Wavelet-Based Respiratory Rate Estimation Using Electrocardiogram

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***Abstract*— Respiratory rate (RR) is expressed as breath per minute (BrPM). RR can function as early detection of chronic heart disease (COPD) and congestive heart failure (CHF). Besides, it is physiologically stated that there is a connection between the heart system and the pulmonary system. From the facts described above, it can be concluded that RR monitoring is needed effectively and periodically. ECG signal is used to find out RR characteristics. This study designed an ECG instrument using HPF 0.05 Hz and LPF 100 Hz analog filter. The DWT method is proposed to obtain an estimate of the respiratory rate signal through the ECG signal. DWT decomposition uses level 8 with a sampling frequency of 250 Hz. Testing is done in three ways and is obtained by each error, including the subject is in the supine position (2.35 ± 1.75), upstairs (2.8 ± 2.18) and treadmill (3.65 ± 3.11). Real-time processing of DWT experiences a delay time of 3 seconds because the computation on DWT to the 8th level takes 3 seconds. Real-time DWT testing was a delay of 3 seconds from breathing signal readings.**

Keywords— Respiratory rate, ECG, Analog filter, DWT

I. INTRODUCTION

Respiratory rate (RR) is the amount of respiration or the number of movements that determine inspiration and expiration that are calculated per unit time, the unit of measurement is expressed as breaths per minute (BrPM). RR can be used for early detection of chronic diseases such as chronic obstructive pulmonary disease (COPD) and congestive heart failure (CHF), even respiratory disorders such as sleep apnea was major risk factors for various heart diseases that provide an initial indication of heart failure [1]. Normal breathing for adults is 12-20 times per minute, if there are conditions RR> 27, indicate abnormalities in the heart system. Besides, physiologically it is stated that there is an association between the heart and pulmonary system described [2]. G. B. Moody explained that ECG is influenced by electrodes mounted on the body's surface to detect electrical activity in the heart which is affected by changes in piston electrical impedance as filling and emptying of the lungs [3]. Respiratory rate is used as one of the important indicators of disorders of the body system, such as those that occur in alveolar ventilation (respiratory rate product and tidal volume) which is controlled by central action, peripheral chemoreceptors and lung receptors [4]. From the facts explained above, it can be concluded that RR monitoring is needed effectively and periodically. To detect the number of RR we can measure using a respirometer, but not all RR conditions can be measured by the device because the patient must be in a conscious condition. it is impossible if the patient is sleep such as in operating rooms and intensive care units (ICU).

In some studies, the non-invasive RR monitoring has been carried out by various methods such as respiratory plethysmography, inductive 3D-acceleration derived respiration rate and introduced respiration derived from ECG. The EDR method is very useful for monitoring vital conditions besides having effectiveness in the use of equipment, the ECG signal and the RR signal can be monitored together and the RR can be derived from the available source i.e. the ECG signal [5].

In the previous study, EDR was taken based on heart rate variability (HRV) and peak amplitude variation (PAV) by evaluating the time interval between the tops of the QRS R complex ECG signals (interval R-R) during the breathing cycle or changes in the QRS amplitude caused by baseline changes on the ECG [1]. The method of heart rate variability (HRV) and peak amplitude variation (PAV) has good efficiency to produce respiratory waveforms. However, there are some disadvantages which are quite computationally intensive and cannot be used in real-time. M. A. M. Oser also explained that to get EDR by means calculate the R-wave amplitude with baseline (R-EDR) or to the S-wave amplitude (RS-EDR) [6], the QRS complex area is also considered an EDR detector [7]. The big disadvantage of this method is having a vulnerability to noise. J. Boyle et al. reported that by combining filters in the frequency range of 0.2-0.8Hz with the interval technique R-R able to produce breathing rates from single-lead ECGs [8]. As shown in [9] that discrete wavelet transform (DWT) is also capable of producing EDR, but in that study, it has not yet been implemented in real-time.

In this paper, we propose the development of a discrete wavelet transform (DWT) method to obtain EDR in real-time. this system to get the characteristics of EDR using DWT. DWT is first analyzed off-line. Furthermore, the known EDR characteristics will be used as a reference to be processed using a real-time algorithm.

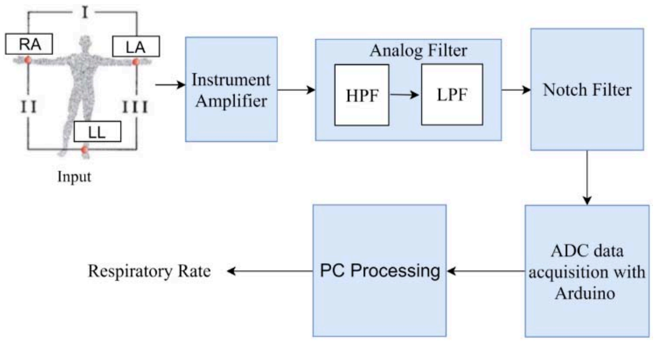


Figure 1. EDR processing method

II. METHOD

A. Design

The DWT method used to obtain the estimated real-time breathing rate by describing the ECG signal obtained from the lead II signal, the block system is shown in Figure 1, to obtain the RR estimate. Overall this system consists of analog signal processing, digital signal processing and discrete wavelet transform (DWT). Analog processing signals consist of several subsystems including instrument amplifier, analog filter, amplifier and notch filters. The accuracy of RR estimation was obtained by comparing the previous respirometer module.

B. Analog Signal Processing

Electrodes were installed to obtain lead II signals, based on Einthoven Equilateral Triangle. Electrode output as instrument amplifier input (AD620), The output signal from the instrument amplifier is still mixed with noise, so analog filters are needed to eliminate noise. The filter designed was adjusted to the characteristics of ECG signal monitoring and was adjusted to the bandwidth of the respiratory frequency signal so that information on respiratory frequency signals can be obtained from the ECG signal, the filtered frequency range is 0.05 Hz - 100 Hz.

- Instrument amplifier

The amplitude of the ECG signal is 0.1 mV - 0.3 mV. The ECG signal amplitude needs to be amplified. An instrument amplifier is needed to strengthen the signal so that it can be read on analog to digital converter (ADC) data. The AD620 instrument amplifier is explained in Figure 2. Strengthening the instrument amplifier is 100 times. The value-based on Equation 1.

$$G = \frac{49.4\,K\Omega}{R_G} + 1 \qquad (1)$$

- Analog filter

The HPF design uses the 1st order filter type as shown in Figure 3, based on the first-order HPF filter based on Equation 2.

$$f_c = \frac{1}{2\pi RC} \qquad (2)$$

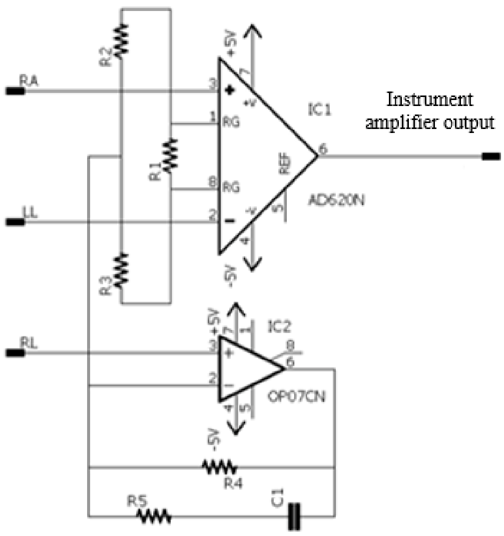


Figure 2. Instrument AD620 amplifier circuit

Low pass filters are designed with a 100Hz cut-off frequency (Figure 4). Designed a series of 2nd order Low Pass Filter Sullen-Key Topology. Value a1= 1.8478; b1 = 1.0000; a2 = 0.7654 and b2 = 1.0000 is the Butterworth coefficient for order 2. Low Pass the 2nd order filter can be calculated with Equation (3) and (4) with a value of C1 = 47nF.

$$R1, R2 = \frac{\left(a1*C2 \pm \sqrt{(a1^2*C2^2 - 4*b1*C1*C2)}\right)}{(4*Pi*Fo*C1*C2)} \qquad (3)$$

$$C_2 \geq C_1 = \frac{4b_2}{a_1^2} \qquad (4)$$

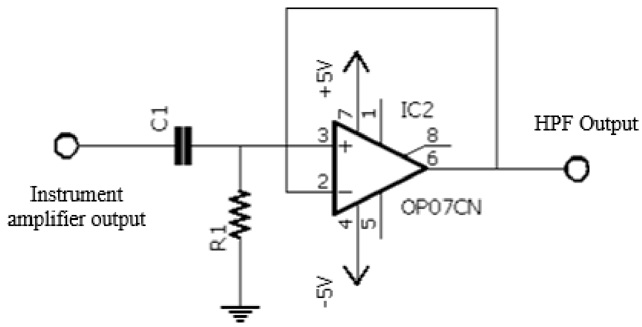


Figure 3. High pass filter design

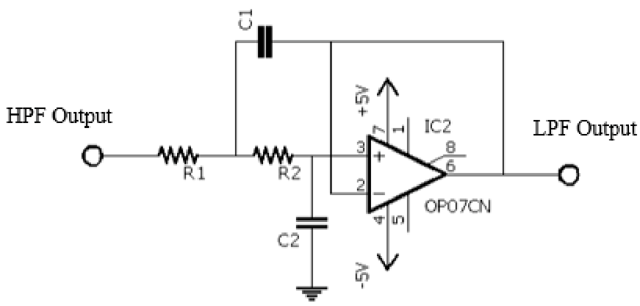


Figure 4. Low pass filter design

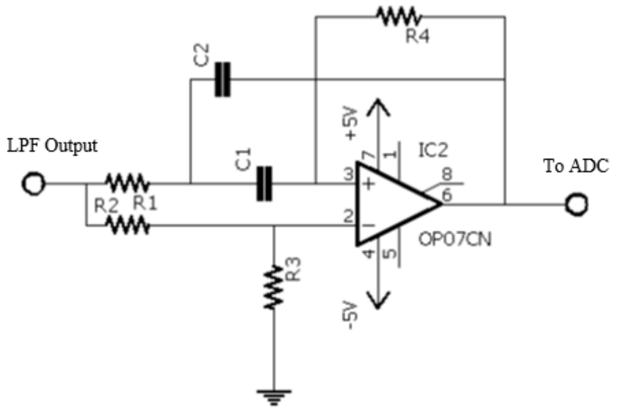


Figure 5. Notch filter design

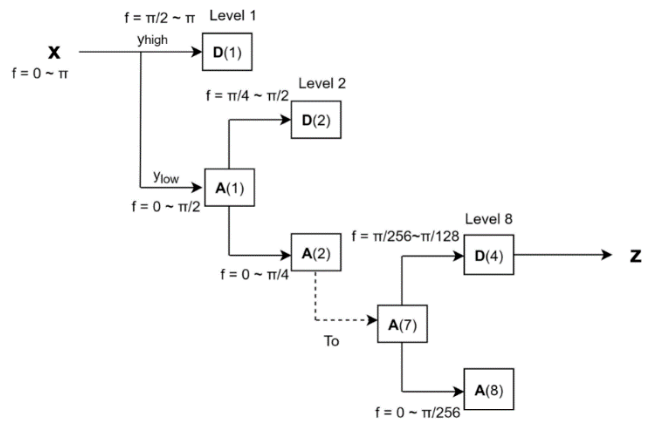


Figure 6. DWT decomposition method

- Notch filter

The Notch Filter circuit in this study is used to eliminate the noise line frequency of 50 Hz in the voltage supply and the oscilloscope. The Notch Filter series is shown in Figure 5. The value of C1 used is 1 µF, RA = 1kΩ and the cut-off frequency (fc) is 50 Hz. The value of center frequency ωr, the value of quality factor (Q), R2, R1, and RB are calculated by Equations (5), (6), (7), (8) and (9).

$$\omega_r = 2.\pi.fc \quad (5)$$

$$Q = \frac{\omega_r}{B} \quad (6)$$

$$R2 = \frac{2}{BC} \quad (7)$$

$$R1 = \frac{R_2}{4.Q^2} \quad (8)$$

$$RB = 2.Q^2.R_a \quad (9)$$

C. Data Acquisition and Signal Processing

The analog ECG signal is fed to ADC, then the signal is sampled at 250 Hz with a resolution of 10 bits and baud rate speed 115200. Data was recorded for 60 seconds to determine of the respiratory rate signal. Digital processing was performed the Arduino UNO microcontroller. In the microcontroller, the output signal from the ECG is digitally filtered to eliminate noise or other unwanted signals. The specifications of the ECG signal are 0.05 Hz and 100 Hz. Whereas the disruption to the electricity grid from PLN is 50 Hz. So that digital LPF filters has been designed with a cut-off frequency of 40 Hz to eliminate noise outside the required ECG signal.

The design of digital filters for ECGs uses state space and system state-space representations given by the two equations based on Equation 10,

$$\begin{aligned} \dot{\boldsymbol{q}}(t) &= \mathbf{A}\mathbf{q}(t) + \mathbf{B}\mathbf{u}(t) \\ \mathbf{x}(t) &= \mathbf{C}\mathbf{q}(t) + \mathbf{D}\mathbf{u}(t) \end{aligned} \quad (10)$$

where $\dot{\boldsymbol{q}}$ is called a state vector which is a function of time, **A** is a state matrix which is a constant, **B** is the input matrix for a constant, **u** Is the input of the timer function, **C** is the output matrix which is a constant, **D** is a direct transition matrix (or feedthrough) which is a constant, **x** Is the output of the timer function.

D. Wavelet Decomposition

Discrete wavelet transform is a decomposition consisting of a low pass filter and a high pass filter, DWT analyzes signals on different frequency bands and uses different resolutions by deciphering the signal into the approximation coefficient (y_{low}) and detailed information (y_{high}), as explained in Equation 11.

$$\begin{aligned} yhigh[k] &= \sum_n x[n].g[2k-n] \\ ylow[k] &= \sum_n x[n].h[2k-n] \end{aligned} \quad (11)$$

The DWT decomposition process is a process of dividing time at a frequency. Because only half of the sample, DWT can characterize all signals. However, the frequency resolution frequency distribution process is doubled. When the band frequency signal only covers half of the previous band's frequency, it effectively reduces the uncertainty in the frequency by half.

The above process is referred to as a coding sub-band which can be repeated for subsequent signal decomposition. Figure 6 illustrates this procedure, where x [n] is the original signal to be decomposed, while h [n] is a low pass filter and g [n] is a high pass.

The transfer of discrete wavelets is the diversion of discrete signals into wavelet coefficients obtained by filtering signals using two different types of filters. The two filters in question are the Low pass filter and High pass filter. The low pass filter represents the base function (tuning function), while the detail filter represents the wavelet. The process of transferring signals with a wavelet produces two coefficients, namely (approximation) and detail coefficients (details). The approximation coefficient is the most important component of a signal, because it contains a low-frequency signal component, while the detail coefficient is a coefficient containing a high-frequency component. The low-frequency component in most signals is the identity of the signal in question while the high-frequency component is the shade of the signal.

E. Experiment

Before estimating in real-time, offline data analysis will first be carried out to determine the characteristics of respiration signals on the ECG. Subject data were collected without taking into account heart problems and subjects aged around 20 to 30 years. Subjects used instrumentation modules and ECG respirometers. ECG data on lead II and respiratory rate were recorded simultaneously using a sampling frequency of 250 Hz.

Figure 7 shows a 30-second ECG signal and a recorded respiratory rate signal. Records are then analyzed offline as shown in Figure 8, DWT decomposition using the mother wavelet db4 obtains characteristic respiration signals on level 8 decomposition. To find out the approximate RR, based on Equation 12,

$$RR = \frac{60}{t_{(n+1)} - t_n} \qquad (12)$$

where RR= Respiratory rate (RR)
t_{n+1}= The period time of the peak R (n+1)
t_n= The period time for the peak R to n.

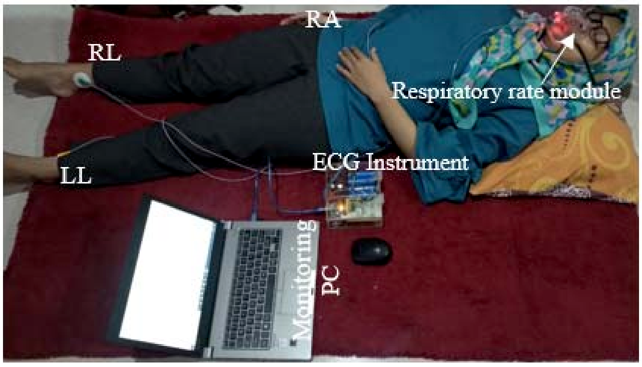
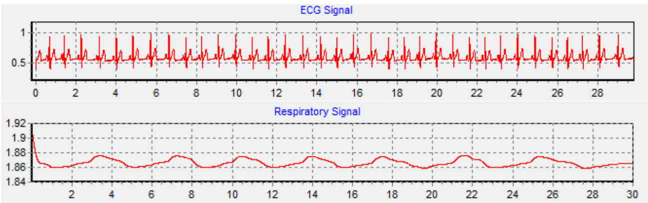
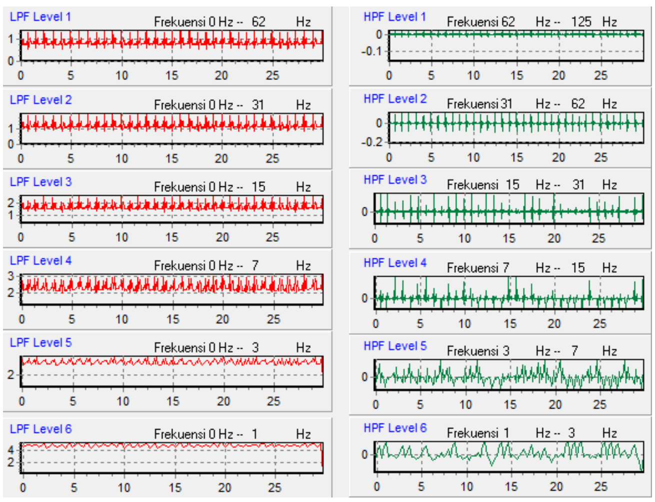
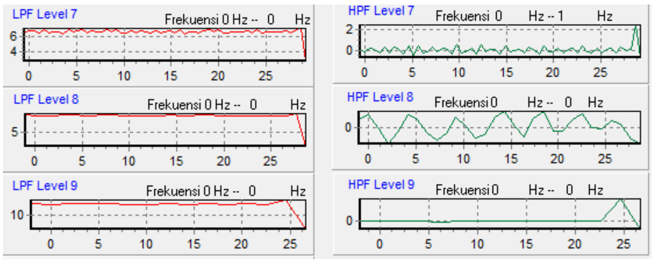


Figure 7. ECG signal and respiratory rate signal recorded

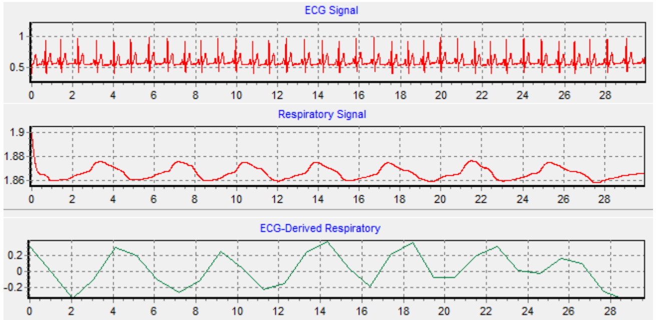


(a)





(b)



(c)

Figure 8. a) Ecg data input and respiratory signal b) DWT process with the mother wavelet db4 c) comparison between the respiratory rate signal results using a respirometer module with EDR which is used using dwt.

Respiratory rate estimated by the proposed method was compared to respiratory rate measured by a sensor as an absolute error. The accuracy of the proposed method was expressed by the mean and standard deviation which acquired with Equation 13 and 14,

$$\mu = \frac{\sum_{i=0}^{N} x_i}{N} \qquad (13)$$

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \mu)^2} \qquad (14)$$

where μ = mean
s= standard deviation
N= number of experiments
x = observed error.

III. RESULT

The following are the results of testing in real-time on the subject using the Delphi program. Carried out by three methods of testing, that is the subject in a sleeping position (supine), upstairs and treadmill. Supine position, the test is carried out in two ways, namely signal capture by means of noise and without noise shown in Figure 10 and Figure 11.

Figure 10(a) the ECG signal is filtered using an analog filter of HPF 0.05 Hz and 100 Hz LPF then the output of the filter is still mixed with noise, digital filtering is done with a 40Hz LPF filter to produce a clean signal output. Figure 10(b) is a respiratory rate signal input obtained from the measurement of the respirometer module simultaneously. Figure 10(c) is the result of an ECG rate signal estimation system using DWT.

Figure 11(a) the ECG signal is filtered using analog filters HPF 0.05 Hz and 100 Hz LPF without digital filtering,

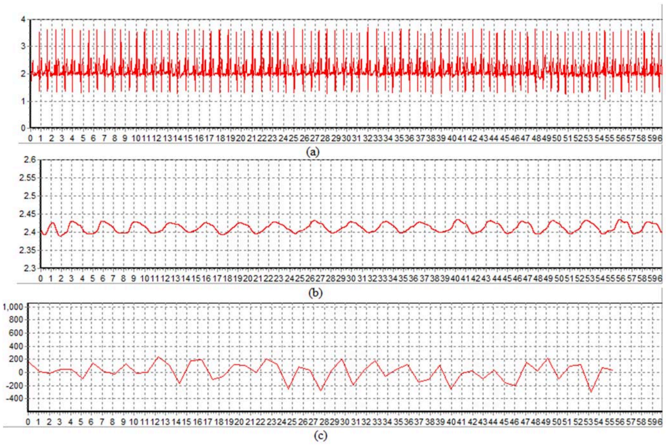


Figure 10. a) ECG signal without noise b) Respiratory rate signal c) DWT prediction signal

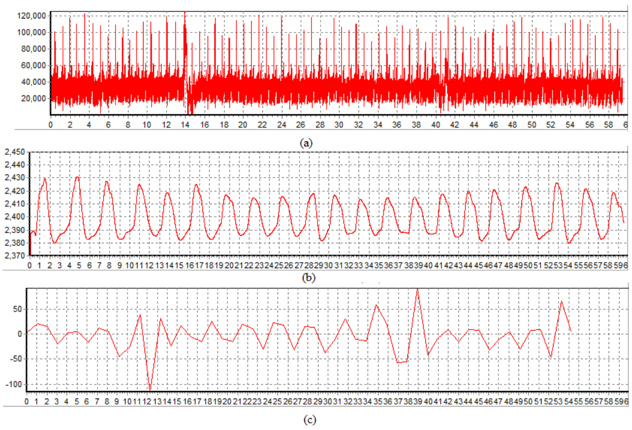


Figure 11. a) ECG signal with noise b) Respiratory rate signal c) DWT prediction signal

so the output of the filter is still mixed with noise and the results of the RR DWT system estimation are shown in Figure 11(c). From the results of the drawing, it can be seen that the DWT system can get an estimate of the respiratory rate signal and the results of the DWT system do not affect even though ECG signal input mixes with noise.

However, this system when used in real-time the estimated output of respiratory rate signals with ECG, has a delay of 3 seconds, because the computation on DWT to the 8th level takes 3 seconds.

IV. Discussion

In this study, the DWT method is proposed to obtain an estimate of the respiratory rate signal using the ECG signal decomposed to N level and obtain the characteristics of the RR signal on the decomposition of the 8th level with a sampling frequency of 250 Hz. The frequency of the respiratory rate signal is in the range of 0.1 Hz to 0.4 Hz. In our experiment, the 1st to the 7th level decomposition of the ECG signal shows the signal information which is not the same as the respiration signal's specification. The 8th level decomposition shows the signal information, and the specification of the decomposed signal is the same as the specification of the respiration signal. But in 9th level decomposition, the signal information is gone. So, the 8th level of decomposition is selected to detect the respiration signal's estimation from ECG. In the DWT system used for the real-time test, the estimation of RR signal from ECG has 3 seconds delay, so using the DWT method cannot achieve 100% accuracy due to the computation on DWT to the 8th level takes 3 seconds. In one cycle there will be a loss of 1 peak wave of respiration.

The accuracy of the results from comparisons between respiratory rate measured and estimated respiratory rate Carried out by three methods of testing, that is the subject in a sleeping position (supine), upstairs and treadmill is shown in Table 1, Figure 12 and Figure 13.

Table 1. comparisons between RRM and ERR (subject in a supine position)

No	**Respiratory Rate Measured (RRM) / minute**	**Estimated Respiratory Rate (ERR) / minute**	**Absolute Error**
1	16	16	0
2	17	12	5
3	19	19	0
4	17	16	1
5	17	15	2
6	14	14	0
7	15	13	2
8	21	18	3
9	13	12	1
10	15	14	1
11	10	14	4
12	13	10	3
13	11	13	2
14	18	11	7
15	22	20	2
16	20	17	3
17	13	16	3
18	20	23	3
19	14	18	4
20	18	19	1
		Average =	2.35 ± 1.75

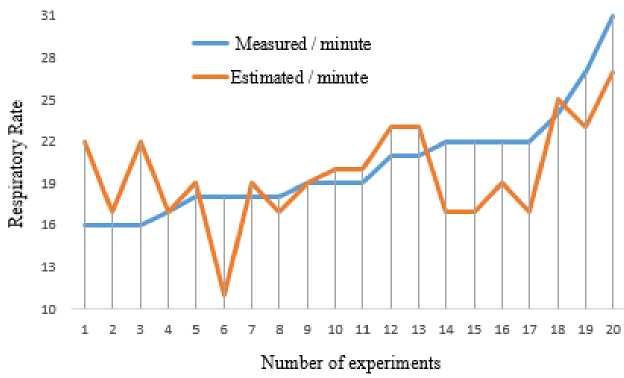


Figure 12. comparisons between the measurement of respiratory rate by the walk up the stairs

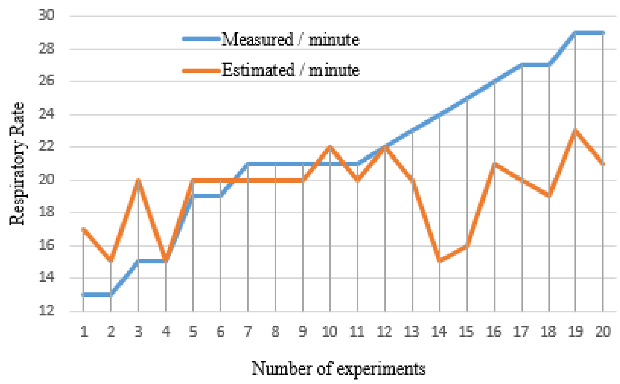


Figure 13. comparisons between the measurement of respiratory rate by the walk on treadmill

The results of the above comparison are obtained by each error: the subject is in the supine position (2.35 ± 1.75), upstairs (2.8 ± 2.18) and treadmill (3.65 ± 3.11).

V. Conclusion

This paper discusses ECG instruments using HPF 0.05 Hz analog filters and 100 Hz LPF. The DWT method is used to obtain the ECG derived respiratory rate. DWT decomposition used level 8^{th} with a sampling frequency of 250 Hz. Subject data collected were men and women without heart problems with ages between 20 and 30 years. Testing was performed in three ways and is obtained by each error, including the subject is in the supine position (2.35 ± 1.75), upstairs (2.8 ± 2.18) and treadmill (3.65 ± 3.11). Real-time processing of DWT experiences a delay time of 3 seconds because the computation on DWT to the 8^{th} level takes 3 seconds.

The next research will be implemented to analyze the subject of anesthetic patients in the ICU room or operating room.

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