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Low Cost and Low Power ECG Recorder Suitable for Low Incomes Populations

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***Abstract* – The lack of hospitals and medical devices is one of the main characteristics of under developed countries. This paper proposes the development of a very low cost and low power consumption module that is used to record Electrocardiogram (ECG) signals at home or in hospital. The pre-amplification is done using the well known AD620. The other analog signal conditioners are the low pass and high pass filters, the right leg drive circuit and the AC voltage level adaptation. A microcontroller (PIC 18F2550) is used for analog to digital conversion and for all the digital processes of the system. The ECG data recorded can be stored into a SD (Secure Digital) memory card. Our module is powered by two 9 volts batteries and it can be connected to any modern terminal through USB port. We designed and implement software that manages this ECG recorder. A friendly user interface has also been elaborated for graphical plotting and displays. The user can set various functioning states of the module through a control panel. As ECG recording is non invasive, we carried on hundreds of tests and the results were all satisfactory.**

***Keywords* – Electrocardiogram (ECG), Low Power Recorder, Low Incomes Population, Telemedicine.**

I. Introduction

Heart diseases are among the leading causes of disability and death. According to the World Health Organization (WHO), cardiovascular disease (heart disease and stroke), which concern more than 17.1 million people each year, are the leading cause of death worldwide. Of these, 78% occurred in developing countries, for which prevention methods are almost nonexistent. Indeed, industrialization and increasing urbanization in developing countries have significantly changed the lives of their inhabitants; new eating habits and increasing physical inactivity are risk factors. These diseases once sidelined in tropical countries behind malaria and other infectious diseases, are taking the lead today [1]. Cardiovascular diseases are thus a public health problem in developing countries. In addition to the deficit of cardiologists in these countries, poverty does not allow to buy specific medical equipments and such devices are expensive and lie increasingly on high tech.

Telemedicine can be an alternative that would make a significant contribution to public health problems in developing countries. Indeed, the technologies associated with telemedicine services enable remote healthcare and the exchange of information relating thereto [2], [3]. Telemedicine also advocates home medical treatment, self-care and remote diagnosis. We intend to achieve an ambulatory system for acquiring the electrocardiogram (ECG) signals, and the recording of these signals in the file format in the SD (Secure Digital) memory card or storing the recorded ECG file in the built-in hard disk of a computer through USB connection. The ECG is a graphical representation of the temporal potential differences between several cutaneous electrodes. It provides knowledge of the electrical phenomena that lead to contraction of the heart muscles. ECG is a valuable tool for assessing the likelihood of cardiac abnormalities. The ECG has become an essential diagnostic tool that measure and record the electrical activity of the heart. A wide range of heart diseases can be detected when interpreting the recorded ECG signals. Although the ECG recording has become a commonplace clinical examination in developed countries, it remains a luxury that only wealthy few can access it in the low incomes countries where cardiologists are rare and mostly being in few big cities. The vast majority of the population lives in rural areas and cannot access these specialists of heart diseases. In our previous work, we have conducted research into the low-cost transmission of ECG signals. To this end, we have developed specific compression techniques of ECG signals by polynomial transformations [4] - [7]. In this work, we address another aspect of the same general problem, proposing a diagnostic tool at very low cost. This brings a partial solution to the situation by allowing the poor patients everywhere in those countries to be able to record their ECGs when necessary. To this end we combine electronic and computer science to design and implement a low cost portable device that will be used to record ECG of a patient elsewhere (at home, in the farm, in the office, in the street, in the ambulance or in the hospital). Our module will then be adapted to the socio-cultural and economic environment of low incomes countries where technology level is under average.

The general principle for modeling, design and calibration of electrophysiological devices is given in [8]. Specific requirement on the electrical characteristics of ECG recorders, various signal processing schemes applied on ECGs and attempt to automatic interpretation of ECG signals are found in [9]. Many works have been devoted in recent years on improving ECG acquisition devices with a focus on the adaptation of the equipment to the new digital communication systems such as mobile telephony [10] - [14]. Studies for the reduction of ECG recorder costs to make them more accessible remain a priority [15], [16]. Our work is fully in line with these objectives. We have proposed a portable and very low power consumption system that records the signals on an SD memory card. It is then possible and easy, using any modern digital terminal for display, storage or transmission of the recorded signals. These signals can be transmitted by SMS to be viewed remotely by a cardiologist that analyze them and make remote medical prescriptions [17]. Today's

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possibilities such as wireless communications and mobility, telephone cable networks, fiber optics and especially the Internet can contribute to improving the quality of life and health of people in third world countries. Telemedicine already made great use in developed countries [18] - [20]. We have then tried in this work to put a first step for a telecardiology system adapted to low incomes regions realities, characterized by very small financial resources, and specific climatic conditions.

The next section of the paper is devoted to the presentation of the electronic architecture of our system. At Section 3, we describe the different aspects of the designed and implemented software that manages this ECG sensor. Some of the results obtained are presented and discussed in Section 4, before the final conclusion.

II. Electronic Architecture

The block diagram of the hardware of our system is shown in Figure 1. It can be divided into five sub-systems: the power supply, the input module including the electrodes, the analog signal conditioning, digital processing and the display.

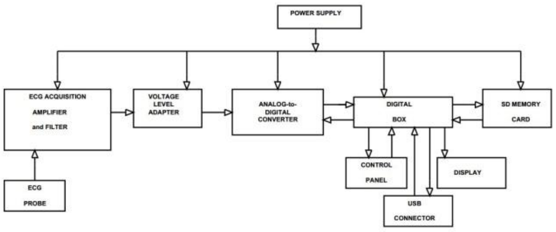

Fig.1. Block diagram of a low cost and low power ECG recorder

A. *The analog signal conditioning module*

We developed two analog modules: the first around the instrumentation amplifier AD620 and a second version using INA118 for comparison purposes. The main function of this block is to amplify the very weak signal of the range of a millivolt (signal of the electrical activity of the heart collected at the surface of the skin). This block also provides the filtering function.

The main body ECG signal is very weak (0 ~ 6 mV). The frequency range is of 0.05 ~ 150 Hz. The recorded ECG is usually mixed with other biological signals such as the respiration signal and some muscle artefacts. The ECG measurement conditions are then complicated. In order not to detect the distortion in clinical value of ECG signal, filtering and amplification are performed: pre-amplifier circuit, high pass filter circuit, low pass filter circuit and a notch filter to suppress the 50 Hz power frequency interference. The Figure 2 shows the analog circuit we used. It is consisting of the amplifiers and filters. As our ECG recorder uses only batteries, there is no need for a 50 Hz notch filter.

The preamplifier is one of the most sensitive elements of the ECG recorder. It requires quality components and exceptional performance. Much work has been devoted to optimizing performance preamplifiers ECG [21], [22]. We opted for an integrated circuit (IC) with low supply voltage and low price that has already been proven: the AD620 from Analog Device. The AD620 is also of small size, low voltage and low power consumption with maximum supply current of only 1.3 mA [23].

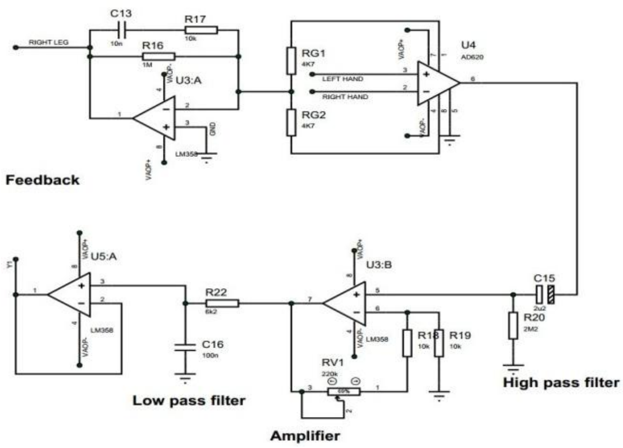

Fig.2. Diagram of the analog signal conditioning subsystem

The expression of the differential gain of the amplification with AD620 is given in [23] by: Gd = 2R / R_G + 1 where R is a 24.7KΩ built-in resistor. We chose a gain G = 7.33 so that the noise from the instrumentation amplifier will not be high. Thus the resistor R_G is 8.233 KΩ. The second amplifier stage is realized using an operational amplifier: the integrated circuit (IC) U_3:B. Using the expression of the gain is given by: T = 1 + (R_{18} + VR_1) / R_{19}, its value is set at 136.37. The theoretical value obtained after calculating (R_{18} + VR_1) is 150 KΩ. The overall amplification gain is then 1000.

The recommended bandwidth for a non-digital conventional ECG filter is between 0.05 Hz and 150 Hz for adults (and between 0.05 ~ 250Hz for children) [8]. A high pass filter rated at 0.5 Hz generates ST distortions. Similarly, a low pass filter must remove noise above 150 Hz. A calibrated low pass filter at 100 Hz or less reduces the amplitude of the QRS and the ability to detect small deflections. The high pass filter is performed by the capacitor C_{15} and the resistor R_{20}. For a cutoff frequency of 0.03 Hz, when C_{15} is set at 2.2 µF, we obtain R_{20} = 2.411MΩ. The normalized value chosen is R_{20} = 2.2 MΩ. The low pass filter is realized using the IC U_5: A, R_{22} and C_{16}. For a cutoff frequency (fc) of 150 Hz, if C_{16}= 100 nF, we obtained R_{22} = 1 / (2π * fc * C_{16}) = 6.366 k Ω. We choose the normalized value R_{22} = 6.8 k Ω. The IC U_3:A, the capacitor C_{13} and the resistors R_{17}, R_{16} constitute the feedback control for the acquisition system. The capacitor C_{13} stabilizes the feedback system. Its value is 10 nF. The feedback circuit is used for the right leg drive that suppresses common mode interferences.

Figure 3 shows the electronic assembly diagram of a second version of ECG acquisition module using the IC INA118. The second stage amplifier, the high pass filter and the low pass filter are identical to those of Figure 2. The only change is in the preamplifier first stage where the IC AD620 is replaced by the IC INA118.

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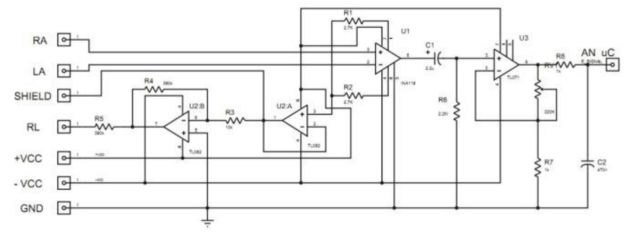


Fig.3. Acquisition Module using the IC INA118

B. *The AC voltage level adaptation*

Most of the PIC microcontrollers have a built in analog to digital converter (ADC) that reads only positive voltages between 0 V and 5 V. However, the ECG signal that we have to sample contains some negative components. It is therefore imperative to appeal to a stage likely to make possible the reading of a signal with negative components; this is the role of the circuit shown in Figure 4.

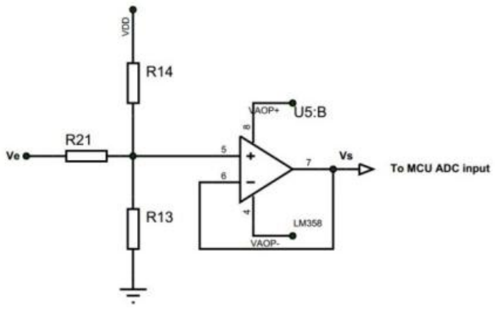


Fig.4. Voltage level adaptation circuit

The expression of Vs is given by the equation (1).

$$Vs = (Ve + V_{DD}) / 3 \quad (1)$$

The PIC microcontroller read the values of the voltage Vs which is a linear function of Ve since V_{DD} is a constant (V_{DD} = 5 V). At the retrieval stage, the value of the recorded signal Ve is determined from the value of Vs rendered using the relationship (2).

$$Ve = 3V_S - V_{DD} \quad (2)$$

The minimum value of Ve (Vemin) must match Vs = 0 and the maximum value of Ve must rise Vs = V_{DD}. For V_{DD} = 5 V, it follows that:

$$Vemin = -V_{DD} = -5\ V \quad (3)$$

$$Vemax = 2 * V_{DD} = +10\ V.$$

These limits are largely sufficient for our implementation.

C. *The digital hardware*

A microcontroller is in the center of the system. It receives and interprets information from the control panel, manages the display, realizes the analog to digital conversion and performs storage. We carry our choice on the PIC 18F2550 which has all the features that we need and even more. This microcontroller produced by MICROCHIP, has a 10 bits internal analog to digital converter. We set the sampling frequency to 310 Hz. The PIC 18F2550 also has the following characteristics: Input / Output ports, an internal SPI module for communication with the SD Memory Card, 256 bytes EEPROM, 2048 bytes RAM (SRAM) , 32 KB Flash memory for programs, an adjustable internal oscillator, 4 timers, USB communication, an Internal frequency multiplier and many other features [24]. The pins of 18F2550 are shown in figure 5.

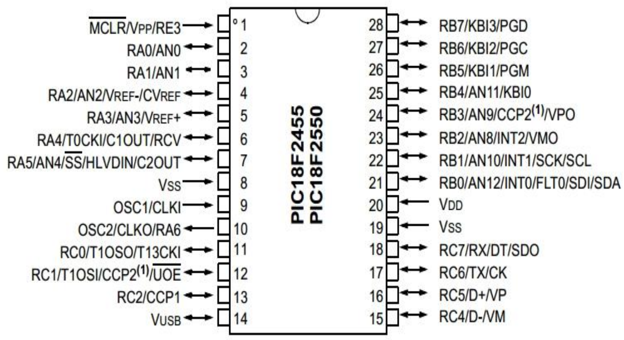


Fig.5. Pins of PIC 18F2550 [24]

D. *Other hardware accessories*

The data recording block is shown in figure 6-a where one can see the interconnection between the microcontroller and the SD (Secure Digital) memory card. The ECG data obtained from the acquisition module is stored in the SD memory card. We used a Nokia 3310 screen to display the various activities being carried out by the system. The assembly embodiment of the LCD is given in Figure 6-b. We use USB 2.0, full speed and interruptible transfer mode for data transmission. The USB connections are given in figure 6-c. The voltage divider formed by the resistors R_{11} and R_{12} enables the PIC to detect the connectivity with USB port. The capacitor C_2 filters the USB supply voltage. The USB port is a serial communication certainly not easy to implement. It transfers data in packet format. The user manipulates the application through a control panel made of three buttons that are shown in Figure 6-d.

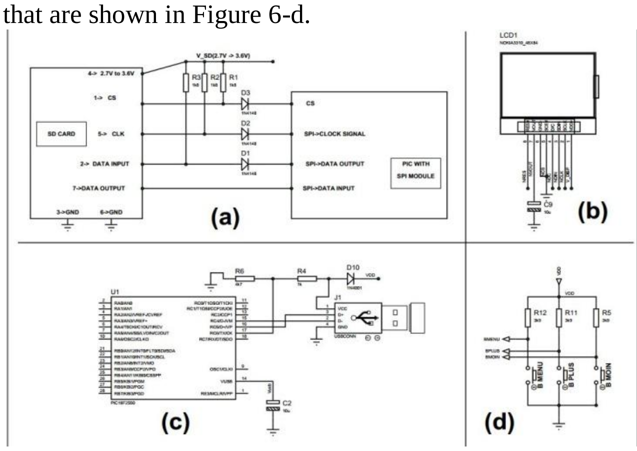


Fig.6. Hardware Accessories: a) Data recording, b) LCD circuit, c) USB connections, d) Control panel

E. *The power supply*

The DC power supply provides several voltage levels as the different elements of the system need specific voltages for normal functioning. We then have to provide 2.7 V to 3.6 V to power the SD memory card, 4.5 V to 5.25 V is needed to power the microcontroller (PIC 18F2550), a symmetric ±9V is used to power the signal conditioning module and 3.6V to power the LCD (NOKIA 3310 display

LCD). The figure 7 shows the power supply circuit where the energy source is made of two ordinary 9-volt batteries.

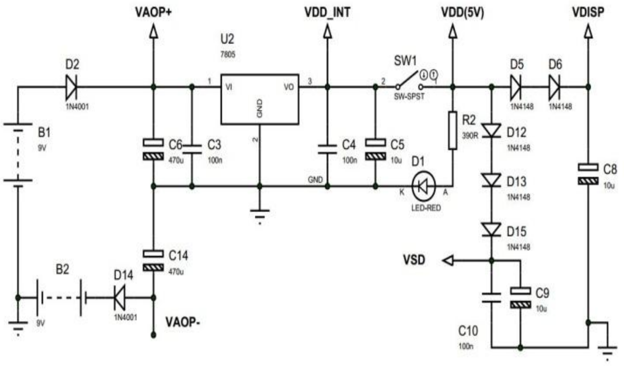


Fig.7. Complete schematic of the power supply

The integrated circuit U1 (7805) is a DC voltage regulator delivering a fixed voltage 5V (V_{DD}). The maximum current it can produce is 1 A. This 5 V voltage supplies the microcontroller (PIC 18F 2550). The diodes D_{12}, D_{13} and D_{15}, connected in series allow to have the voltage of 3.2V (VSD) for the memory card. The voltage for the NOKIA 3310 LCD display is obtained by connecting D_5 and D_6 in series. This delivers the desired voltage of 3.6 V (V_{DISP}). The capacitors C_3, C_4 and C_{10} are decoupling capacitors while the capacitors C_5, C_6, C_8, C_9 and C_{14} perform the filtering operation. The diodes D_2 and D_{14} protect the circuit from an accidental inversion of the battery terminals. The power requirements are inventoried in Table 1. It comes that that the ECG sensor needs less than 3 W and cannot exceed a maximum current consumption of 461.3 mA.

Table 1: Power estimation

module	Range of voltage	Maximal current	Maximal power
microcontroller	4.5 to 5.25V (5 V)	300 mA	1.500 W
SD card	2.7 to 3.6V (3.2 V)	75mA	0.24 W
operational Amplifiers	± 9V	3 x 10mA	0.54 W
Preamplifier AD620	± 9V	1.3 mA	0.27 W
The liquid crystal display	3.6V	5 mA	0.018 W
Voltage regulator	5 V	50 mA	0.25 W
Total		**461.3 mA**	**2.818 W**

F. The overall hardware circuit

The global electronic circuit in which all the modules described above have been assembled is presented in figure 8. We have also realized another version of this circuit by replacing the preamplifier AD620 by INA118. The circuit in figure 3 was used in that case for analog signal conditioning.

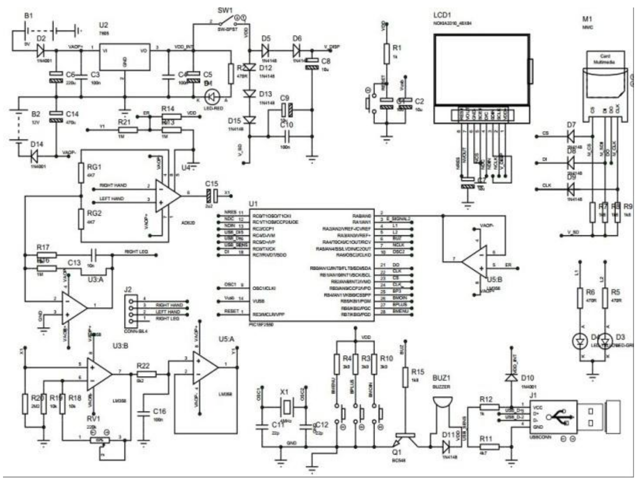


Fig.8. Global electronic circuit.

III. Software

The digital electronic combined to the software stands for the brain of the entire ECG recorder. The firmware flowchart is presented in figure 9.

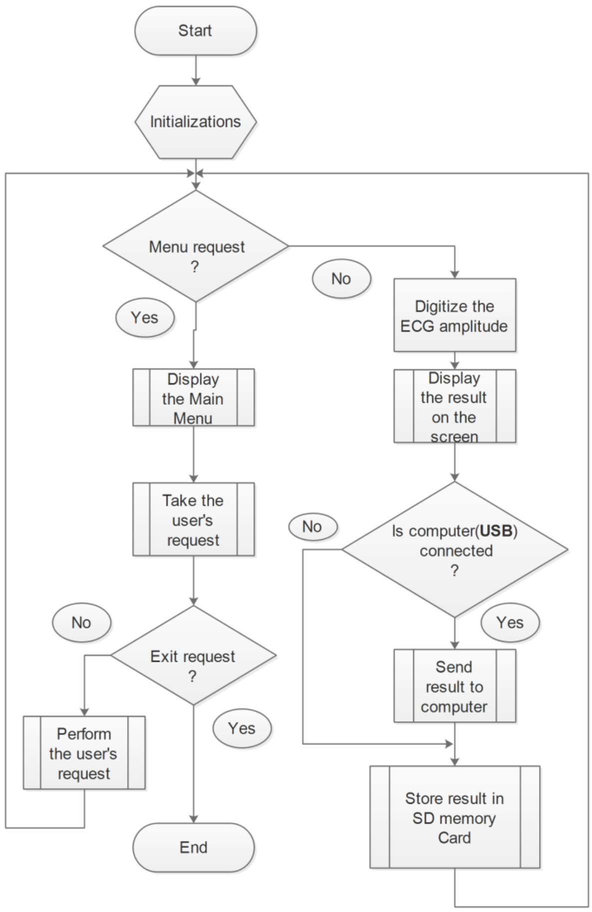


Fig.9. The firmware flowchart

Given the length of the source code, we have not fully taken up in the paper. To facilitate the understanding of the firmware, we will comment only on some of its core functions. The initialization function is given below.

void init (void):

This function has neither input parameter nor output parameter. It initializes the microcontroller Inputs/Outputs, the screen, the memory card and other modules. It is executed at the starting of the microcontroller. It contains the following statements:

G. Initialization of inputs and outputs

ADCON1=0b00001110; //Configure only AN0 as analogue input.

CMCON = 7; // Disable comparators.

TRISA=0b00000011; // Configure RA0 and RA1 as input and others as output.

TRISB=0B11110000; // Configure RB3:RB0 as outputs and RB7:RB7 as inputs.

SPI1_Init_Advanced (_SPI_MASTER_OSC_DIV64, _SPI_DATA_SAMPLE_MIDDLE, _SPI_CLK_IDLE_LOW, _SPI_LOW_2_HIGH); // Initialise the PIC's SPI module

H. Initialization of the display

init_displayer(); *//Initialize the graphic LCD.*

display_text("ECG RECCORDER"); *// Display the title message "ECG RECCORDER" on the LCD*

I. Initialize the SD Memory Card

The memory card is initialized with fifty try in case of difficult action. If there is successful action before fifty trying, show initialization success message (" SD-CARD OK ").

n_essaies=50; mmc_error=1;!//Prepare fifty tries.

While ((mmc_error!=0) && (n_essaies>=1))

{ mmc_error=Mmc_Init();

xy_position(0,1);display_text(" INIT SD-CARD ");

Wait_for(50);n_essaies--;

}

if(n_essaies>2) { xy_position(0,1); display_text(" SD-CARD OK "); }

Here below is an important function we developed for our ECG sensor. This function reads the value of the ECG signal (the voltage present on the analog to digital converter 'channel zero' of the microcontroller) and converts it into character string, in order to allow recording in the file (created in SD memory card). It contains the program lines given below.

J. Reading of the ECG signal

void ECG_Capture ():

ADC_R=ADC_Read(0); ADC_Val=ADC_R * 0.004888; //Read AN0 with 5V reference

FloatToStr(ADC_Val,&x1) ; //Convert the value into string format x1 .

K. Writing the ECG signal in the file

If (Mmc_Fat_Assign(fichier1, 0x80)) //Create the file to save ECG's samples if no exist

{ xy_position(0,0); display_text(" ASSIGN WELL ");

Mmc_Fat_Append(); //Skip to the last position of the file

xy_position(0,1); display_text(" RECORDING ");//Notice the action to the user.

while(B_MENU)

{ LED_REC=1; ECG_Capture();// Read the ECG signal.

Mmc_Fat_Write(x1,9);

//Store the sample in the file.

LED_REC=0; Wait_for(2); //delay 2 ms;

}

}

IV. Experimental Tests, Results and Discussion

We have developed a friendly-user display interface, providing opportunities for enlarging portions of the plots. The user can visualize the numerical values of the signal samples by simply pointing the cursor on a specified position of the graph. He can also adapt the grid and the scale at will. The user can bring up a window to read the sequence of sample values of the plotted signal. There is a menu where the user can input and display the identity of the patient or his physiological parameters. The display interface is shown in Figure 10.

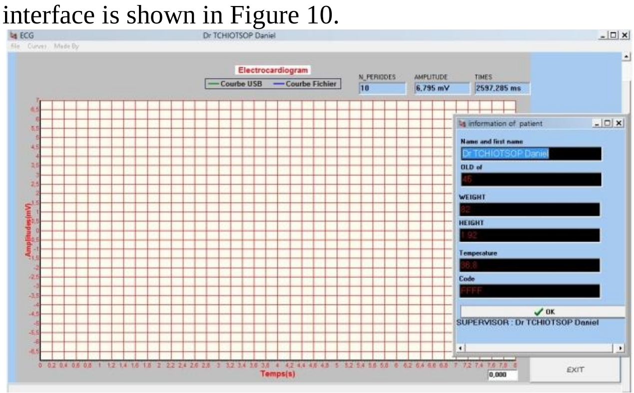
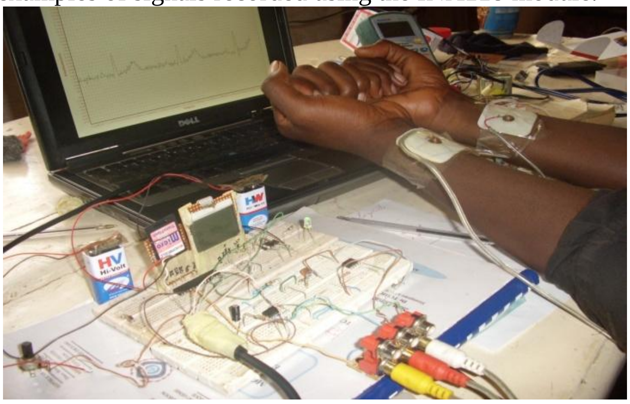


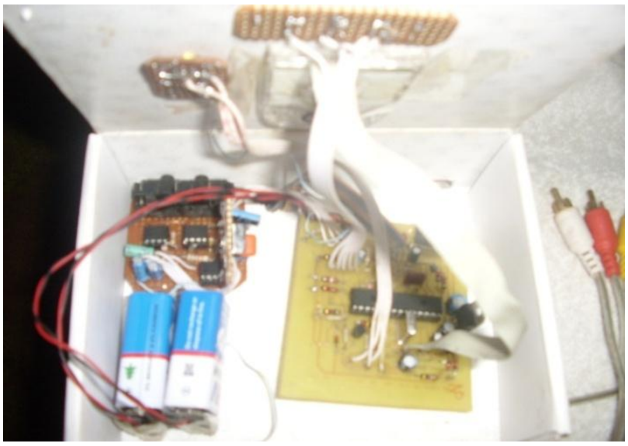
Fig.10. The display interface

It can be observed in Figure 11-a, the picture our module during adjustment and tests. The final realization of our ECG recorder is shown in Figure 11-b where the electronic circuits studied above have been transferred on printed circuit boards (PCB).

We conducted more than three hundreds ECG recordings using our instrument on 42 persons. Most of the volunteers whom ECGs were recorded were university students wanting to know the physiological status for their ECGs. The results obtained were satisfactory. It appeared that the acquisition using AD620 brings up better ECG tracings than using INA118. The ECGs obtained using INA118 seemed noisier but when we positioned the electrodes closed to the chest, the results obtained were also very interesting. Some of these results are shown in Figure 12. In figure 12-a, we can see on the left, a window showing the identity of the patient, its physiological parameters and the values of recorded ECG samples. On the right we have the plot of the ECG signal corresponding to the samples' values shown on the left. Two other tracing of ECG recorded with our instrument are presented in figure 12-b. The ECG presented in figure 12-a and in figure 12-b were recorded using the AD620 acquisition module while those shown in figure 12-c are some examples of signals recorded using the INA118 module.

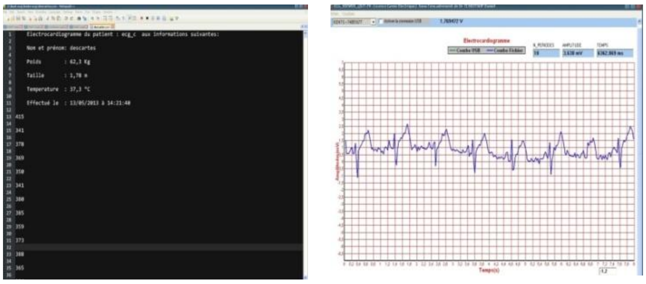


(a)

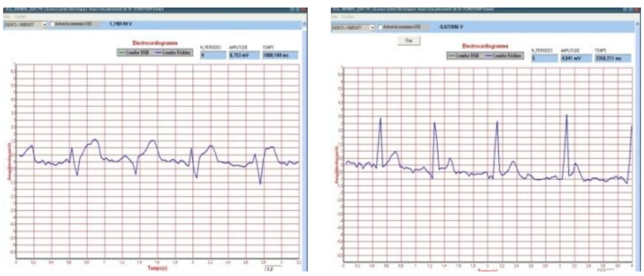


(b)

Fig.11. Experimental testing step and the final realization on PCB



(a)



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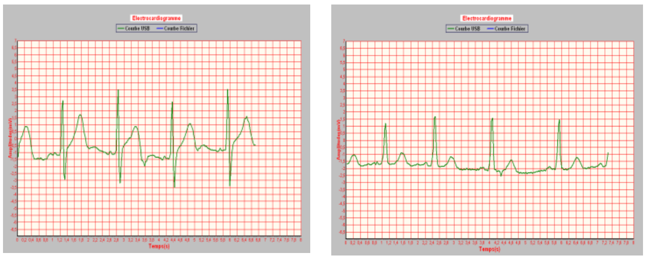

(c)

Fig.12. Extracts of results

V. Conclusion

We designed and implemented a functional, stable and portable tool for recording ECG. Our instrument is low cost and low power consumption. With our system, the poor in underdeveloped countries can access the clinical examination of the ECG which is vital under certain circumstances.

Our device enables individuals to easily conduct their own self-ECG testing and analysis after a simple training. On the other hand, collecting the data of the SD memory card can also be used for long-term analysis of the data processing and diagnosis. In future work, the system should be connected to networks and other communication facilities to be remotely used. We also emphasize in perspective to incorporate into the software, QRS detection, cardiac rate analysis and some simple ECG interpretation procedures. This will enables non cardiologist doctors of developing countries to make some prognostic of diagnosis on cardiac diseases.

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