A Heart Sound Acquisition and Analysis System Based on PSoC4

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Abstract: In order to improve the way of cardiovascular disease census, a heart sound acquisition and analysis system based on PSoC4 acquisition board and PC software is developed. The heart sound signal is detected, processed and auscultated by acquisition board, and then sent to PC via Bluetooth for analysis. In the software, a specific duration heart sound is real-time displayed and automatically analyzed. It not only can realize visual auscultation, but also can identify normal and abnormal heart sound by graphical representation, and give the parameters of heart function. The clinical test with 62 heart sound data verifies the usefulness and practicability of the system. It will have a strong practical value for remote medical care and home care in the future.

Key-Words: *Heart Sound (HS), Acquisition and Analysis System, PSoC4 (Programmable System on Chip), Hybrid Programming*

1. Introduction

The outline of Chinese cardiovascular disease report 2014 shows that cardiovascular disease death ranks first in the urban and rural residents, while the countryside was 44.8%, the city was 41.9% [1]. And with the growing aging population and the acceleration of urbanization process, the cardiovascular disease patients will continue rapidly increasing. Hence, the prevention of cardiovascular disease has become a hot social concern. General investigation of cardiovascular disease is an effective method. However, due to the limitation of regional environment and medical conditions, cardiovascular disease census needs the portable and accurate medical diagnostic instrument with low cost.

Clinical diagnosis methods of cardiovascular disease mainly include echocardiography, intracardiac catheter technique, etc. The above diagnostic instruments are not only large, inconvenient to carry, and invasive examination, but also will cause big physiological burden to patients. HS, generated from heart valve opening and closing, tendon and muscle contraction and relaxation, the impact of the blood flow and blood wall vibration, is an important noninvasive detection means for cardiovascular disease. It is cheap, convenient, safe and noninvasive and can reflect the mechanical movement status of heart and great vessels. Heart murmur and HS distortion are important diagnostic information for early detection of cardiovascular disease. Instead of electrocardiogram, HS can also acquire the parameters of heart function to evaluate one’s heart function. So it can be used as a routine method in early detection and prevention of cardiovascular disease.

However, traditional HS auscultation has low accuracy and mostly relies on the sound resolution of human ear and doctors’ clinical experience, and it is limited in the generalization of cardiovascular disease census. So, in order to solve the problem of

Received: 2017/6/22, Accepted: 2017/9/11.
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cardiovascular disease prevention and control work and meet the needs of grassroots census, providing a more visual and reliable auxiliary to the doctor, a research for a HS acquisition and analysis system is proposed.

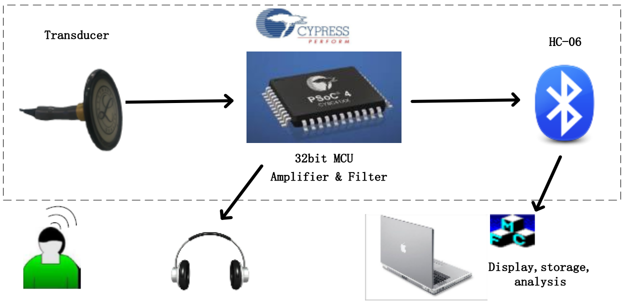

Fig. 1 Block schematic of the whole system

The current mainstream technologies in the embedded microcontroller processor technology are SCM (Single Chip Microcomputer), ARM (Advanced RISC Machines), DSP (Digital Signal Processing), CPLD (Complex Programmable Logic Device)/FPGA (Field-Programmable Gate Array), etc. SCM is low power consumption and low cost, but slow and simple function. DSP is fast speed and strong function, but the cost is higher. CPLD/FPGA is also fast speed and can realize the flexible design of digital circuit, but the development efficiency is low. ARM has strong function and can develop more complex system, but is difficult to learn. In recent years, PSoC technology is appeared and can realize programmable design of analog circuit, digital circuit, microcontroller circuit on a single chip, which will represent the development direction of electronic information technology. It is advantageous to develop a new generation product of high integration, low cost, small volume and low power consumption by using PSoC technology. PSoC4 has a superior cost-effective 32bit ARM Cortex-M0 microprocessor kernel. It is integrated with a lot of portable medical electronic analog and digital devices. It not only has a small profile, but also low power and low cost. So, PSoC4 is chosen as the main control chip of the HS acquisition and analysis system [2].

The research introduces the system hardware and software module design in detail for HS signals collection, pretreatment, wireless transmission, real-time waveform displays and graphical analysis results display. At the same time, in order to comprehensively evaluate cardiac function of mechanical state, the results of the analysis not only include the common indexes parameters such as scatter diagram and heart rate, but also calculates the ratio of the first and second HS amplitude (heart inotropic intensity) and the ratio of the systolic and diastolic time (heart chronotropic intensity) to evaluate the ability of myocardial contraction and whether the cardiac blood time is enough or not. Finally, a reference analysis results are given to evaluate heart function comprehensively.

2. The HS acquisition and analysis system

The block schematic of the whole system [3] is shown in Fig.1. The system can be divided into two parts: the acquisition board and PC based software. Firstly, the transducer, a highly-sensitive microphone, senses the HS and converts them into analog electrical signal for further signal processing. Then, the PSoC4 is used to process HS in analog and digital ways, and send processed digital signal to PC via Bluetooth and analog signal for auscultation. Finally, the PC software enables the signal to be real-time displayed and automatically analyzed when the acquisition is finished. The improved wavelet threshold shrinkage algorithm [4] is used for noise reduction to improve the signal to noise ratio (SNR) of HS. The cardiac sound characteristic waveform (CSCW) extraction method based on the single-degree-of-freedom (SDOF) [5][6] model is used for analysis. Meanwhile, the easy-understanding graphs and parameters of heart function are used for achieving the visualization of diagnostic results.

The whole system design is divided into four steps. First, design the hardware circuit and hardware program of acquisition board. Second, design software in PC to receive the HS signal acquired by acquisition board for further analysis test. Third, improve the existing analysis algorithm of HS according to the signal stored in PC. Forth, integrate PC acquisition software and HS analysis algorithm, and connect acquisition board for overall test. Detailed design of each part is presented separately as follows.

2.1 The HS acquisition board

The acquisition board has three functions: firstly, detect and pre-process HS signal; secondly, send the digital signal to PC via Bluetooth; thirdly, real-time auscultate HS.

2.1.1 The design of hardware circuit

HS transducer. Since the HS is a kind of weak signal and its frequency spectrum is about 20~700Hz, in order to pick up HS signal, circuit is designed according to the existing auscultation head structure in our laboratory. The HS transducer is comprised of a microphone (audio-technica®, AT899) and a traditional chest-piece (Littman, ClassicIISE) made by 3M company. The specifications of microphone are shown in Table 1.

Table 1 Specifications of microphone

Frequency response	20~20000Hz
Sensitivity	-43~-46dB
Impedance	200ohms
SNR	64dB

Processing model. The core of processing model is PSoC4 chip, which is mainly applied to filter the unwanted signal out of HS frequency band, convert analog signal to digital ones, control the transmission of HS data and change the volume in auscultation. The internal block schematic of PSoC4 is shown in Fig.2. The system clock is configured to be 48MHz.

While the output of HS transducer is very feeble, about -80mV~ +80mV tested by the oscilloscope when it is supplied by 3.3V DC power and limited current by 10K resistance, and the amplitude range of input analog signal in PSoC4 is 0~+3.3. So a bootstrap amplifier is designed to amplify and uplift the signal to adapt further process. It is comprised of an operational amplifier in PSoC4 and some peripheral components. The output current intensity of the amplifier is set to be 10mA.

In order to avoid high frequency noise and reserve the interesting frequency of HS, a low-pass filter, whose cut off frequency is set to be 700Hz mentioned before, is designed. It is a second order Butterworth filter built by an operational amplifier configured as the bootstrap amplifier and some simple peripheral components.

After the previous operations, a 12-bit depth analog to digital converter (ADC) in PSoC4 is used to convert analog HS signal to digital signal. According to Nyquist Theorem, in order to avoid frequency aliasing, sample frequency can’t be less than two times of the maximum frequency of the signal. Here, the sample rate is 2kHz.

While the HS frequency band involved in this paper is 20~700Hz, the signal frequency below 20Hz need to be filtered. However, the PSoC4 only has two operational amplifiers, which we have already used before. So, in order to control the cost, we embed a type of Butterworth IIR directly high-pass filter, whose cut off frequency is 20 Hz.

UART is used to connect Bluetooth model and realize data transmission with PC. The communication mode is 115200bps, 1 stop bit, no parity bit, 8 data bits. And a Bluetooth model HC-06 is chosen as slave model.

Auscultation model is used to realize real-time auscultation. The circuit is made around the headphone amplifier chip LM4811, which can realize 16 volume levels by two control line. Capsense and touch board are used in auscultation volume control and data transmission control. The Capsense mode is configured to be button and the button scanning resolution is 12bit. The Internal design of PSoC4 is shown in Fig.3.

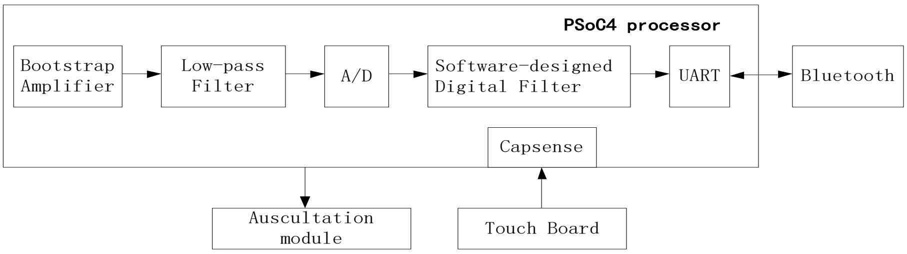

Fig. 2 Internal block schematic of PSoC4

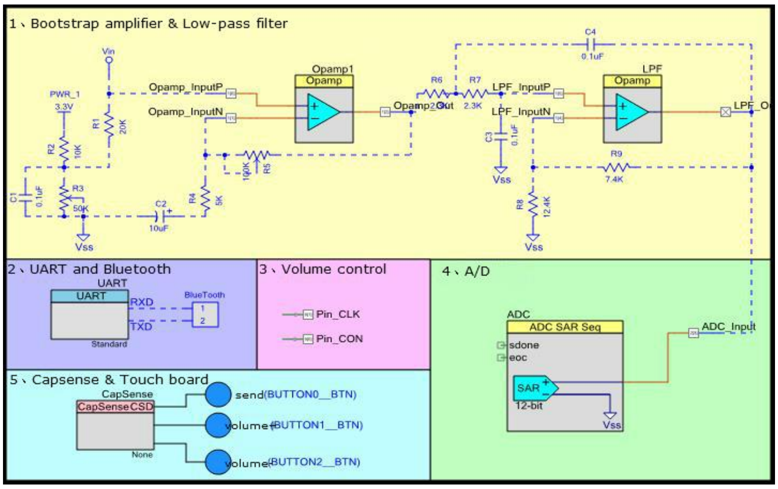

Fig. 3 The Internal design of PSoC4 in PSoC Creator3.1

2.1.2 The design of hardware programming

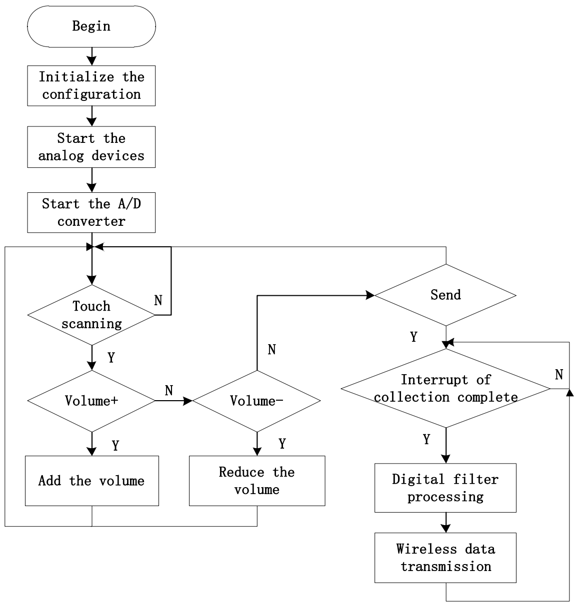

Fig. 4 The software flow chat in PSoC4

The flow chart of programming in the PSoC4 is shown in Fig.4. When the system is powered on, the PSoC4 begins to initialize the configuration, including the operational amplifier, GPIO, A/D converter, UART and interrupt, etc. Then, start the A/D conversion and begin to collect data. When the sending touch key is touched and a conversion is finished, begin to process the converted data. Finally, when the data processing is completed, send the processed data by bytes.

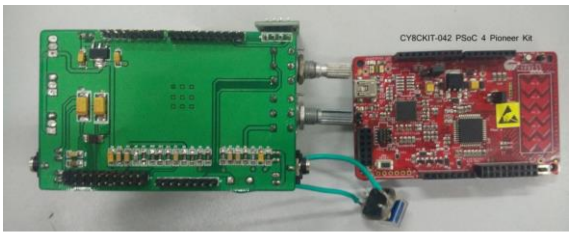

Fig. 5 PCB of acquisition board

The complete acquisition board is shown in Fig.5. The green printed circuit board (PCB) is designed to be perfectly matched with the red one, CY8CKIT-042 PSoC 4 Pioneer Kit. The HS of a normal Male is acquired by the acquisition board and presented on the Agilent DS05014A oscilloscope. The unprocessed HS signal and processed ones are shown in Fig.6. CH1 is the original HS signal, which Pk-Pk is189mV and contains a lot of glitch noise. While CH2 is hardware processed ones, which Pk-Pk is 1.5V, about 8 times magnified compared with the original signal, and not only the glitch noise is filtered, but also the most characteristics of original signal are retained.

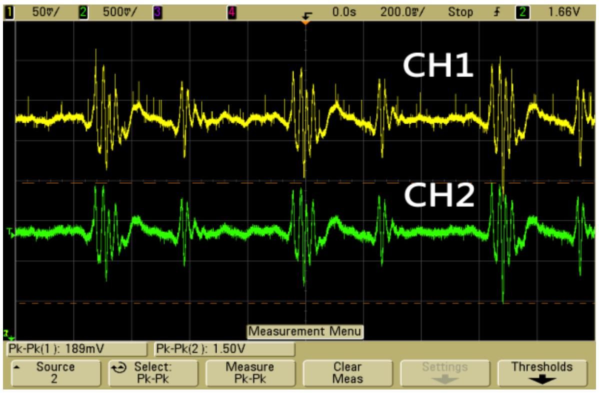

Fig. 6 The result of hardware processing on a normal Male HS

2.2 The software for monitoring and analysis of HS

The software for monitoring and analysis of HS is developed in MFC for Microsoft Visual Studio 2010, which provides a powerful programming environment for the development of applications. In MFC, a user interface is made to show the real-time HS waveform, acquisition control, information of participant and analysis result. The flow chart of software is shown in Fig.7 and the interface is shown in Fig.8.

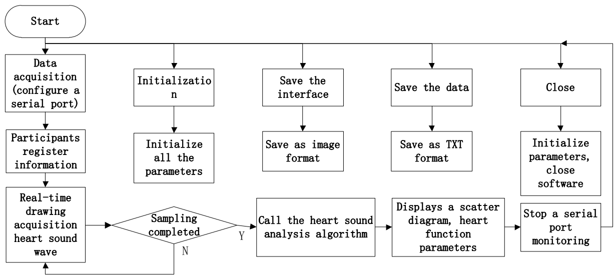

Fig. 7 The flow chart of software

Fig. 8 The interface of HS acquisition and analysis for a health person

The interface shows the acquisition HS waveform in the upper left. And the individual informal of patient is displayed in the middle, including name, gender, year, weight, height and so on. The analysis results shown in the right will be introduced in the next part.

In order to employ the analysis algorithm of HS developed in MATLAB and realize automatic analysis, VC++ and Matlab hybrid programming based on COM (Component Object Model) is applied, which can run program out of Matlab environment and realize the transplantation and engineering of HS algorithm.

2.2.1 The parameter extraction for HS diagnosis

Time-domain analysis algorithm of HS data is developed by Biomedical Information Processing

Laboratory of Electrical and Electronic Information Institute in Xihua University. First, normalize the input HS. Second, denoise it by the improved wavelet threshold shrinkage algorithm. Third, SDOF is used to extract the HS envelop. Forth, a threshold value (THV) line is selected to cross with the HS envelop and extract the diagnostic parameters [T1,T2] and [T11,T12] defined in Fig.9 and Table 2. In this study, the threshold value is determined by 1/5 of average value of HS envelop according to the previous experimental results.

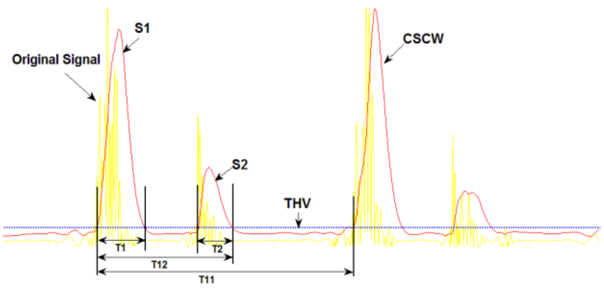

Fig. 9 CSCW and HS diagnostic parameters

Table 2 Definition of heart sound diagnostic parameters

Parameters	Definition
T1	The duration of S1
T2	The duration of S2
T11	The time intervals of two adjacent S1
T12	The duration between the start of S1 and the end of S2

In the end, display the diagnostic parameters by the scatter diagram [7] for easy understanding and calculate heart function parameters defined in Table 3.

According to different range of heart rate, bradycardia, normal and tachycardia can be determined. And the heart inotropic ability and heart chronotropic ability are divided into four levels [10], that is strong(S), good(G), weak(W) and no ability(N). The diagnostic results of the scatter diagram and the heart function condition will be found in the right side of the interface shown in Fig.8.

2.2.2 Hybrid programming

Hybrid programming [8] includes two parts. The first part is to create COM component in Matlab. The second part is to call COM component in VS2010.

In the first part, the three steps are displayed below.

(1) Configuration compilation environment.

(2) Establish M file. The filename involved in this paper is 'hsanalysis', which contains the HS analysis algorithm mentioned before. The function name is 'function [HR,CB1,CB] = hsanalysis(n)', while the output parameters 'HR', 'CB1' and 'CB' respectively means heart rate, S1/S2 and D/S. 'n' is the input data of HS. One thing worthy our attention is that the input data is one-dimensional line array of columns. So we need to transpose it before the subsequent processing.

Table 3 Definitions of heart function parameters

Parameters	Definition
HR(times/minute)	Heart rate(60/T11)
D/S	Heart chronotropic ability ((T11-T12+T2)/(T12-T2))
S1/S2	Heart inotropic ability (Peak ratio of S1 and S2)

3. Clinical verification

In this section, HS signal acquisition and analysis system is validated effectively by normal and abnormal cases. Fig.8 shows the acquisition HS waveform and analysis result of one normal HS.

The diagnostic parameters [T1, T2] and [T11, T12] shown in scatter diagram are concentrated within the two discriminated circles [7,9] and the heart rate is 67 times per minute. It indicates that the HS is normal. The S1/S2 is 3.26189 in the range of 2.25~3.33 [10], which means that the systolic ability of this participant is strong. The D/S is 1.59316 in the range of 0.10~1.60, which means that the diastolic ability is relatively good.

Besides, 62 college students' HSs are acquired and analyzed by this system, which are shown in Table 4. According to results of scatter diagram, the HS of No.3 student is discriminated to be abnormal due to the tachycardia and diagnosed by doctor before. Other ten students are misjudged. So the accuracy rate of HS is about 83.87%. In addition, the cases with the ability of heart inotropic marked by '-' will be discussed further because the value of S1/S2 larger than the upper limit of the super level may be a pathological abnormality of heart.

Table 4 The HS analysis result of 62 college students

No.	Gender	Age	Analysis result of HS (apex area of heart)					
			HR (times/min)	S1/S2	Heart inotropic ability	D/S	Heart chronotropic ability	Scatter diagram
1	Male	20	55	1.20299	W	2.08787	S	Abnormal
2	Female	18	96	1.60771	W	1.12571	W	Abnormal
3	Male	19	130	4.599	-	0.58406	W	Abnormal
4	Female	18	78	1.29034	W	0.96312	W	Abnormal
5	Female	19	56	0.76604	W	1.8603	G	Abnormal
6	Male	24	54	3.22303	S	2.09725	S	Abnormal
7	Female	19	82	3.43936	-	1.10605	W	Abnormal
8	Female	19	97	1.56194	W	1.15911	W	Abnormal
9	Female	20	93	0.95213	W	1.0808	W	Abnormal
10	Female	21	58	1.02107	W	1.84515	G	Abnormal
11	Male	20	58	1.59182	W	1.95584	G	Abnormal
12	Male	23	65	1.06551	W	1.40527	W	Normal
13	Male	24	59	2.01646	G	1.8551	G	Normal
14	Male	24	66	2.11496	G	1.70559	G	Normal
15	Female	24	72	1.76945	W	1.54242	W	Normal
16	Female	25	64	1.07641	W	1.61055	G	Normal
17	Male	24	60	2.12609	G	1.78549	G	Normal
18	Male	25	76	2.47915	S	1.54243	W	Normal
19	Male	21	81	1.53969	W	1.51292	W	Normal
20	Male	20	63	1.71228	W	1.49693	W	Normal
21	Male	20	65	2.15784	G	1.76954	G	Normal
22	Male	20	74	0.75327	W	1.73078	G	Normal
23	Male	19	61	2.7435	S	2.03246	S	Normal
24	Female	19	74	1.79601	W	1.20976	W	Normal
25	Female	20	87	1.14098	W	1.17226	W	Normal
26	Female	19	68	1.01686	W	1.45239	W	Normal
27	Female	19	79	1.4475	W	1.08703	W	Normal

28	Female	20	61	2.53632	S	1.58433	W	Normal
29	Female	19	67	0.9438	W	1.65668	G	Normal
30	Female	17	68	1.22786	W	1.61195	G	Normal
31	Female	19	87	0.89215	W	1.14333	W	Normal
32	Female	18	77	1.83638	G	1.29834	W	Normal
33	Female	19	82	1.46605	W	1.37734	W	Normal
34	Female	19	58	2.2341	G	1.97334	G	Normal
35	Female	24	69	2.2222	G	1.25832	W	Normal
36	Female	24	82	2.89267	S	1.12413	W	Normal
37	Female	19	70	1.29439	W	1.35922	W	Normal
38	Female	20	72	1.81629	G	1.26543	W	Normal
39	Female	18	65	0.74518	W	1.81979	G	Normal
40	Male	20	88	3.60557	-	1.03668	W	Normal
41	Male	25	70	1.83644	G	1.51121	W	Normal
42	Male	26	75	3.73571	-	1.17616	W	Normal
43	Male	19	90	1.6354	W	1.2208	W	Normal
44	Male	21	82	2.34477	S	1.48462	W	Normal
45	Female	19	64	1.53692	W	1.70987	G	Normal
46	Female	18	67	2.01195	G	1.42437	W	Normal
47	Female	20	59	0.92361	W	1.68428	G	Normal
48	Female	19	85	2.56839	S	1.20724	W	Normal
49	Female	20	72	1.03704	W	1.49226	W	Normal
50	Female	18	76	1.57848	W	1.50711	W	Normal
51	Female	20	89	1.86435	G	1.28337	W	Normal
52	Female	20	80	1.21974	W	1.40845	W	Normal
53	Female	18	77	1.84712	G	1.38985	W	Normal
54	Male	23	70	1.63562	W	1.57216	W	Normal
55	Male	19	60	1.16571	W	2.04019	S	Normal
56	Male	19	91	2.43613	S	1.17259	W	Normal
57	Male	25	67	3.26189	S	1.59316	W	Normal
58	Female	23	93	2.78945	S	1.03756	W	Normal
59	Male	25	65	1.84069	G	1.63579	G	Normal
60	Male	25	66	0.60932	N	1.94234	W	Normal
61	Male	23	73	3.26594	S	1.45603	W	Normal
62	Male	18	67	1.03073	W	1.80782	G	Normal

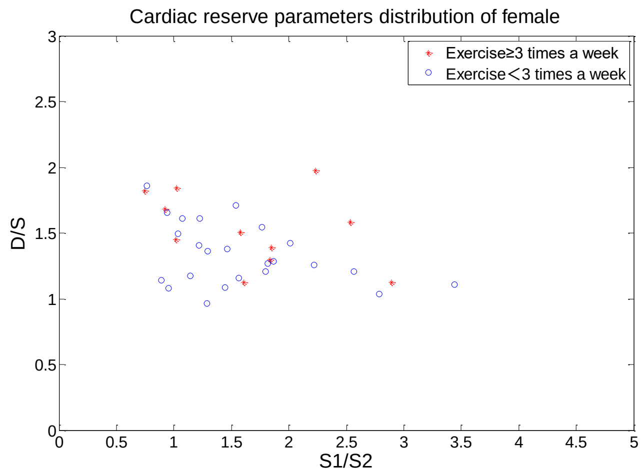

Fig. 10 The cardiac reserve parameters distribution of female cases

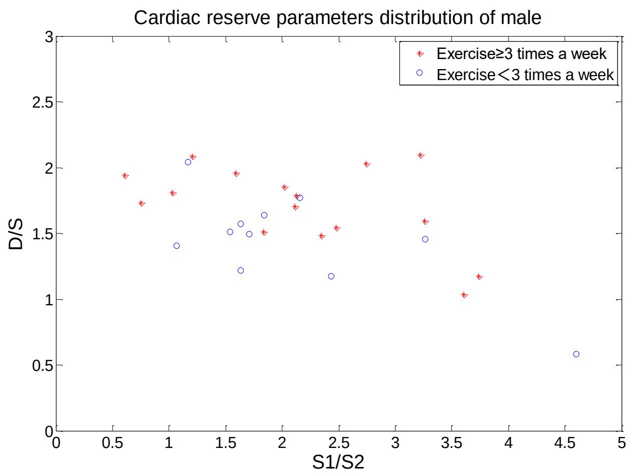

Fig. 11 The cardiac reserve parameters distribution of male cases

The 61 healthy students are divided into four different groups shown in Table 5. The scatter diagrams of cardiac reserve parameters (HR, S1/S2 and D/S) are shown for female and male in Fig.10 and Fig.11 respectively. The red ◊ shows the parameters of the cases taking exercises more than 3 times/week and the blue □ shows these of the cases taking exercises less than 3 times/week. It is easy to see that the cardiac reserve parameters distribution of female is tight, while the male is loose, which means that the cardiac reserve abilities among men are very different. The parameters values of the cases with more exercises are bigger than these of the cases with fewer exercises. It is found that the exercise in part can improve the condition of heart function.

Moreover, it is obvious that the female's heart rate generally faster than men according to the results shown in Table 5. And higher exercise frequency will make lower heart rate, larger average values of S1/S2 and D/S compared with low exercise frequency, which means that the students who exercise more will have stronger heart inotropic ability and chronotropic ability both men and women. Experiments show that the collection and analysis system involved in this article can detect the abnormal of the heart sound and reflect the condition of the cardiac function.

4. Conclusion

In this paper, a HS acquisition and analysis system is designed, which can realize the HS acquisition, broadcast, transmission, display and analysis. In this system, PSoC technology is used to design analog, digital, micro control circuit on a single chip, reducing the cost of hardware development. With the help of wireless transmission, the convenience of system is improved.

The application of hybrid programming in HS analysis reduces the cost software development and provides an effective way for HS algorithm from theory research to engineering application. The clinical test verifies the usefulness and practicability of the system. It can detect the abnormality of the heart sound and show the condition of the heart function by the parameters. It will have a strong practical value for remote medical care and home care in the future

Table 5 The analysis of cardiac reserve parameters

Exercise frequency	Gender	Number	AVG±SD（HR）	AVG±SD（S1/S2）	AVG±DS（D/S）
≥3 times a week	Male	16	67.375±9.701374	2.167231±0.949285	1.70905±0.307495
	Female	11	70.63636±12.11836	1.845481±0.644121	1.528222±0.253064
＜3 times a week	Male	10	72.3±11.26499	1.658136±0.699535	1.527675±0.285408
	Female	24	76.95833±10.71561	1.588781±0.65412	1.33445±0.23282

*AVG means average value, SD means standard deviation.

Acknowledgement

This project is supported by the National Natural Science Foundation of China (Grant No. 61571371).

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