquisition at rest, for further rhythmic analysis, using the bipolar leads sensor configuration that we propose. BITalino could clearly identify a sinus rhythm from a rhythm where Atrial Fibrillation is present. Atrial fibrillation is a very complex and relevant clinical pathology and its identification and electrocardiographic documentation has a high clinical significance, given the therapeutic implications that this pathology implies.

There were also found promising results that suggest that the use of this low-cost device can support ECG morphological analysis in the prevention and diagnosis of other cardiac disorders, such as conduction blocks and its origins.

QTc interval can vary with age and gender of the subject, and it is generally estimated to be higher in women than in man [11]. The cut-off values found in the state-of-art are defined for the classic 12-lead ECG. For these reasons, further investigation needs to be carried to define appropriate cut-off values for modified bipolar leads, due to its inherent morphological characteristics. The fact that we have a reduced number of ECG leads can be a limitation for an appropriate estimation of this important electrocardiographic marker, although the use of the QTc interval is still very useful in certain clinical situations (i.e., patients that take medication which can affect the duration of the ventricular systole and diastole).

The possibility of performing longer ECG acquisitions with BITalino, through which a broader and richer set of data can be collected, allied with its accuracy and low-cost, are additional arguments for its use in future investigation with people with cardiovascular disease.

Acknowledgements. Our team would like to thank to all the anonymous volunteers that agreed to collaborate with this study and also to Hospital da Senhora da Oliveira Guimarães, namely, the Cardiology Department that supported with the data acquisition process.

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