Development of Low-Cost ECG System for Comprehensive Monitoring Heart Function

prihatin oktivasari
Bandung Institute of Technology
Ishartati Ishartati
Jakarta State Polytechnic
Riandini Riandini
Jakarta State Polytechnic
Amy Hamidah Salman
Bandung Institute of Technology
Freddy Haryanto
Bandung Institute of Technology
Suprijadi Suprijadi (supri@fi.itb.ac.id)
Bandung Institute of Technology

Research Article

Keywords: Electrocardiography, HRV, heart function

Posted Date: March 2nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-255887/v1

Abstract

A simple system, a low-cost, fully automated, and design for monitoring RR interval Electrocardiography (ECG) signal described in this paper. The platform, named Simple Low-Cost Electrocardiography System (SLES), is capable of monitoring RR interval and R peaks in 3 lead standards. The system is in .exe format, so it can be easily installed on a computer. The system's goal is to design a fully integrated system for measuring a characteristic of Heart Rate Variability (HRV) parameters for various applications in heart signal research and education. The ECG signal is analog filtered and amplified and processed from analog to digital. Eventually, the ECG signal will be shown on the monitor after digital filtering. The data obtained from the ECG will accurately reflect the status of human heart health. The system has the benefits of small volume, low power consumption, low cost, and real-time operation. All design and development reports, files, and system software will be given non-commercial use online on https://github.com/oktivasari.

Introduction

The heart is an organ that is vital for the human body. The emergence of abnormalities in the heart can be fatal for patients. At present, a device has emerged that provides health monitoring of vital signs that allow for free movement and observation during regular patient activity. For decades, arrhythmias have been the primary cardiovascular disease. It is very vital to identify heart disease. Heart activity can be recorded as ECG. The use of ECG for individuals is still minimal, expensive, and licensed. Currently, monitoring of heart signals can be done manually by individuals. Also, it can be independent, scheduled control, and efficient through the application of ECG systems in hospitals [1], [2], [3] with various ECG platforms or operating systems [4].

For example, the first heart monitoring device, called an ECG heart rate monitor, was introduced in 1977, and wireless personal heart monitors in 1983 [5]. In 2012, the ECG signal acquisition circuit's architecture was implemented in detail, which included analog filtered, amplified, digital field, displayed in the LCD after digital low-pass filtering in Digital Signal Processing, and the collected ECG data process [6]. Still, there are limitations because it uses the high-cost chip TMS320VC5509A [6].

The design of ECG data acquisition and processing systems is mainly achieved through the use of microcontrollers. Nevertheless, its processing functionality is restricted, and its storage capacity is too small, so it can not access old and complicated acquisition signals [7], and the limited digital data stream can only be saved on an SD memory card, allowing the ECG signal to be processed later on the Computer [1][7].

The ECG amplifier shall have a high input impedance, low output impedance, minimal bandwidth, and power-efficient as possible [8]. Besides, it should have a reasonable cost, a high power-supply-rejection ratio (PSSRR), and a common-mode rejection ratio (CMRR) [8]. Instrumentation amplifiers are needed to suppress unwanted common-mode signals.

One method to monitor heart conditions is to use the HRV method. HRV is a physiological phenomenon in which the time intervals between heartbeats have different values. Various things can affect HRV, including the influence of the autonomic nervous system, fitness, Body Mass Index (BMI), blood volume returning to the heart (venous return), respiration, arrhythmia, etc. [9]. In this study, it is being presented the development of a simple, a low-cost ECG solution with an integrated system in it, which can identify R-R intervals and average HR by using the time domain's HRV method. In the system, there was a statistics & histogram menu for monitoring the value of the RR interval per second, P onset-offsets, QRS onset-offsets, T-onset, amplitude, ISO level, and ST level. All values of the features will be processed into input for the HRV analysis.

As mentioned above, many technologies and tools have been developed, as existing systems are too costly for tracking heart signals and too big for individuals to purchase and use in real-world applications [8]–[12]. Furthermore, no fully open-source ECG framework will allow for modifications for different purposes. So we are proposing a new open source in .exe file, simple system, small and inexpensive system that can store heart signals in real-time.

We have developed a completely simple ECG system (SLES) equipped with an AD 8232 sensor, and the National Instrument (NI) My-DAQ and ECG Sensor. The advantage of AD 8232 is a low cost, low power, portable (dimensions: 3.5 cm x 3 cm), has a fast recovery feature, thus improving filter settings and CMRR 80 dB (dc to 60 Hz), can apply gain and to filter out near dc signals simultaneously, and fully integrated single-lead ECG front end, with a special biological signal conditioning function, especially for the ECG signal conditioning from and the output is an analog [13, 14, 15, 16]. NI My-DAQ is a low-cost data acquisition device that uses NI LabVIEW-based software to measure and analyze real-time signals.

In this study, several variable's values are obtained from the ECG record [14], average NN interval/heart rate, the deviation between the minimum and maximum NN intervals/heart rate, the standard deviation of the NN interval/ standard deviation of the NN interval (SDNN), NN 50, pNN50 and RMSSD [15]. Compared to similar devices at low prices [16]–[18], there are advantages to our system can detect normal heart function conditions in real-time. Many commercial ECGs involves high costs for infrastructure, software, operations and maintenance, and user training. In contrast to the ECG that we design, it is cheaper and easy system redesign and implementation with the block diagram and experimental setup uses three leads, the standard bipolar limb lead, and ECG system represented with the waveform, which the upright axis, is the amplitude (mV or V), while the horizontal axis is time (seconds or milliseconds) [19, 20, 21], shown in Fig. 1. This experiment, although low-frequency noise caused by member movements can occur [1] and [22].

Characteristic features of the designed device are: low cost per unit, low power requirement, create a file with a two-second entry in the form of the same heart signal and can thus be imported directly to the monitor, the ready availability of components and ease of construction, capability to use .exe through the multiple operating systems, the possibility to scale-up a large number of devices, ability to monitor battery voltage, power to run on 12 V batteries, available to monitor RR interval in real-time, easy to assemble and modify all system resources. One significant difference between our system and the previous platform is that our system transmits data in real-time and saves a graph of the heart signal to the monitor. Platform dimensions are 20 cm × 15 cm × 7 cm (width × length × height), and weigh about 1 kg, input 5 V, output 0-5 mV, AD8232 input 3.3 V, and output 0-5 V, allowing portability and accessibility for monitoring in the indoor or outdoor environment.

Results

In this segment, we compared SLES with commercial ECG. We developed an ECG system to collect data every 10 seconds and send it to a computer for further storage and analysis. Compared with commercial ECG 12 leads products, we use V5 data from commercial ECG transmission to be as fair as possible with data available from our products, which only uses three standard leads. The ECG signal's comparison result with three leads, and the commercial ECG 12 lead products in the Hospital is shown in Fig. 2. Data collected at the Hospital, with average patient age of 40-70, and most have heart defects. One of the purposes of capturing ECG data was to see all the ripples on the graph (Fig. 2b and 2c).

Various amplification and filtration tests have been conducted during electrocardiogram signal processing to minimize noise (Fig. 2d). The performance of all the ECG devices (statistics-histogram-waveform) tested were shown in Fig. 3a. The signal results for Fig. 2-3 were taken from the same respondents.

The results of the processing of two programs, ECG features extraction and HRV method in the time domain of the HRV analysis, were shown in the statistics & histogram menu. The illustration in Fig. 3 showed the time domain HRV and the signal for the sample with exercise and relaxation on the same respondent with fewer exercise conditions. The histogram in Fig. 3a tends to spread out, indicates that the heart rate before doing the exercise was less and the variable time interval. On the other hand, the histogram shape in Fig. 3b tends to be closer and dominant at a particular time axis point. The histogram indicates that the heart rate after doing more exercise is constant at intervals that are typical to be the same. An increase in the mean HR value because exercise expends energy, making the heart rate work harder. Increasing the mean HR value will result in a decreased mean RR because the RR interval's time size is inversely proportional to the mean HR.

The histogram (Fig. 3) at the top tends to spread out and indicates that the heart rate before exercising is less and the variable time interval. In contrast, the shape of the histogram at the bottom tends to be closer and dominant at a particular time axis point, that the heart rate after doing more exercise is constant at intervals that are typical to be the same. Values that were processed from ECG feature extraction are displayed in various features, while the HRV analysis results were shown in statistics and histogram tabs. The significance of irregular heartbeat depends on various factors, such as the ECG pattern produced, the frequency and length of activities, the frequency, and duration of events, combined with other symptoms identified simultaneously [23]–[25]. Regular monitoring for a long time provides a record of heart activity during daily life.

Many factors may affect the HRV index, such as gender, insulin resistance, BMI, hyperlipidemia, hypertension, ischemic and non-ischemic cardiomyopathy, and smoking status [26]–[28]. For example, an increased BMI can independently decrease HRV, particularly central adiposity, such as the class of hypertensives [28].

Participants were divided into four BMI levels (gender, weight, and height) and based on physical activity, by answering questions about physical activity habits, with options for each intensity (number of sports activities in a week, exercise duration, type of exercise (low, moderate, and heavy)). This test will focus on categories of BMI values, ideal and overweight. Standard BMI for Indonesian (Table 1), and formula in equation 1 [29]. Class 1 and 2 consists of males with a BMI value of 18-25 kg/m^2 or ideal category, and with a BMI value of 25-27 kg/m^2, the category fat [30]. Simultaneously, group 3 consists of the ideal class of women with a BMI value of 17-23 kg/m^2. Otherwise, obese women with a BMI value of 23-27 kg/m^2 were in class 4. Table 2 showed the RR and HRV values' results for each class that there was an increase in the HR value and a decrease in the RR value for conditions from relaxation to exercise [31].

See formula 1 in the supplementary files.

Discussion

The main findings in this study were: (i) a simple and a low-cost system; (ii) the system can record RR and HR values for further analysis; (iii) signal quality similar to ECG commercial tool. The SLES provides real-time monitoring of heart function.

Patients can efficiently operate the device themselves and can save the signal results for consultation with doctors. In this study, the detection of R wave to R wave intervals was a feature that plays an essential role in the HRV method, with the mean and HR mean RR values contained in the time domain. From the results of the heart signal images before and after exercise in Fig. 3, tended to experience a density and an increase of 4 beats in the 10-second sample of sampling, concluded that the signal pattern after exercise would increase the rate because it releases energy and makes the heart work harder.

Compared with the results of other studies with the much more expensive ADAS tool for three leads [32], the results in Fig. 3 shown there was no significant difference in the quality of the recorded signal. The results were the same without any significant difference compared with the signal from hospital commercial ECG equipment (Fig. 2a).

The test was carried out on 20 participants with four groups according to BMI value and gender. Class 2 and 4, which contain overweight male and female subjects and less exercise, tend to have a high HR mean above 100 bpm after exercise (Table 2). All classes after exercise showed an increase in HR values and a decrease in RR values. The value of BMI and activity can be one factor that can affect the heart's work because a more significant body requires more oxygen-filled blood to flow to all body tissues, so the heart has to work harder. Besides, the heart in the body that rarely did exercise tends to beat faster. In contrast to people who often did sports, the heart will beat more stable.

This study's limitations were diagnostic decision automation, which will need to develop proper ECG control and a sufficiently adequate database, privacy, and security [18] for future work. The R-R can represent important information about physiological stress and fatigue levels during and after training [33][34]. In incorporation P onset-offset value, QRS onset-offset, T onset-offset, ST level, and R peaks, the addition of physiological outcome measures, such as stress levels, physiological, and body mass index structure, would allow a more flexible and affordable option for an individual monitor. We also designed a versatile system for further improvements, such as Bluetooth, Wi-Fi, prints, etc.

A single product's overall price is estimated at $ 30 for the 3-lead model, with more production leading to reduced prices. Commercial research-level ECG devices in the Hospital can be costly around. In the market, a 12 channels commercial ECG used in hospitals costs around $ 1,093.99-16,950, and a three channels commercial ECG with a hospital scale is in the range of $ 900-1500, with a variety of products from several countries. Low-cost ECG is becoming more readily available, but the challenges mentioned above are limited. This ECG design is a low cost because the system is formed in format .exe and then made an installer that can include the LabVIEW Run-Time engine (free). It makes the device easily adaptable to the learning needs of students, researchers, or doctors. The complete hardware is available in Table 3. We discuss a description of our hardware's architecture, together with software that runs on devices available online on https://github.com/oktivasari. SLES is what we plan to focus on in the future, such as supporting laboratories for hardware-based education and adding other detection components for a complete hearth functionality detection approach.

Methods

Operating Procedure of ECG Hardware. The operation of the tool starts with attached three electrodes to the cable, connected the cable with the AD8232 module, and adjusted AD8232 with NI My-DAQ by configuring pins. The 3.3V IN pin on the AD8232 is coupled to + 5V on the NI My-DAQ, GND PIN on AD8232 connected to AGND pin on M-DAQ, the output on pin AD8232 was connected to pin Ai1 on NI My-DAQ, connected NI My-DAQ with computer via USB cable; attached the electrodes to the patient, provided that: red pad electrode was positioned on the right arm of the patient, a yellow electrode was placed on the patient's left arm, and a green electrode was placed on the patient's leg [19]. Finally, the ECG system (.exe) was opened, then checked the database and ECG signal data to ensure the tools can run properly.

Operating Procedure of ECG System. System operation includes installation of the system ECG, open the ECG system, run the ECG system after finished connecting the device, open the waveform menu to see the ECG signal, where the y-axis is amplitude. The x-axis is time, and we can see the signal before and after filtering.

Method of Noise and Filtering. One of the biggest challenges with ECG hardware is noise reduction. Noise elimination is done by filtering the signal both with high pass filters and low pass filters. In this tool, AD8232 works as a filter. The ability to amplify small ECG signals and eliminate the effects of DC signal offset voltages caused by op-amp and offset internal offsets due to the less ideal non-polarizing effect of the electrodes. The primary forms of noise are Baseline Wandering, which gets superimposed on a biopotential signal. Baseline Wandering usually originates from breathing at wandering frequencies between 0.15 and 0.3 Hz. In this experiment, Baseline Wandering was eliminated. Digital highpass filters or wavelet transforms are used to eliminate baseline wandering by eliminating trending ECG signals. After removing Baseline Wandering, the resulting ECG signal is stationary and explicit than the original signal.

Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Acknowledgements

The authors would like to thank the Ministry of Research and Technology / National Research and Innovation Agency for financial support for the development of devices and measurements in the hospital, with No. 2/AMD/E1/KP.PTNBH/2020.

Author contributions

S., F.H., A.H.S., supervised the work and reviewed the data. P.O. developed the idea. P.O., and I. built up the hardware, the system and take measurements in the hospital. R. prepared figures and tables. All authors discussed the manuscript.

Competing interests

The authors declare no competing interests

References

[1] J. P. Teixeira and A. Ferreira, “Ambulatory Electrocardiogram Prototype,” in *Procedia Computer Science*, 2015, vol. 64, pp. 800–807.

[2] S. L. Guo, L. N. Han, H. W. Liu, Q. J. Si, D. F. Kong, and F. S. Guo, “The future of remote ECG monitoring systems,” *Journal of Geriatric Cardiology*, vol. 13, no. 6. Science Press, pp. 528–530, 2016.

[3] A. Sengupta, S. Roy, and A. Sengupta, “A Simple and User friendly tool for determining R-R intervals from the time series data of Electrocardiogram,” vol. 5, no. 1, pp. 214–218, 2014.

[4] A. Purohit, “Calculate ECG Parameters through Labview.”

[5] M. AlGhatrif and J. Lindsay, “A brief review: history to understand fundamentals of electrocardiography,” *J. Community Hosp. Intern. Med. Perspect.*, vol. 2, no. 1, p. 14383, 2012.

[6] A. Bansal and R. Joshi, “Portable out-of-hospital electrocardiography: A review of current technologies,” *J. Arrhythmia*, vol. 34, no. 2, pp. 129–138, 2018.

[7] K. Wang, S. Ma, J. Feng, W. Zhang, M. Fan, and D. Zhao, “Design of ECG signal acquisition system based on DSP,” *Procedia Eng.*, vol. 29, pp. 3763–3767, 2012.

[8] L. Xiu and Z. Li, “Low-power instrumentation amplifier IC design for ECG system applications,” *Procedia Eng.*, vol. 29, pp. 1533–1538, 2012.

[9] S. G. Aydin, T. Kaya, and H. Guler, “Heart Rate Variability (HRV) Based Feature Extraction for Congestive Heart Failure,” *Int. J. Comput. Electr. Eng.*, vol. 8, no. 4, pp. 272–279, 2016.

[10] R. Amelard *et al.*, “Feasibility of long-distance heart rate monitoring using transmittance photoplethysmographic imaging (PPGI),” *Sci. Rep.*, vol. 5, no. September, pp. 1–11, 2015.

[11] D. Dias and J. P. S. Cunha, “Wearable health devices—vital sign monitoring, systems and technologies,” *Sensors (Switzerland)*, vol. 18, no. 8, 2018.

[12] P. Kakria, N. K. Tripathi, and P. Kitipawang, “A real-time health monitoring system for remote cardiac patients using smartphone and wearable sensors,” *Int. J. Telemed. Appl.*, vol. 2015, 2015.

[13] Analog Devices, “AD8232 (1 channel) Single-Lead ECG 2/3 electrode,” *Data Sheet*, pp. 1–28, 2013.

[14] A. Sobrinho, L. D. da Silva, A. Perkusich, P. Cunha, T. Cordeiro, and A. M. N. Lima, “Formal modeling of biomedical signal acquisition systems: source of evidence for certification,” *Softw. Syst. Model.*, vol. 18, no. 2, pp. 1467–1485, Apr. 2019.

[15] H. M. Wang and S. C. Huang, “SDNN/RMSSD as a surrogate for LF/HF: A revised investigation,” *Model. Simul. Eng.*, vol. 2012, 2012.

[16] R. H. Rakin, A. Siam, M. R. Hossain, and H. U. Zaman, “A low-cost and portable electrocardiogram (ECG) machine for preventing diagnosis,” in *1st International Conference on Robotics, Electrical and Signal Processing Techniques, ICREST 2019*, 2019, pp. 48–53.

[17] S. Deb, S. M. R. Islam, J. Robaiatmou, and M. T. Islam, “Design and implementation of low Cost ECG monitoring system for the patient using smart device,” *ECCE 2017 - Int. Conf. Electr. Comput. Commun. Eng.*, no. November, pp. 774–778, 2017.

[18] M. A. Serhani, H. T. El Kassabi, H. Ismail, and A. N. Navaz, “ECG monitoring systems: Review, architecture, processes, and key challenges,” *Sensors (Switzerland)*, vol. 20, no. 6, 2020.

[19] P. Oktivasari, M. Hasyim, A. Hs, and H. Freddy, “A Simple Real-Time System for Detection of Normal and Myocardial Ischemia in The ST segment and T Wave ECG Signal,” pp. 327–331, 2020.

[20] Joseph J. Carr, “Designer’s Handbook Instrmtn/Contr Circuits - Joseph J. Carr - Google Books,” *Academic Press*, 2012. .

[21] P. Kligfield *et al.*, “Recommendations for the Standardization and Interpretation of the Electrocardiogram,” *Circulation*, vol. 115, no. 10, pp. 1306–1324, Mar. 2007.

[22] B. Nilsson and W. F. DeGrado, *Engineering and design*, vol. 5, no. 4. 1995.

[23] B. Christe, “Introduction to Biomedical Instrumentation: The Technology of Patient Care - Kindle edition by Christe, Barbara. Professional & Technical Kindle eBooks @ Amazon.com.,” *Cambridge University Press*, 2009. .

[24] P. Davey, *ECG at a Glance*, First. A John Wiley & Sons, Ltd, 2008.

[25] Karen M. Ellis, *EKG Plain and Simple by Karen M. Ellis*, 2nd ed. Prentice Hall, 2006.

[26] D. F. Vasconcelos, L. Fernando, and J. Junior, “Cardiac Autonomic and Ventricular Mechanical Functions in Asymptomatic Chronic Chagasic Cardiomyopathy.”

[27] T. Benichou, B. Pereira, I. Tauveron, D. Pfabigan, S. Maqdasy, and R. Dutheil, “Heart rate variability in type 2 diabetes mellitus: A systematic review and meta-analysis,” 2018.

[28] T. S. Rodrigues and L. J. G. Quarto, “Body mass index may influence heart rate variability,” *Arquivos Brasileiros de Cardiologia*, vol. 111, no. 4. Arquivos Brasileiros de Cardiologia, pp. 640–642, 01-Oct-2018.

[29] A. Misra and N. V. Dhurandhar, “Current formula for calculating body mass index is applicable to Asian populations,” *Nutrition and Diabetes*, vol. 9, no. 1. Nature Publishing Group, 01-Dec-2019.

[30] A. Classification, “Indonesian Children and Adolescents ’ Body Mass Index :,” vol. 21, no. Icsshpe 2019, pp. 263–266, 2020.

[31] S. Zaki, H. Kazmi, H. Zhang, W. Aziz, and O. Monfredi, “Inverse Correlation between Heart Rate Variability and Heart Rate Demonstrated by Linear and Nonlinear Analysis,” pp. 1–10, 2016.

[32] F. Abtahi, J. Snäll, B. Aslamy, S. Abtahi, F. Seoane, and K. Lindecrantz, “Biosignal PI, an affordable open-source ECG and respiration measurement system,” *Sensors (Switzerland)*, vol. 15, no. 1, pp. 93–109, 2014.

[33] J. I. N. G. U. O. Dong, “The role of heart rate variability in sports physiology (Review),” *Exp. Ther. Med.*, vol. 11, pp. 1531–1536, 2016.

[34] T. O. F. Contents and K. E. Y. Terms, “Stress and Recovery Analysis Method Based on 24-hour Heart Rate Variability,” in *Proceedings of IEEE ICDM 2011 Workshops*, 2011, pp. 1–13.

Tables

Women		Men	
Thin	< 17 kg/m^2	Thin	< 18 kg/m^2
Ideal	17 – 23 kg/m^2	Ideal	18 – 25 kg/m^2
Fat	23 – 27 kg/m^2	Fat	25 – 27 kg/m^2
Obesity	> 27 kg/m^2	Obesity	> 27 kg/m^2

Table 1. Differences between BMI women and men in Indonesia.

Class	BMI (kg/m^2)	Relaxation		After Exercise	
		HR (bpm)	RR (s)	HR (bpm)	RR (s)
1	19.7-25.0	61-87	0.70 - 0.98	89-115	0.53-0.68
2	25.2-30.2	68-95	0.63 – 0.89	99-120	0.51-0.66
3	18.7-22.0	63-74	0.68 – 0.95	79-99	0.62-0.77
4	23.3-30.4	75-99	0.60 – 0.79	101-117	0.52-0.60

Table 2. Data on the range of HR and BMI for each class.

-

Designator	Component	Number	Total cost – currency ($)
Op-amp as amplifier and filter	AD8232 Module Details: Operating Voltage – 3.3V, Analog Output, Leads-Off Detection	1	5.96
Sensor to capture the electrical activity of the heart	Disposable Conductive Electrode Pads ECG EKG Self Adhesive	1	8.99
The cable that connects the electrode module and AD8232	Electrode sensor cable	1	6.1
As a decrease in resistance	Gel electrode	1	5.95
Total Cost			30.06

Table 3. Bill of materials (ECG system).

Figures

(a)
(b)
(c)

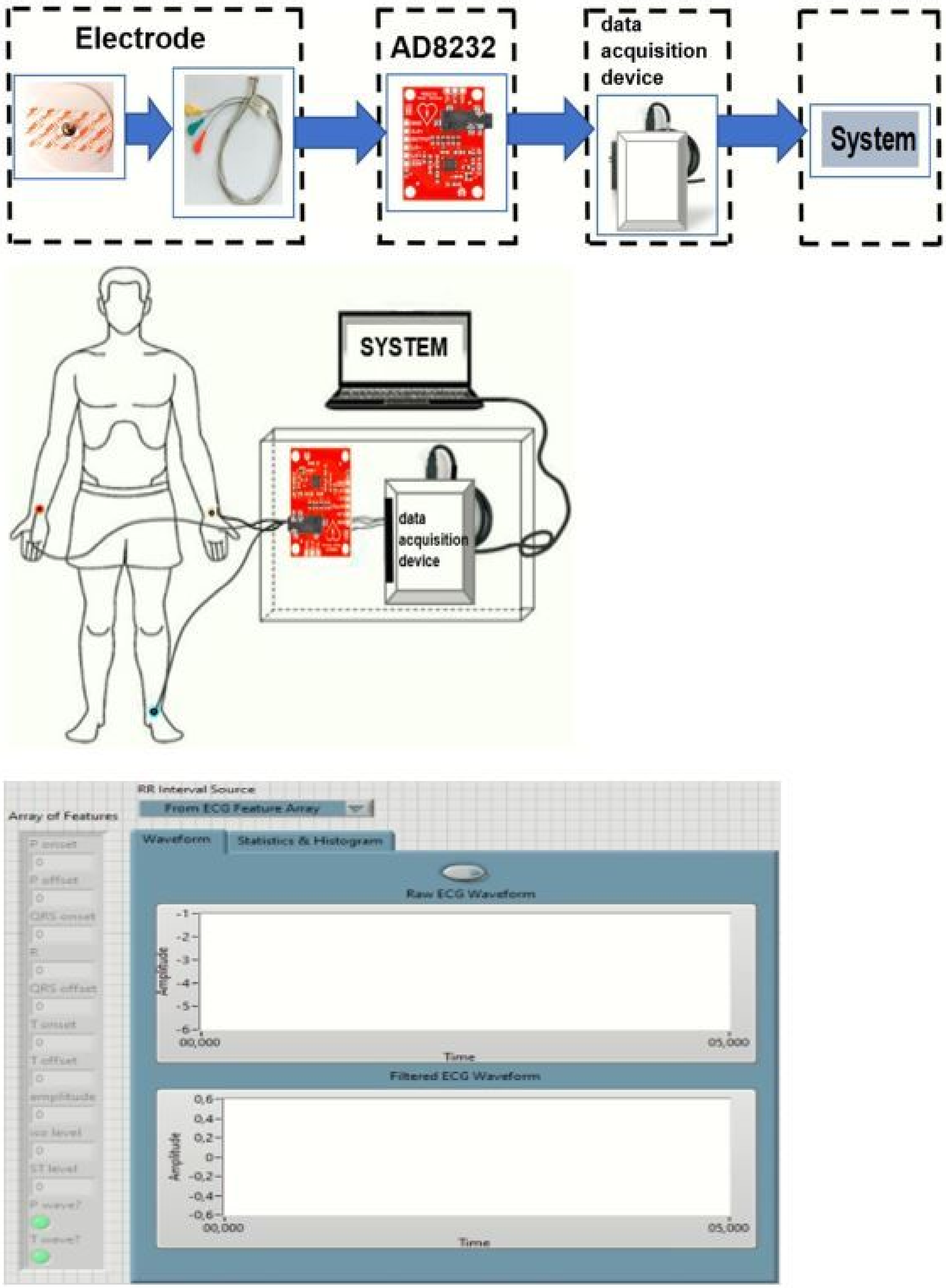

Figure 1

The ECG system. (a) Block diagram of a simple ECG system. The system includes an electrode sensor, three leads, AD8232 module as an amplifier and filter, MyDAQ module for data acquisition device, and a monitor to display data. The electrode sensor captures the cardiac biopotential signal. Signals collect and process by data acquisition device, and results can be shown on a monitor by the ECG system. (b) Experimental setup for testing of the ECG system. In the heart signals measurement, the electrode sensor is placed in the right arm, left arm, and left leg. (c) Screenshot of a recorded ECG system. The system displays RR intervals, average HR values from the ECG feature array, and waveform and statistic-histogram.

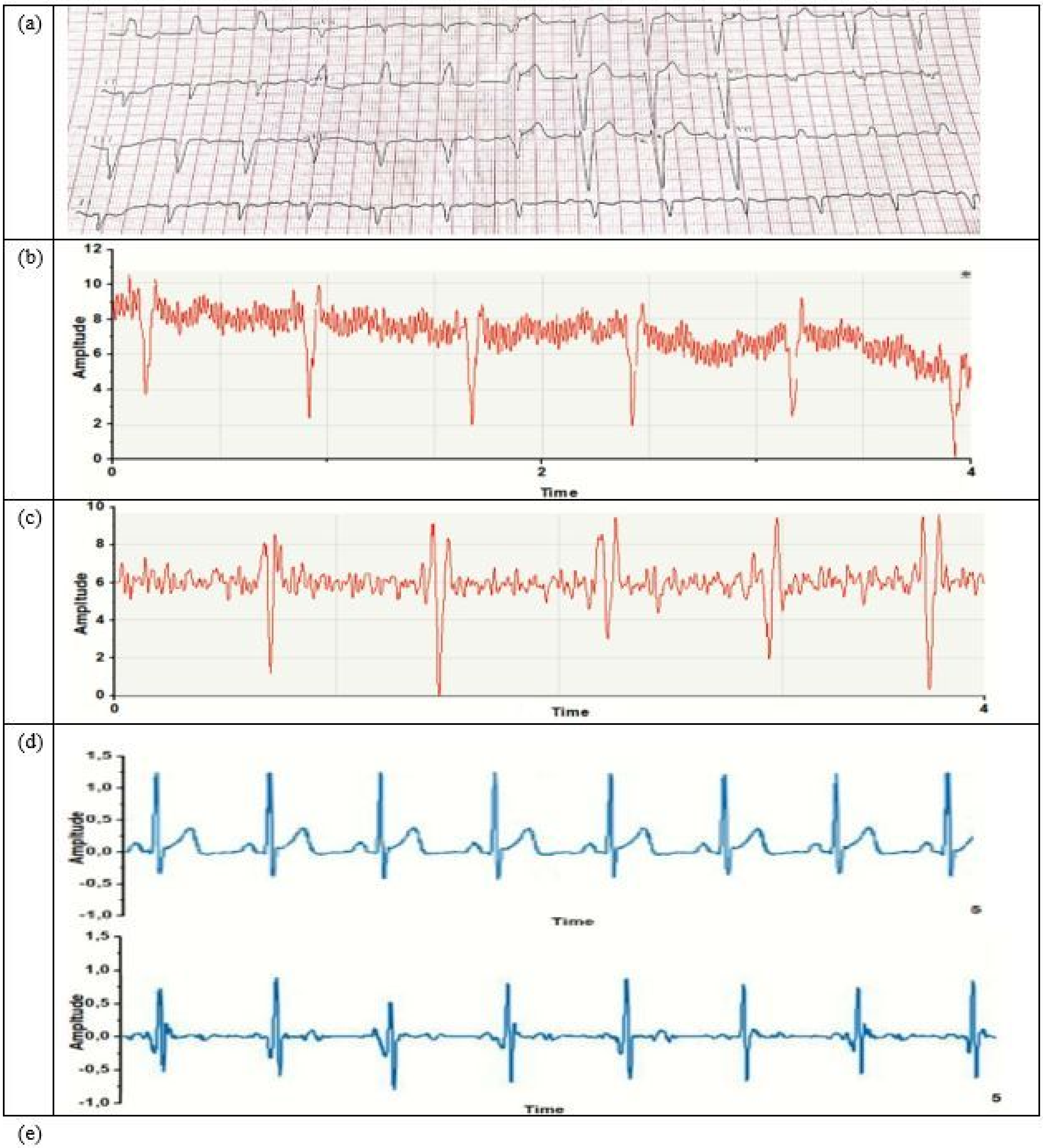

Figure 2

The comparison signals of the commercial ECG 12 leads (a) and signals of a recorded 3-leads ECG file (b) before and (c) after filtered in 4 seconds. The data was taken directly from the same patient in the hospital. (d) ECG signal before and after filtered in 5 seconds. ECG signal was better after filtering.

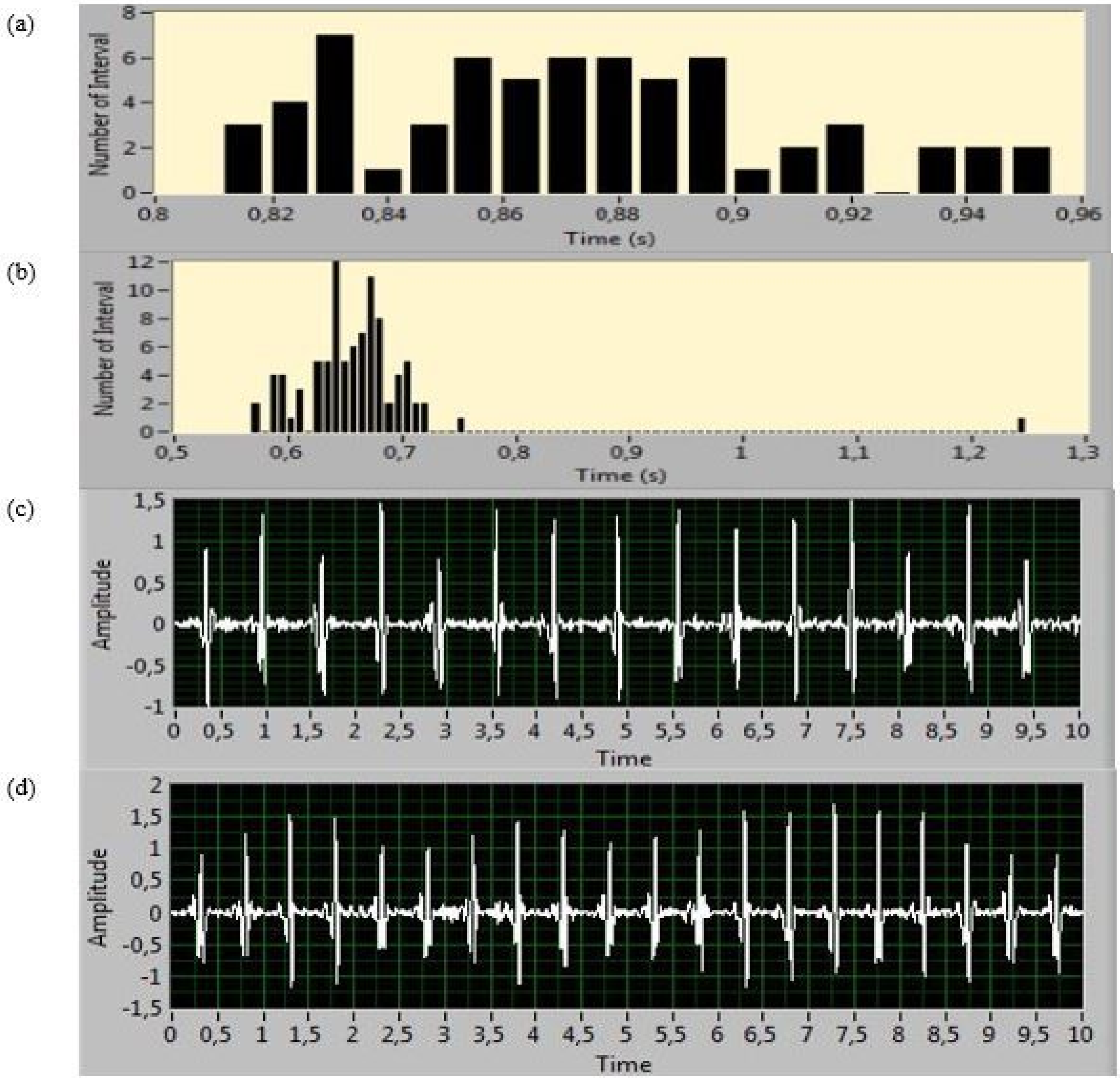

Figure 3

HMI: Time-domain HRV, when (a) before and (b) after exercise. There was an increase in the HR value from 69 to 92 bpm and a decreased RR value from 0.872 to 0.66 seconds. Signal Samples for (c) before and (d) after exercise. There tends to be an increase in the number of signals in training conditions.