Extracting Respiration Rate from ECG Raw Signals

This paper describes a method for extracting respiration rate from ECG raw signals. The method has been tested on 26 voluntary subjects and the respiration times obtained have been compared with the respiration rate acquired from Philips Physiological Monitor (MP60). This technique is applicable to any type of automated ECG analysis, in real-time and without the need of additional hardware.

1. Introduction

The knowledge of respiration associated to the electrocardiogram (ECG) can be useful health monitoring in daily life. For example, it is used for differentiating obstructive from central and complex sleep apnea [1] or assessing cardiopulmonary coupling during sleep [2]. Moreover it is used for understanding the clinical significance of certain cardiac arrhythmias.

There are many respiration recording techniques and the choice is tied to the type of pathology given to study. Devices such as spirometers [3] and nasal thermocouples [4] measure air flow into and out of the lungs directly, carrying out careful and accurate measures. However, the devices can interfere with respiration. The breathing can also be recorded indirectly by measures of the variation of body volume. For this purpose, the transthoracic inductance and impedance plethysmographs [5], whole-body plethysmographs [6], strain gauge measurement of thoracic circumference and pneumatic respiration transducers are utilized. All these methods require dedicated devices too.

ECG-Derived Respiration Monitoring Method [7] gives almost the same results without the need of dedicated devices. This method only needs three-lead ECG. The method proposed here finds respiration rate from ordinary ECGs. It is a technique of signal
analyzing and it does not require any dedicated devices. This method is particularly useful in situation where the ECG is the only available data source.

2. Methods and Algorithms

Figure 1 shows the sequential steps of the method. From ECG raw signals collected by the MP60, we extract the R-R maxima and the R-R intervals. These data are saved in 2 vectors and plotted each vector. Then, the result of each curve with many maxima can be calculated easily. By comparing with the respiration rate given by the MP60, we can affirm that each maximum corresponds to a respiration cycle. Details of these steps are described as follows.

![Figure 1. Sequential steps of the method](image)

2.1 The R-R maxima and R-R interval extraction from raw ECG signals

Nowadays, there are many algorithms which have been implemented in order to detect the QRS peaks in an ECG waveform (Figure 2) [8]. The concept for this algorithm was taken from Gustafson [9]. The first derivative is calculated at each point of the ECG:

\[ Y(n) = X(n+1) - X(n-1), 1 < n < 8190 \]  

(1)

The first derivative array is then searched for points which exceed a constant threshold \( Y(i) \geq 0.15 \). Then the next three derivative values \( Y(i+1), Y(i+2), \) and \( Y(i+3) \) must also exceed 0.15. If the above conditions are met, point \( i \) can be classified as a QRS candidate if the next two sample points have positive slope amplitude products, that is, both \( Y(i+1)X(i+1) \) and \( Y(i+2)X(i+2) \) are positive.
Fig. 2 Definition of R-R Maxima (Rk) and R-R Interval (RRk) from ECG signal

After that we obtain R-R maxima, it is easy to calculate the R-R intervals by subtracting the corresponding time Tk of the R-R maxima as shown in Figure 2.

2.2. Variation of R-R maxima and R-R intervals plots

After saving the R-R maxima and the R-R intervals into two vectors, we plot them and count the maxima of their variation with an algorithm (Figure 3). We can see the peaks clearly so we do not need a very complicated algorithm to extract them. However, although the plot of the R-R maxima variation seems clear, the plot of R-R intervals variation gives better results particularly in apnea case. Actually, we do not use R-R maxima variation because we can not detect the apnea condition and it is more sensitive to noise (Figure 4). Hence, in this paper, the variation of R-R intervals were used in the rest parts.
2.3. Three methods to filter curve in apnea case

In apnea case (Figure 4), particularly during the breath held, the curve needs to be filtered as shown in the inside curve of rectangular shape in the Figure 5(a). For this purpose, we propose three methods and have implemented the algorithms using R-R interval variation as follows:

Method 1:

In order to reduce the sensitivity of the curve, we apply the principle of “moving average” of every 5 values according to their standard deviation. We choose the value close to 0.0025. Then, we extract the maxima (Figure 5(b)).

Method 2:

It consists to extract from the variation of R-R intervals plot, the significant maxima according to a threshold value equal to 0.0020 (Fig. 5(c)).

Method 3:

It is a mix of methods 1 and 2. First, we apply the principle of “moving average” of every 5 values according to their standard deviation (0.0025) then we extract the significant maxima according to a threshold value (0.0020) (Fig. 5(d)).
3. Experiment Conditions

The method has been tested on 26 voluntary subjects (16 men and 10 women, aged 19 to 28 years) and the respiration times obtained have been compared with the respiration rate acquired from Philips Physiological Monitor (MP60).

For short time data recording, we collect ECG data and respiration times at the same time via MP60. We can also check it with the waveform recorded by the MP60. For longer data recording, the MP60 gives us the respiration rate average every 5 seconds. With all this information gathered, we know the real respiration rate of the subject and can compare them with our results.

1) Experiment I

For the first experiment, we just collect ECG data from 10 volunteers during about 5 minutes. The persons are awakened and sit on a chair. Our purpose is to find if there is a relation between R-R maxima and R-R intervals extracted from ECG signal and the
respiration. Then we want to compare the variation of RR maxima and of RR intervals results with the real respiration rate.

(2) Experiment II

For the second experiment, 6 volunteers are in the same conditions as the first experiment. They breathe about 5 minutes but they stop breathing in the middle to simulate apnea for 35 seconds to 1 minute. This experiment helps us to prove that the respiration is linked to the variation of R-R intervals. After filtering the curve with three methods, we compare the results with the real respiration rate.

(3) Experiment III

For this experiment, we collect ECG data from 5 men and 5 women during 30 to 80 minutes. During this time, the subjects are asked to take a nap. Our purpose is to prove that the method works for longer and stable data. We compare our results with the respiration rate given the MP60.

4. Experiment Results

In this study, the only data we need are ECG and respiration rate recorded by the MP60. At first, we can check the first step of our method: the R-R maxima and R-R intervals extraction. For an adult, the normal heart rate is between 60 and 100 beats per minute and a little less when the person is sleeping. The normal respiration rate is between 12 and 20 times per minute. If all this information is verified, we can compare our method results with the real respiration rate given by the MP60.

4.1 Experiment I Results

The results of this experiment (Table 1) show that the number of the variation of R-R intervals instead of R-R maxima is close to the number of the respirations counted from MP60. It means that the variation of R-R intervals can give us the real respiration rate. Furthermore, the plot of the results on Figure 6 also shows us that the results are better if we use R-R intervals instead of R-R maxima. That is why, for the next experiments, we will only use the variation of R-R intervals.

Moreover, the method of variation of R-R interval is quite accurate according to the Receiver Operating Characteristic (ROC) curves [11]. We evaluate accuracy of our method in experiment I as shown in Table 2. Both the sensitivity and specificity are over 96%.
Extracting Respiration Rate from ECG Raw Signals

Table 1. Experiment I Results

<table>
<thead>
<tr>
<th>No.</th>
<th>Gender / Age</th>
<th>Record time (min)</th>
<th>HR average (bpm)</th>
<th>No. of Resp. from MP60</th>
<th>Variation of RR maxima</th>
<th>Variation of RR interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F / 20</td>
<td>3.5</td>
<td>84</td>
<td>76</td>
<td>91</td>
<td>73</td>
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<tr>
<td>2</td>
<td>M / 24</td>
<td>4.7</td>
<td>74</td>
<td>40</td>
<td>56</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>M / 24</td>
<td>5.0</td>
<td>78</td>
<td>43</td>
<td>92</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>M / 23</td>
<td>4.7</td>
<td>74</td>
<td>81</td>
<td>81</td>
<td>84</td>
</tr>
<tr>
<td>5</td>
<td>F / 20</td>
<td>4.8</td>
<td>86</td>
<td>60</td>
<td>117</td>
<td>60</td>
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<tr>
<td>6</td>
<td>M / 20</td>
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<td>73</td>
<td>60</td>
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<tr>
<td>7</td>
<td>M / 20</td>
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<td>74</td>
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<tr>
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<td>F / 20</td>
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<td>53</td>
<td>100</td>
<td>101</td>
<td>98</td>
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<tr>
<td>9</td>
<td>M / 23</td>
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<td>74</td>
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<td>110</td>
<td>111</td>
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<tr>
<td>10</td>
<td>M / 22</td>
<td>4.5</td>
<td>83</td>
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</tr>
</tbody>
</table>

Average ± SD 73.7±22.5 89.0±19.2 74.2±19.8

p value 0.0479 0.5850

Table 2. Experiment I Method Accuracy

<table>
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<tr>
<th>No.</th>
<th>Total HR No.</th>
<th>No. of Resp from MP60</th>
<th>Variation of RR interval</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>TP</td>
<td>FN</td>
<td>FP</td>
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<td>3</td>
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<td>289</td>
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</tbody>
</table>

Average ± SD 96.1±5.9 99.4±0.6 98.9±0.9
4.2 Experiment II Results

The results of this experiment with apnea (Table 3) are also close to the number of the respiration counted whatever the filtering method utilized as it is shown in Figure 7. The parameters of each method are the same in each case. We notice that we could get better results by adjusting the parameters in method 3. The variation of R-R intervals plot and these results prove us that the respiration is linked to the variation of R-R intervals. The sensitivity, the specificity and accuracy average in this case are between 88% and 100%. It is shown in Table 4.

Table 3. Experiment II Results

<table>
<thead>
<tr>
<th>No.</th>
<th>Gender/Age</th>
<th>Record time (min)</th>
<th>HR avg (bpm)</th>
<th>Apnea time (s)</th>
<th>No. of Resp. from MP60</th>
<th>Variation of RR interval (method 1)</th>
<th>Variation of RR interval (method 2)</th>
<th>Variation of RR interval (method 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F / 20</td>
<td>4</td>
<td>81</td>
<td>35</td>
<td>45</td>
<td>54</td>
<td>48</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>F / 20</td>
<td>3.2</td>
<td>69</td>
<td>60</td>
<td>46</td>
<td>54</td>
<td>47</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>M / 22</td>
<td>3.7</td>
<td>75</td>
<td>48</td>
<td>64</td>
<td>66</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>4</td>
<td>M / 24</td>
<td>3</td>
<td>70</td>
<td>41</td>
<td>36</td>
<td>42</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>5</td>
<td>M / 23</td>
<td>2.8</td>
<td>71</td>
<td>32</td>
<td>36</td>
<td>42</td>
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<td>34</td>
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<td>6</td>
<td>M / 24</td>
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<td>72</td>
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<td>52</td>
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<td></td>
<td></td>
<td>Average ± SD</td>
<td>49.0±12.3</td>
<td>55.0±11.2</td>
<td>50.5±13.3</td>
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<tr>
<td></td>
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<td></td>
<td>p value</td>
<td>0.0018</td>
<td>0.2264</td>
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</table>
Table 4(a). Experiment II Method 1 Accuracy

<table>
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<tr>
<th>No.</th>
<th>Total HR No.</th>
<th>No. of Resp. counted from MP60</th>
<th>Variation of RR interval</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TP</td>
<td>FN</td>
<td>FP</td>
<td>TN</td>
</tr>
<tr>
<td>1</td>
<td>325</td>
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<td>45</td>
<td>9</td>
<td>0</td>
<td>271</td>
</tr>
<tr>
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<td>220</td>
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<td>46</td>
<td>8</td>
<td>0</td>
<td>166</td>
</tr>
<tr>
<td>3</td>
<td>278</td>
<td>64</td>
<td>64</td>
<td>2</td>
<td>0</td>
<td>212</td>
</tr>
<tr>
<td>4</td>
<td>210</td>
<td>36</td>
<td>36</td>
<td>6</td>
<td>0</td>
<td>168</td>
</tr>
<tr>
<td>5</td>
<td>199</td>
<td>36</td>
<td>36</td>
<td>6</td>
<td>0</td>
<td>157</td>
</tr>
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<td>316</td>
<td>67</td>
<td>67</td>
<td>5</td>
<td>0</td>
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</tbody>
</table>

Average ± SD 88.3±4.9 100±0.0 97.6±1.0

Table 4(b). Experiment II Method 2 Accuracy

<table>
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<tr>
<th>No.</th>
<th>Total HR No.</th>
<th>No. of Resp. counted from MP60</th>
<th>Variation of RR interval</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td>TP</td>
<td>FN</td>
<td>FP</td>
<td>TN</td>
</tr>
<tr>
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<td>325</td>
<td>45</td>
<td>44</td>
<td>4</td>
<td>1</td>
<td>277</td>
</tr>
<tr>
<td>2</td>
<td>220</td>
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<td>41</td>
<td>6</td>
<td>5</td>
<td>173</td>
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<td>0</td>
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</table>

Average ± SD 93.6±4.2 98.8±1.0 97.8±1.3

Table 4(c). Experiment II Method 3 Accuracy

<table>
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<tr>
<th>No.</th>
<th>Total HR No.</th>
<th>No. of Resp. counted from MP60</th>
<th>Variation of RR interval</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TP</td>
<td>FN</td>
<td>FP</td>
<td>TN</td>
</tr>
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<td>279</td>
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<td>64</td>
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<td>67</td>
<td>52</td>
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</tr>
</tbody>
</table>

Average ± SD 98.5±2.1 97.6±1.6 97.8±1.2

http://grc.yzu.edu.tw/
4.3. Experiment III Results

The results of this experiment (Table 5) confirm that the method definitively works at normal persons no matter the ECG recording time. The respiration rate calculated by Experiment I method is very close to the respiration rate average given by the MP60 as shown in Figure 8. Therefore, the method from Experiment I still gives good results for longer and stable normal person data.

Table 5. Experiment III Results

<table>
<thead>
<tr>
<th>No.</th>
<th>Gender / age</th>
<th>Record time (min)</th>
<th>HR average (bpm)</th>
<th>Resp. MP60 Avg. (/min)</th>
<th>Std. dev. (/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M / 22</td>
<td>66.4</td>
<td>55.7</td>
<td>15.8</td>
<td>1.5</td>
</tr>
<tr>
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<td>M / 23</td>
<td>38.2</td>
<td>63.0</td>
<td>18.0</td>
<td>2.8</td>
</tr>
<tr>
<td>3</td>
<td>M / 24</td>
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<td>56.4</td>
<td>17.3</td>
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<td>71.6</td>
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<td>38.7</td>
<td>95.1</td>
<td>15.9</td>
<td>3.0</td>
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<tr>
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<td>50.4</td>
<td>85.6</td>
<td>14.5</td>
<td>1.8</td>
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<td>83.9</td>
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<td><strong>Average + SD</strong></td>
<td><strong>p value</strong></td>
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</table>

Figure 7. Comparison of the filtering methods
5. Discussion and Conclusions

We discover another method to find respiration rate from ECG raw signal. At the moment, this method is limited to normal persons but we hope that it will work on patients in surgery. The results obtained have been shown to be correlated with respiration.

To summarize, we have good results in this study concerning experiments at normal persons but not at patients. In this research, we analyze the variation of R-R intervals because the results are better. Actually, the use of R-R maxima or R-R intervals depends on the algorithm chosen for detecting QRS peaks in an ECG waveform. But normally, the R-R maxima are more sensitive to noise and we can see it in the apnea experiment. Therefore, 3 methods are utilized to filter the curve. The methods 1 and 2 have one parameter and the method 3 has two parameters. For this experiment, we fix the parameters value and we can get better results by analyzing each case. So, we can improve the method concerning the detection of apnea especially that we notice that the variation of R-R intervals shows the respiration status. Moreover, the experiment III results validate the method. The numbers shown in the Table 5 are quite consistent. Indeed, the lower the standard deviation, the more the subject is sleeping well during longer time and so the more results are better. Furthermore, we notice that the more the volunteer does not move the better the results are. So the method will not work on moving persons. Actually in this case, even the commercial product of MP60 can not record data well either.
On the other hand, the method cannot be applied to patients. The variation of R-R intervals is not clear enough to find respiration cycles with our algorithm due to noise. For example, when the doctor used electric knife to stop bleeding, the patient’s ECG signal will be affected by electric knife. So in a future work, we need to design a smart and intelligent algorithm for detecting patients’ respiration during surgical operation under artificial ventilation.

The advantages of this method are to utilize the existing hardware to obtain additional information without the need of extra devices. This method is particularly useful in situation where the ECG is the only available information source (like a Holter recording). To conclude, this method can really provide a basis for estimating respiration rate and for detecting apneas.

6. References


