Original Article

A Real-Time Remote ECG Monitor with IoT: Application in Cellphone with Arduino Device

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Objective: Generally, the price of single-lead electrocardiogram (ECG) monitors in operating rooms is more than a hundred thousand New Taiwan Dollars (TWD). These machines are not necessarily equipped with the function of remote monitoring. In addition, physicians usually do not have a simple way to obtain ECG samples for signal analysis. We aimed to create a prototype based on the concept of "low-cost, fast, and low-tech" for both experimental research and ECG data collection.

Methods: This study tested the connection of Arduino Uno with the single-lead ECG monitor AD8232 chip and transmission of the ECG signal through wifi from Raspberry Pi 3B+ to the physicians' cell phones to provide real-time remote ECG monitoring.

Results: The cost (about 3000 NTD) lowering can speed up and promote research. In addition, the device can be applied in a patient with a resting heart rate between 60 – 100 bpm, but may not be accurate for patients with arrhythmia or tachycardia. The validation of AD8232 was performed and compared with clinical ECG by simultaneously measuring 600 seconds for one individual.

Conclusions: We created this prototype to enable real-time remote monitoring and allow physicians to obtain the data for subsequent analysis such as the analysis of frequency domain data based on the fast Fourier transform (FFT) method. However, the device can be applied in a patient with resting heart rate between 60 – 100 bpm, but may not be accurate for patients with arrhythmia or tachycardia.

Key words: ECG, RR intervals, Fast Fourier transform, Arduino

Introduction

We aimed to use the Remote Desktop Client on Android cell phones to connect to Raspberry Pi 3B+ and Arduino Uno through wifi to achieve real-time remote electrocardiogram (ECG) monitoring, embodying the pristine idea of Internet of Things (IoT) . The motivation of this work is to lower the cost of monitoring and provide the concept of IoT for international medical stude-

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-nts at our instittute who would return to their counties where expensive medical equipment may not be available.

The concept IoT was initially introduced in 1995 in the book "The Road Ahead" written by William Henry Gates III (or Bill Gates).[1] That gave us some insights into his smart home's ideas. He believed that all kinds of home appliances would be able to connect to smartphones in the future, thereby originating the IoT concept. Later, it was not until 1998 that the term "Internet of Things (IoT)" was formally proposed by Kevin Ashton,[2] director of the Auto-ID Center at the Massachusetts Institute of Technology in the United States. According to the concept of IoT, physical devices and virtual (digital) items can be interconnected to facilitate all sorts of control, detection, and services via data acquisition and communication technology over the global internet infrastructure.[3]

In the past, physicians could only observe the vital signs by standing next to the patients. In the future, with the implementation of the prototype concept, doctors from different disciplines can remotely monitor in real time and discuss their patients conditions. This device can also be adopted in emergencies. For example, emergency medical technicians (EMTs) can apply the ECG electrodes to the correct sites to allow emergency physicians to have a real-time understanding of the patients' status through the network.[4-6] Moreover, during the process of transferring patients from the emergency department to the operating room, anesthesiologists can view patients' real-time ECG data on the their cellphones.[7]

This research combined Arduino, Heart Rate Monitor and Raspberry Pi to record the ECG signals, instantly plot the ECG waveform and provide remote monitoring. Furthermore, the signals were evaluated for correctness through Fourier transform.

Materials and Methods

Software and hardware

The hardware in this study comprised

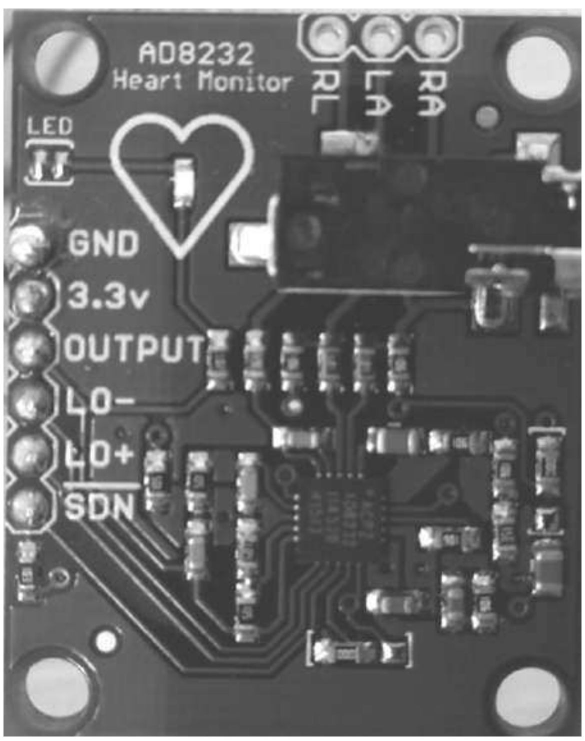

Fig. 1 The Heart Rate Monitor AD8232 chip, powered from 3.3V DC, with analog output suitable for signal conditioning of cardiac electrical activity for heart rate monitoring.

Fig. 2 Arduino Uno: An open-source, low-cost microcontroller platform priced at about 1,000 TWD.

three major components, one of which is the AD8232, Heart Rate Monitor chip (Fig. 1) (Power voltage: 3.3V DC; Output: analog output). It is suitable for signal conditioning of cardiac electrical activity for heart rate monitoring. Another major component is Arduino Uno (Fig. 2), which is an open source development platform. Both its open source hardware and software enable users to develop a wide range of applications. It is suitable for the development of various types of sensors or the employment in IoT. The third one is Raspberry Pi (Fig. 3), which is a Linux-based single-chip computer board. It was developed by the Raspberry Pi Foundation in the United Kingdom for the purpose of facilitating basic computer science education by providing low-priced hardware and free software. The board we used was Raspberry Pi 3B+. Raspberry Pi is very lightweight (i.e., only 42g) and suitable for merging into portable devices. Its business-card size takes up nearly no space.

The software used in this study was as follows: (1) Arduino IDE 1.8.4, (2) Excel® Office 2016, (3) Matlab® 2014a, (4) Microsoft Remote Desktop 8.1.61.323 for Android phones, and (5) The operating system for the Raspberry Pi: Raspbian (Version: June 2018). Figure 4 shows the hardware connection of Arduino with AD8232 in this study.

Methods

This study used the connection of Arduino Uno with the single-lead ECG monitor

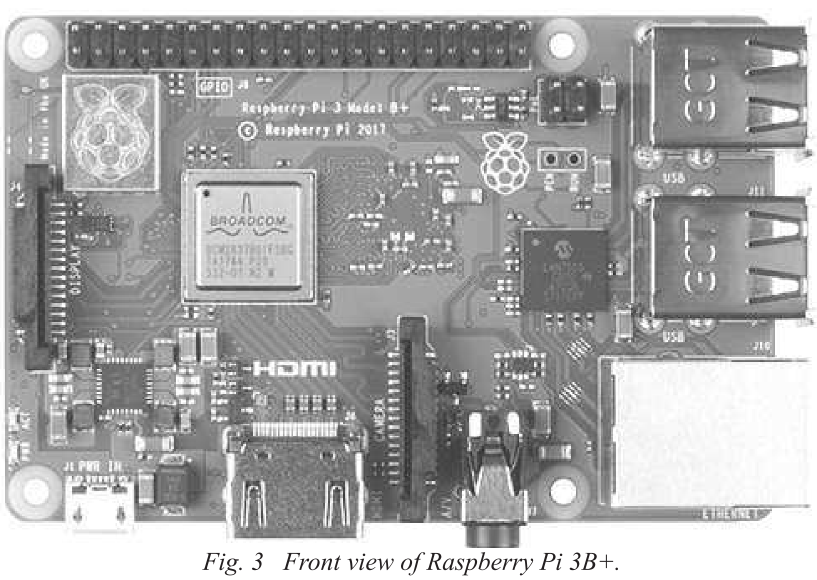

Fig. 3 Front view of Raspberry Pi 3B+.

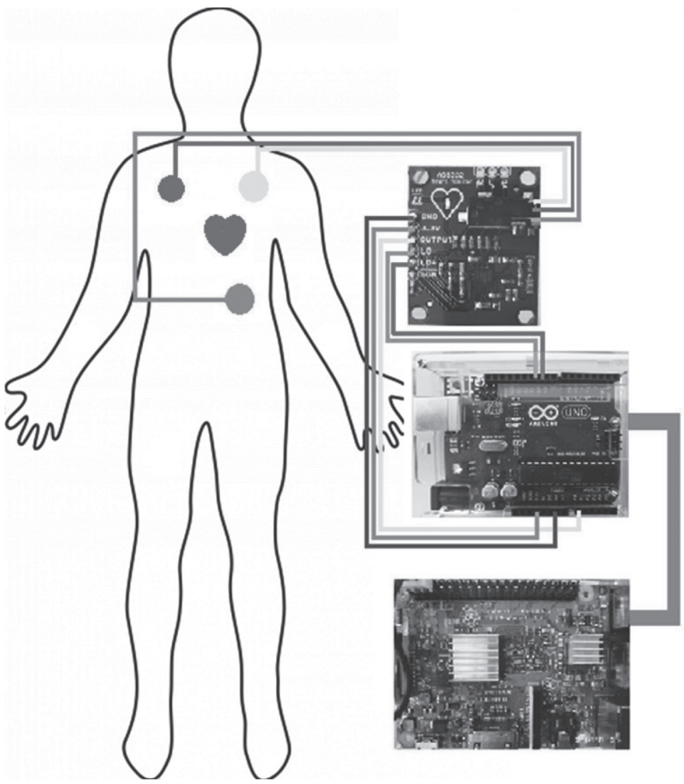

Fig. 4 The diagram of hardware connection of Arduino with AD8232. Shown was the Raspberry Pi 3B+ computer (bottom), connected with Arduino Uno (middle). The upper one was the heart rate monitor AD8232 chip.

AD8232 chip and transmission of the ECG signals through wifi from Raspberry Pi 3B+ to the physicians' cell phones to enable remote real-time ECG monitoring. The overall operation process was as follows:

(1) A 40-year-old male volunteer without any history of heart disease, after a 10-minute rest, was placed with the ECG electrodes onto the right arm, left arm, and left leg in a sitting position.

(2) The ECG signals were acquired for 600 seconds at 9600 baud.

(3) The wifi-enabled Raspberry Pi 3B+ was responsible for sending the acquired ECG signals through Arduino Uno to users, who used Remote Desktop Client to connect to Raspberry Pi 3B+, to achieve remote monitoring.

(4) Finally, a total of about 12,000 analog signals obtained were subject to analysis in Excel® and Matlab®. Setting time (second) as the X-axis and analog ECG signal amplitude as the Y-axis, we remade the line chart and obtained Figure 5 by Algorithm 1.

Fast Fourier transform (FFT) analysis

Algorithm 1. Acquisition of ECG signals form Arduino Uno.

```
Open Arduino Uno Serial Port and set the communication speed 9600bps (Bits Per Second)
Define pin 10 and pin 11 as input
for loop
  if pin 10 or pin 11 = 1
    Transfer data message (ex: "!") to an external computer
  else
    Read A0 signal
  end if
  Delay 1 millisecond
end for
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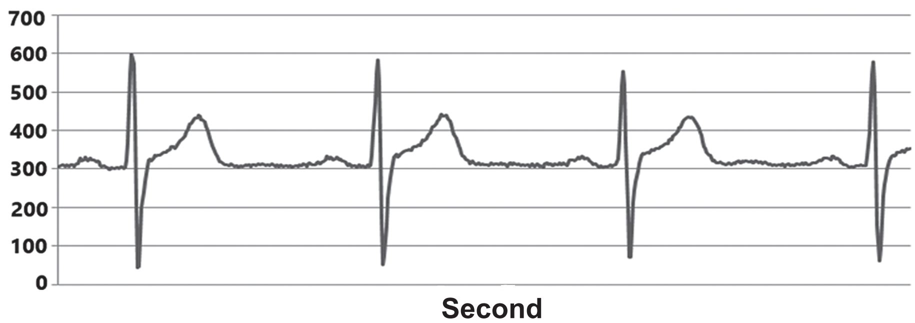

Fig. 5 The ECG graph re-charted with Excel® by using signal sampling for 4 seconds.

The time domain method was first used for ECG signal analysis, but the limitation was that there were not enough features to study the acquired signals. In this study, we employed the inbuilt fast Fourier transform (FFT) analysis in Excel®. FFT is a widely known method, which transforms time domain signal to frequency domain to obtain the frequency coefficient. FFT is one the of transformation methods in signal processing and has many applications in frequency analysis and signal processing. Compared with discrete Fourier transform (DFT), FFT is an algorithm that prevails in speed and achieves the same result.

We also used Matlab® to analyze the same data, and the result was consistent with that obtained in Excel®. The formula of FFT is defined below in formula (1).

$$(1)\ XK = \sum_{n=0}^{N-1} \chi e^{-nk\,2\pi i/n}$$

The k in the formula is an integer, ranging from 0 to N-1. There are various techniques that can effectively compress ECG signals, and one of the most important techniques is FFT through Algorithm 2.

The general process consisted of the following steps:

(1) Acquire ECG samples and input the signal data into Excel® and Matlab®.

(2) Compress the signal by removing low frequency components.

(3) Perform an inverse FFT to recover the signals.

Subsequent to data analysis, we obtained the graph as shown in Figure 7. The ECG showed only a single peak along the frequency axis (Fig. 7), which confirmed the correctness of our sampling. This also suggested that our study could provide the users with simple steps to ECG signal analysis.

Algorithm 2. The ECG signal process by FFT.

1	Input ECG data
2	Transfer the ECG data to Fourier domain (Let the variable = XK)
3	Define the noise data (I) = XK < max(XK) × 0.2
4	Find I XK and set to 0
5	Using inverse Fourier transform to restore ECG signal
6	Draw the sampling date of ECG signal
7	Save

Validation with clinical ECG monitor (Philips IntelliVue MP60)

The validation of AD8232 was performed and compared with clinical ECG by simultaneously recording 600 seconds for one individual. The RR intervals estimated by AD8232 and ECG were compared with MA plot and tested by Wilcoxon signed-rank test.

Results

Figure 6 shows real-time ECG signals on a cell phone measured from a 40-year-old male volunteer. Table 1 demonstrates the first 20 signals obtained by the present method.

The validation of AD8232 was performed and compared with clinical ECG by simultaneously measuring 600 seconds for one individual. There were about 722 RR intervals acquire from AD8232 and ECG. Differences

Fig. 6 A volunteer's real-time ECG displayed on the smartphone.

in RR intervals between AD8232 and ECG were examined by Wilcoxon signed-rank test (Fig. 8). The RR intervals between AD8232 and ECG were not significantly different with a *p*-value of 0.058. Meanwhile, the MA plot (i.e. Bland-Altman plot) was adopted to investigate the difference in RR intervals measured between AD8232 and ECG (Fig. 9). The MA plot showed the difference in RR intervals within ± 0.1 second.

Discussion

The results in this study indicated that, with the employment of Arduino Uno, Raspberry Pi, and the AD8232 heart rate monitor, real-time remote monitoring of variations in patients' ECG was able to be achieved.

This created prototype based on the concept of 'low-cost, fast, and low-tech' is available for both experimental research and ECG data collection. The cost lowering can speed up and promote research. In addition, the device can be applied in a patient with a resting heart rate between 60 – 100 bpm, but may not be accurate for patients with arrhythmia or tachycardia.

The embodiment of IoT concept allows a variety of vital signs monitors to be interconnected. Healthcare specialists can control all kinds of instruments via cell phones, and concurrently the real-time vital signs from the instruments can be sent back to specialists, thereby enabling timely treatment.

Generally, there is no simple way for physicians to download patients' ECG data. This research provides a low-priced and accurate technique for physicians to analyze ECG sig-

Table 1. ECG samples obtained from the first 20 cases.

ECG analysis					
Sample	time (second)	mV	Fast Fourier Transform	Amplitude	Frequency index
1	0	307	169668	169668	0
2	0.005	305	-17.6186666656548+401.967803877164i	402.353740	1
3	0.01	308	672.366849958141+351.224661790531i	758.574942	2
4	0.015	311	-7371.91530276351+2852.0344049682i	7904.38077	3
5	0.02	308	-386.090333429692+434.340801872445i	581.134818	4
6	0.025	307	-477.86993342392+538.179091094651i	719.719672	5
7	0.03	310	3591.25082931313-5959.20843662326i	6957.67545	6
8	0.035	308	199.155779705726-471.682448153492i	512.003277	7
9	0.04	307	194.737571499894-545.748866224149i	579.451936	8
10	0.045	311	-1566.11562364533+5426.92938223973i	5648.38743	9
11	0.05	311	-20.7829775777795+669.251928541244i	669.574548	10
12	0.055	307	178.645465308221+692.703353677583i	715.368533	11
13	0.06	310	-183.440988038873-3202.58957791265i	3207.83893	12
14	0.065	313	-243.231126779342-360.687571373489i	435.036671	13
15	0.07	313	-76.6915916424473-295.861791246942i	305.639983	14
16	0.075	320	-675.561647404377-928.114862462337i	1147.94631	15
17	0.08	327	-135.486813233144-491.574156803128i	509.903744	16
18	0.085	321	45.2156976149764-1005.56142342451i	1006.57748	17
19	0.09	324	-1113.26245233786+4268.50229490858i	4411.28837	18
20	0.095	330	-390.26514752854+1257.57217621366i	1316.73636	19

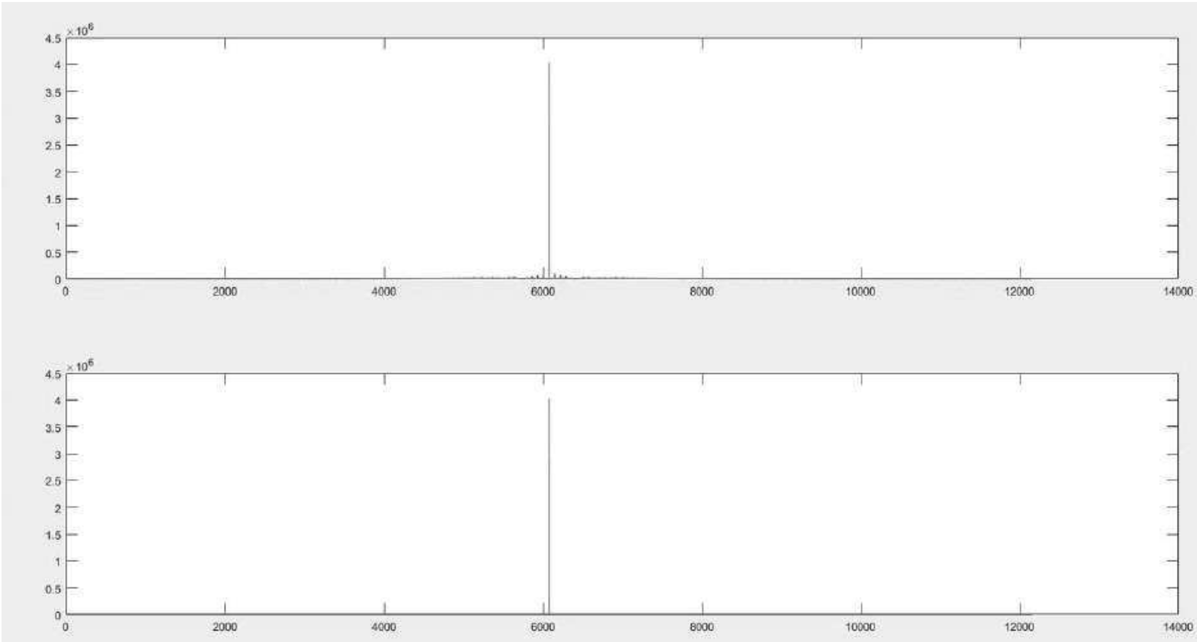

Fig. 7 The upper panel was obtained using discrete Fourier transform (DFT) in Matlab®. The lower panel showed the enhanced result after noise filtering.

nals. In this study, the same ECG sample was analyzed and processed in Excel® and Matlab®, using FFT algorithm to transform data from time domain to frequency domain. Moreover, it can also be used to analyze heart rate, heart rate variability, and sympathetic nerve activity.

There are several reasons for choosing Arduino and Raspberry Pi:

(1) Raspberry Pi is highly expandable and low-cost. It can work with various electronic gadgets from many manufacturers. A variety of chips can be chosen and connected with Raspberry Pi, such as pressure sensors and SpO_2 sensors.

(2) The integrated development environment (IDE) for Arduino is well-developed. Developers can specialize in the development of various types of new electronic devices.

(3) Open source — An idea of sharing. Open source hardware refers to a hardware design made publicly available by the original designer so that anyone can realize how it works to facilitate further modification and improvement. It also allows the development of individual and commercial products.

In this study, we used FFT in Excel® to conduct the analysis. However, FFT was weak in providing accurate location information regarding the frequency. The inbuilt FFT in Excel® does not have the function of shift. Therefore, we used Matlab® to verify the Excel® results, which were shown to be consistent. This suggests that such an analytic approach is worth promoting because of the high popularity of Excel®.

Such a prototype may not replace the current laboratory or hospital equipment, but the IoT concept we proposed is aimed at enabling real-time analysis and discussion on the same patient's condition among physicians of different disciplines regardless of their locations. Moreover, the application can be promoted in medical colleges or senior high schools so that students can better understand the principles of ECG to increase the educational depth in the field of cardiac electrophysiology.

As ECG recording devices continue to increase in popularity, the need for ECG analysis also continues to grow. ECG signals of importance in the time and frequency domains can be extracted by the prototype. The result of the present study showed that extracted data from

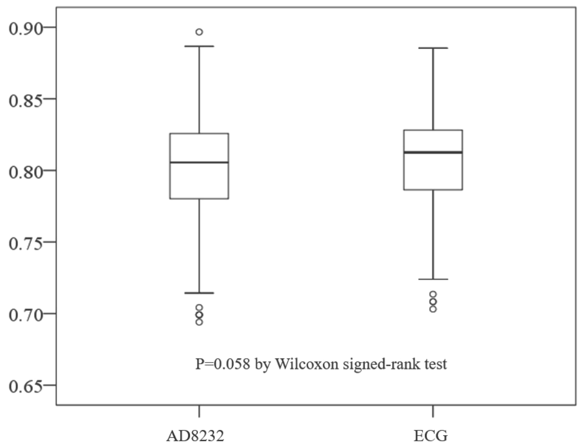

Fig. 8 Box plots of RR intervals between AD8232 and Philips ECG monitor and P-value by Wilcoxon signed-rank test.

the post-processing algorithm were compatible with those shown on the Philips ECG monitor.

Although such a prototype cannot replace the current hospital equipment, the IoT concept we proposed enables physicians from different locations to discuss and analyze the ECG data at a lower cost.

Limitations

The estimated RR intervals might be inaccurate from only one effective sample in this study. However, this was a prototype and conceptual device for monitoring possible arrhythmia. At this stage, only normal sinus rhythm was collected for validation of the present device. More samples from different individuals are needed for supporting our findings. Further studies regarding variations in both heart rates and morphologies are warranted to test the validity of the present device for clinical use in the future.

In conclusion, we created a prototype of a read-time remote ECG monitoring device to allow physicians to obtain the data for subsequent analysis (e.g., frequency domain data) based on the FFT method.However, although the device can be applied in a patient with a resting heart rate between 60 – 100 bpm, it may not be accurate for patients with arrhythmia or tachycardia.

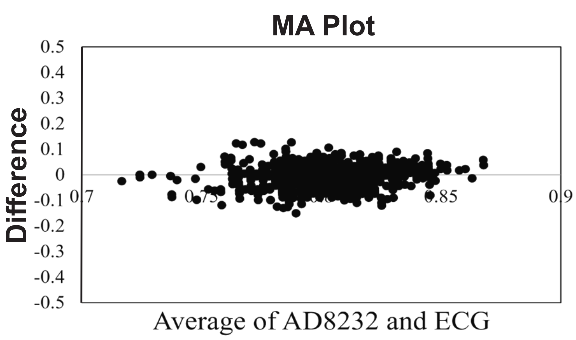

Fig. 9 MA plot of differences in RR intervals between AD8232 and ECG.

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