Energy Packing Efficiency Based Threshold Level Selection for DTW ECG Compression

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ABSTRACT

In this research, the compression method of Electrocardiogram (ECG) signal is proposed. This method is based on Wavelet Transform with EPE threshold level selection. Also, the advantage of Dynamic Time Warping (DTW) is applied in this algorithm for efficiently compression of ECG signal, particularly in irregular period signal. There are many researches working on compression algorithm of ECG signal. Almost of them have good result in compression of regular period signal whereas the result is not satisfied when those techniques are applied to irregular period signal. DTW technique is applied for this purpose which replaces of Period Normalization process. DTW maps ECG signal to the most correlate point of reference beat. Therefore all beats seem to have equal length while all signal beats still remain the same. From DTW, the residual difference value is decreased that helps to reduce the error which occurring from Period Normalization process. Discrete Wavelet Transform (DWT) is applied to decompose residual signal into wavelet coefficients after that the redundant information is eliminated by thresholding. To higher the ratio of compression while remain the significant clinical information, the threshold level is chosen based on Energy Packing Efficiency (EPE). This threshold technique helps to remove the insignificant information depending on the conserved energy in each frequency band. The performance is evaluated on both regular and irregular period records of MIT-BIH arrhythmia database. This method improves compression error and moreover, the peak information which is essential information of ECG is always reconstructed at the exact position. Also, the setting of threshold value based on EPE can efficiently increase the compression ratio higher than the conventional method.

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1. INTRODUCTION

ECG is one of very importance clinical information for cardiologist. The disorder of electrical conduction in heart can be diagnosed as the risk of cardiac arrhythmias [1]. For diagnosis, the ECG signal will be recorded, transmitted, monitored and processed. The memory consuming for ECG processing is high. Therefore, many methods were invented to reduce the size of memory consuming for efficiently ECG processing. Compression methods are done in many techniques which classified into three main categories, Parameter Extraction such as vector quantization, Direct Time Domain technique such as AZTEC and Transform Domain technique such as wavelet transform [2-5]. The objective of compression is increasing Compression Ratio (CR) meanwhile essential information is not lost in reconstructed signal. Percent Root Means Square Difference (PRD) is one parameter to evaluate how well of quality in reconstructed signal. There is a tradeoff between CR and PRD that increasing of CR will reduce the quality of reconstructed signal which is the increasing of PRD. One of algorithm resulting in good performance both in CR and PRD is average beat subtraction and residual differencing method [6]. This method did well on regular period signal but not for irregular period signal. That is affected from Period Normalization process which makes all beats to have equal length. When the signal is irregular in period, the large difference between the reference beat and the signal beat occurs. That is because signal beat is subtracted by the mismatching value. On this research, the Dynamic Time Warping (DTW) technique is applied instead of Period Normalization process in preprocessing method. This technique matches the signal beat to the most correlate point of reference beat, so that all signal beats are subtracted by the closest value. This makes the residual value to be smaller. Therefore, the DTW technique helps to reduce the residual value between signal and reference beat [7]. In consequence, the error reduces in reconstructed signal and compression ratio increases. The Discrete wavelet Transform (DWT) and threshold technique which based on EPE are applied to increase efficiency in compression ratio. In conventional threshold technique which based on the maximum of wavelet coefficient's magnitude is not suitable. From our previous work, when the threshold value is set to twice, the increasing of compression ratio is not higher than 0.05 %. In this proposed method, the threshold value is set based on the level of reserved energy of wavelet coefficient in each level of decomposition. This thresholding technique increases the compression ratio up to 25 %.

2. THE ALGORITHM

Fig. 1 shows process of the proposed compression method. First, R peak is detected in QRS complex detection and then reference beat is determined from searching every beat to find the most repeated period and each value of reference beat. Afterward signal is aligned to reference beat by Dynamic Time Warping technique. The residual difference is computed from subtracting signal and match point of reference beat. After that the Discrete Wavelet Transform is used to decompose signal into wavelet coefficients and the thresholding process sets zero value to the insignificant coefficients. Finally, signal is compressed by encoding.

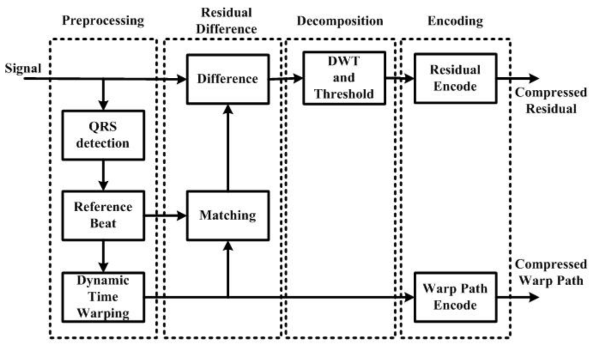

Fig.1: Block diagram of proposed compression algorithm.

In Fig. 2 is the reconstruction process of this algorithm. The compressed residual and warp path are decoded and then the Inverse Discrete Wavelet Transform combines all coefficients into reconstructed residual signal. In the mean time, the warp path is calculated back to match the reconstructed residual signal with the reference beat. Then the matching point of reference beat is added back to the reconstructed residual signal.

2.1 Preprocessing

The morphology of ECG is shown in Fig. 3. Firstly, each beat is split from the whole signal. QRS complex of each beat is detected using algorithm of Hamilton and Tompkins [6] which process steps are band pass filtering, differentiating, squaring, moving averaging and the peak decision rule. This algorithm

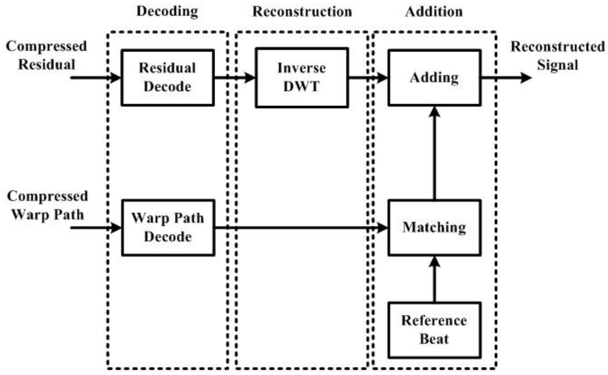

Fig.2: Block diagram of proposed reconstruction algorithm.

provides 99.7% accuracy of QRS Complex. The period of ECG signal is defined between R-R interval which is illustrated in Fig. 3.

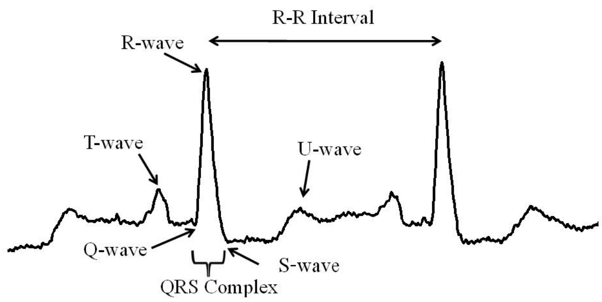

Fig.3: ECG Signal.

After every beat is found, the reference beat is determined. The period of reference beat is chosen from the most frequent period to gain the smallest residual difference. The most repeated period is searched from all signal beats and the most frequent period occurring is defined as the reference period. After that, each point of reference beat is computed from averaging each point of every beat which its period equals to the reference period. In residual difference method, the residual is calculated from the difference between the reference beat and signal. Generally, signal period is normalized to be equal to the period of reference beat such as extending the original signal by zero or mean value [8]. For the regular period, the signal is perfectly reconstructed but not for irregular period signal. The high residual difference occurs when normalized period signal is subtracted by the deviate point of reference beat. The Period normalization process increases the residual value that makes more errors in reconstruction. In this paper, the Dynamic Time Warping technique is presented to decrease the magnitude of residual value. When the reference beat is determined from the most frequently detected period of ECG signal, then DTW is used to warp every point of each beat to the reference beat.

2.2 Dynamic Time Warping Algorithm

The Dynamic Time Warping (DTW) technique is applied to reduce the residual value from residual differencing process. This technique replaces of the Period Normalization process. Dynamic Time Warping is the non linear matching technique and usually used in speech and pattern recognition. This technique is the robust measurement and can compare the similarity between two signals which are not equal in time series ignoring both the local shift and the global shift of signal [9]. DTW will match the most correlate points between compressed or stretched beat to the reference beat as illustrates in Fig. 4, the upper is the shorter period beat, the middle is the reference beat and the lower is the longer period beat, respectively. This technique maps all signal beats to the most similarity point of reference beat with no concerning to the length of beat.

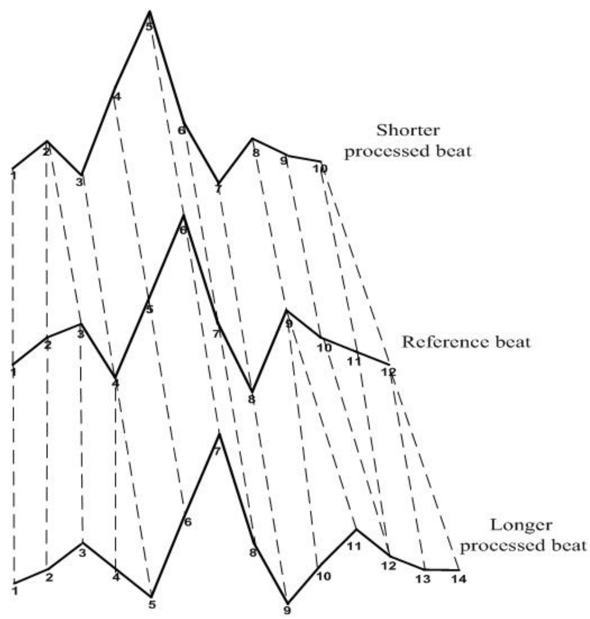

Fig.4: *Matching of similarity between processed beat to reference beat.*

The cost matrix and the optimal warp path are illustrated in Fig. 5. The warp path is searched after the adjacent lowest value cell of cost matrix. This path matches similar points between two beats which their period lengths are not equal.

The given two time series X and Y with lengths I and J, respectively.

$$X = x_1, x_2, ..., x_i, ..., x_I \quad (1)$$

$$Y = y_1, y_2, ..., y_j, ..., y_J \quad (2)$$

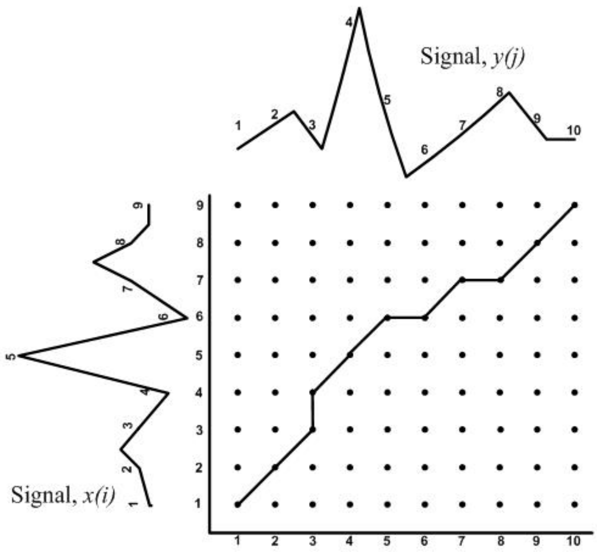

Fig.5: *Calculation the optimal warp path from cost matrix.*

A warp path, W, indicates the matching pair between signal X and signal Y.

$$W = w_1, w_2, ..., w_k, ..., w_K; \max(I, J) \leq K < I + J \quad (3)$$

Where K is the length of warp path and the element of warp path, $w_k = (i, j)$, is the matching index.

There are some constraints of warp path, W, that must begin and stop in diagonally opposite corner of cost matrix and be monotonically increasing as (4) and (5). Therefore every index of each time series must be matched.

$$w_1 = (1, 1), w_K = (I, J) \quad (4)$$

$$w_k = (i, j), w_{k+1} = (i', j'); i \leq i' \leq i+1, \; j \leq j' \leq j+1 \quad (5)$$

The optimal warp path, W, is only the minimum of distance warp path, $D(w_{ki}, w_{kj})$, as shown in (6).

$$W = \min \left[\sum_{k=1}^{K} D(w_{ki}, w_{kj}) \right] \quad (6)$$

This path could be calculated using dynamic programming to fill the cost matrix. The value in each cell of the cost matrix is the minimum warp distance, $D(i, j)$ of two time series of point i and j as in (7).

$$D(i, j) = Dist(i, j) + \min \{D(i-1, j-1), D(i-1, j), D(i, j-1)\} \quad (7)$$

Where $Dist(i, j)$ is usually the Euclidean distance between x_i and y_j.

On this proposed method, the modified warp path is computed to any warp path which length, K, is longer than the length of processed beat, J. In this case, that warp path is shortened to the length of the processed beat. If single point of the processed beat maps to more than one point of the reference beat, warp pair which gives the minimum Euclidean distance between two signals is chosen as in (8).

$$w_j = \min\{..., w(i-1,j), w(i,j), w(i+1,j), ...\} \quad (8)$$

Then the length of total warp path is equal to the length of overall signal.

Each element of warp path contains the index of matching pair between all signal points and reference beat points.

2.3 Residual Difference

The residual will be calculated from each warp pair which contains the matching index between processed beat and reference beat. The warp pair indicates which point of reference beat will be subtracted from processed beat to receive the residual difference. The residual difference is acquired by (9).

$$\text{Residual}_j = y_j - x_i, w_k = (i,j) \quad (9)$$

In this case, the residual value will be small because each signal point, y_j, is subtracted by the closest value of reference point, x_i.

2.4 Discrete Wavelet Transform and Threshold

Residual signal composes of both significant and redundant information. Discrete Wavelet Transform (DWT) is used to decompose the residual signal into sub-band wavelet coefficients. In this research, the daubechies wavelet is chosen because the daubechies wavelet shape is compact enough to receive the information precisely in time [10]. The result of transformation composes of approximation coefficient and detail coefficient in each level of decomposition. The value of coefficient in detail coefficient is relatively low comparing to the approximation coefficient.

Threshold is applied to mitigate the insignificant data in each level of decomposition. The coefficient which its magnitude is lower than significant level is set to zero value. This mitigation process causes non-significant distortion in reconstructed signal because of energy invariance property of orthonormal wavelet transform.

The significant of coefficient is determined by threshold value which based on Energy Packing Efficiency (EPE) [11, 12]. The EPE is a percentage quantity that presents a measure of the total preserved energy of a certain sub-band after thresholding with respect to the total energy in that sub-band before thresholding and is defined as (10)

$$EPE_{Ci} = \frac{\bar{E}_{Ci}}{E_{Ci}} \times 100\% \quad (10)$$

Where $\bar{E}_{Ci}$ is the total energy of coefficient in level i after thresholding and $\bar{E}_{Ci}$ is the total energy of coefficient in level i before thresholding.

Table 1 shows the contributing energy in each sub-band using three level of decomposition.

Table 1: *Energy contribute in each sub-band level*

Record no.	Energy in each sub-band (%)			
	E_{CA3}	E_{CD3}	E_{CD2}	E_{CD1}
100	51.9959	17.3365	18.2441	12.4234
103	53.5950	17.5552	16.4549	12.3950
105	73.9209	12.3468	8.3194	5.4130
117	82.8088	7.9987	5.4714	3.7210
119	95.6474	2.5858	1.1003	0.6665
203	91.8760	4.9271	2.2584	0.9384

Most of energy contributes in lower sub-band especially in approximation coefficient. Energy presenting in approximation coefficient level, E_{CA}, is varying from 52% to 96% of total energy which depends on point number and shape of signal. To prevent the significant distortion, the approximation coefficient is preserved by setting high value of EPE. The energy in detail coefficient level, E_{CD}, is less in higher sub-band level and the difference of energy between adjacent sub-band levels is relative small which is not greater than 5.9% in regular case and 2.7% in irregular case of the total energy in that sub-band. Therefore, the same EPE value of each level of detail coefficient is chosen. The magnitude of detail coefficient is lower than the magnitude of approximation coefficient and the number of detail coefficient is larger than that of approximation coefficient. To achieve of elimination of redundant information, the EPE of detail coefficient can be selected in small value. The following algorithm is defined to calculate the threshold value [12].

1. Calculate the total Energy, E_{Ci} in each level i of the wavelet coefficient, X.

$$E_{Ci} = \sum X^2 \quad (11)$$

2. Desire the retained energy in wavelet coefficient after thresholding, $\bar{E}_{Ci}$ such as $\bar{E}_{Ci} = 0.99E_{Ci}$.

3. Reorder the wavelet coefficient in descending order of the magnitude, X_s.

4. Use the following pseudo code to compute the threshold value.

Set energy = 0
Set k = 0
While energy $<\bar{E}_{Ci}$
    k = k+1
    energy = energy $+(X_s[k])^2$
end
threshold = $X_S[k]$

The threshold value of each sub-band is repeat calculated from this algorithm. This procedure will eliminate the non- significant information from decomposed signal and still remain desired energy of signal.

2.5 Encoding

After threshold procedure, the redundant information is eliminated by setting to zero that causes majority of signal to be zero value. Huffman method is the minimum-redundancy coding which is suitable for this kind of information. In this proposed method, signal after thresholding is encoded using Huffman encoding method before being recorded or transmitted. Since mostly of signal value is zero value and the advantage of Huffman method, this encoding process obviously reduces the data size of ECG signal.

3. RESULT OF COMPRESSION

In this research, MIT-BIH arrhythmia database is used to test the algorithm performance. The ECG sampling rate is 360 Hz with 11 bits/sample. The efficiency of compression is usually evaluated by two indicators; percent root means square difference and compression ratio.

Percent Root Means Square Difference (PRD) which is the distortion of reconstructed signal comparing to original signal.

$$PRD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{\sum_{i=1}^{n} x_i^2}} \times 100\% \tag{12}$$

Where, x_i is the original signal and $\hat{x}_i$ is the reconstructed signal. Compression Ratio (CR) is the ratio between the original data size and the total compressed data size

$$CR = \frac{N_x}{N_{total}} \tag{13}$$

Where N_x is the size of original signal and N_{total} is the size of total compressed signal which is defined as (14)

$$N_{total} = [N_{compress\ residual} + N_{reference\ beat} + N_{warp\ path}] \tag{14}$$

Where $N_{compress\ residual}$ is the size of compressed residual signal, $N_{reference\ beat}$ is the size of reference beat and $N_{warp\ path}$ is the size of warp path.

On this research, another indicator of Compression Ratio, CR2, is defined when warp path data size is not included in calculation as (15).

$$CR2 = \frac{N_x}{N_{compress\ residual} + N_{reference\ beat}} \tag{15}$$

For performance testing, this method is tested with 100,000 points of MIT-BIH signal. Two classes of signal are experimented, regular period signal record no. 100, 103 and 105 and irregular period signal record no. 117, 119 and 203. The PRD and two types of compression ratio are used to judge the performance. CR1 which is the ordinary compression ratio is defined as (13) and CR2 is defined as (15).

One parameter which affects the compression ratio and PRD is the threshold level. In this proposed method, the threshold value is selected by varying two parameters of Energy Packing Efficiency, EPE. The setting of EPE level is based on the distribution of energy in each level of sub-band wavelet coefficient. Therefore, the Energy Packing Efficiency of approximation coefficient, EPE_{AC}, varies from 50% to 99% and the Energy Packing Efficiency of detail coefficient, EPE_{DC}, varies from 20% to 90%.

For regular period signal testing, the results are shown in Table 2. The proposed method performs efficiently outcome in a better in PRD and higher in CR than previous method comparing to the Table 3. In Table 3, the results from previous method are shown. The threshold technique of the previous method is that the coefficient which magnitude is lower than the setting value of maximum coefficient's magnitude is eliminated.

From proposed method, the PRD of this technique is always less than one although the preserved energy of thresholded signal reduces to half.The energy contributed in approximation coefficient of regular period signal is about 52% - 74% of the total energy. In this experiment, both PRD and compression ratio are varied by EPE setting. EPE_{AC} and EPE_{DC} have similar impact on PRD but EPE_{DC} is a bit more influence than EPE_{AC} on compression ratio especially in CR2.

The reconstructed signal and error when this algorithm is tested on regular period signal are displayed in Fig. 6, Fig. 7 and Fig. 8. The maximum error between original and reconstructed signal is plotted at sampling number 400.

For irregular period signal testing, the proposed algorithm gives much better PRD than the result in Table 3 and [8], [13], especially during irregular beat.

Table 2: *CR and PRD of proposed method with 100,103 and 105 (regular)*

Record no.	Threshold (EPE)		PRD	CR1	CR2
	EPE_{AC}	EPE_{DC}			
100	99%	90%	0.1400	3.1725	6.2802
	99%	50%	0.2502	3.6397	8.4197
	90%	20%	0.3309	3.8804	9.8301
	50%	50%	0.3591	3.9499	10.2889
103	99%	90%	0.1648	3.1945	6.8875
	99%	50%	0.2994	3.5481	8.7726
	90%	20%	0.4115	3.7167	9.8803
	50%	50%	0.4414	3.7734	10.2916
105	99%	90%	0.1746	3.0566	6.2509
	99%	50%	0.2673	3.5393	8.6686
	90%	20%	0.3747	3.7551	10.0889
	50%	50%	0.5251	3.7314	9.9198

Table 3: *CR and PRD of previous method*

Algorithm	Record no.	PRD	CR1
Previous Method by threshold at 50% of maximum magnitude	100	0.3257	3.2456
	103	0.3676	3.1020
	105	0.3202	3.1096
	117	0.3428	3.2370
	119	0.8050	3.2453
	203	0.9880	3.4443

Therefore, this research focuses on the compression of irregular period signal such as signal record 117, 119 and 203.

From evaluation of energy in each level of subband, the energy of approximation coefficient is more than 82%. Especially in high varying signal, the energy is about 95%. Therefore, degree of energy contributing in approximation coefficient indicates the regularity of signal.

From Table 4, the testing shows the results that PRD of this proposed algorithm is low because of the DTW algorithm improving the alignment between each beat and reference beat to have equal length. Consequently, error from Period Normalization process will not occur. For compression ratio, the performance is better than previous method but still low. The increasing of CR1 value is small even though the retained energy is decreased to half. This method still does not achieve for CR1 because total compressed data is added up by warp path which data size is larger than data size of compressed residual signal. Moreover, threshold setting has no effect on warp path's size. Last column of Table 4 shows CR2 value when the warp path is not included in calculation. The compression ratio excluding warp path, CR2, is higher than two times of the compression ratio including warp path, CR1, especially in case of small EPE_{DC} setting.

Table 4: *CR and PRD of proposed method with 117,119 and 203 (irregular)*

Record no.	Threshold (EPE)		PRD	CR1	CR2
	EPE_{AC}	EPE_{DC}			
117	99%	90%	0.1982	3.0522	5.7178
	99%	50%	0.2753	3.6213	8.1033
	90%	20%	0.4406	3.9362	9.8704
	50%	50%	0.6602	3.8173	9.1551
119	99%	90%	0.7510	3.5041	7.2556
	99%	50%	0.8775	3.9496	9.4666
	99%	20%	1.6248	4.0556	10.0996
	50%	50%	3.2230	4.0469	10.0461
203	99%	90%	0.7580	3.5485	6.7580
	99%	50%	0.9102	4.0103	8.6565
	90%	20%	1.6284	4.2552	9.8849
	50%	50%	3.1157	4.2480	9.8462

The threshold's effect on irregular period signal is different from those on regular period signal. When EPE_{AC} value reduces, it makes small change in higher compression ratio but large change in higher PRD, which is more than three times. If EPE_{DC} value decreases, compression ratio has much increasing while PRD has not much increasing.

Fig. 9, Fig. 10 and Fig. 11 are the test results of signal 117, 119 and 203 respectively. The maximum error is marked at sampling number 400.

There is another achievement of proposed method that all peaks are always reconstructed at the same instant as in original signal. This is the benefit from Dynamic Time Warping technique which maps the peak of original signal to the peak of reference beat. Therefore, the peak will be always added back to where it's original position in reconstruction process. From Fig. 9 shows that there is only small error around peak point when applied this algorithm to signal record 117. Even though, record 119 and 203 which are highly varying period as shown in Fig. 10 and Fig. 11, all peaks remain in reconstructed signal and at the exact position.

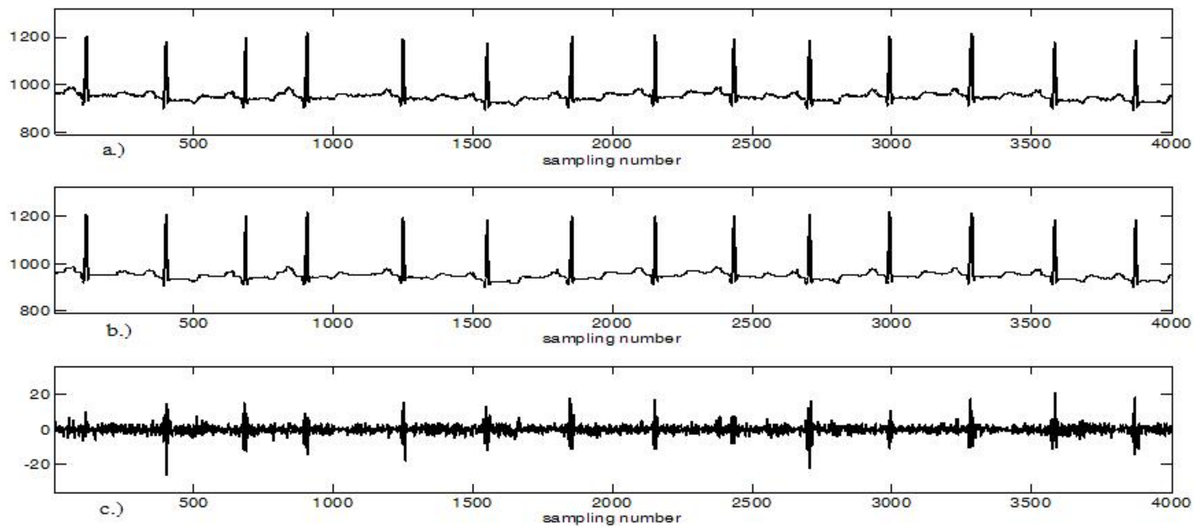

Fig.6: *Record 100 at EPE_{AC} =99% and EPE_{DC} =50% threshold setting a.) Original signal b.) Reconstructed signal c.) Error between (a) and (b).*

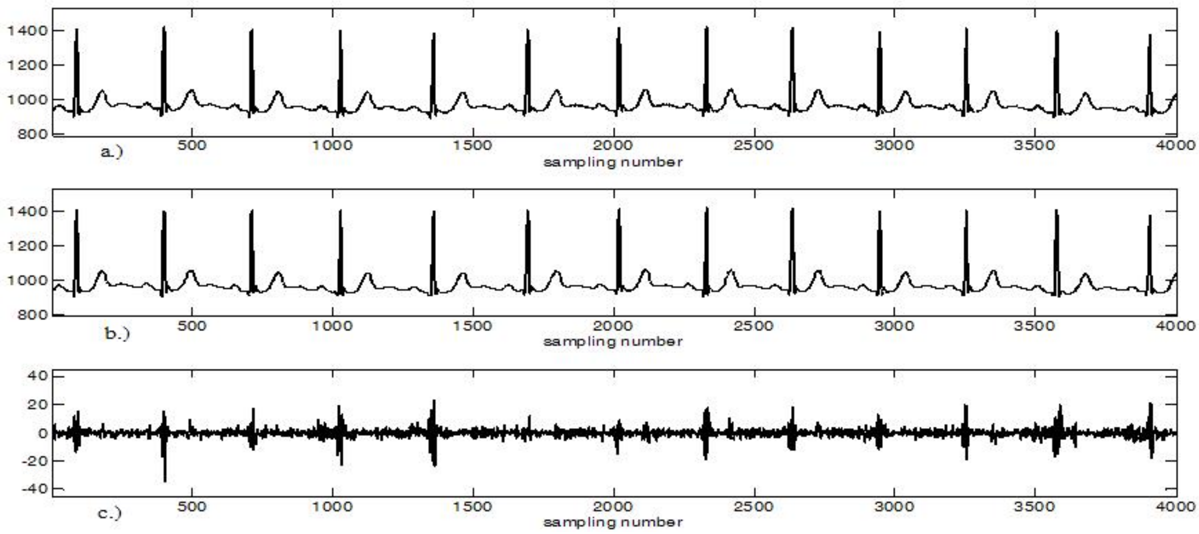

Fig.7: *Record 103 at EPE_{AC} =99% and EPE_{DC} =50% threshold setting a.) Original signal b.) Reconstructed signal c.) Error between (a) and (b).*

4. CONCLUSION

The aim of this proposed method is to improve the algorithm of ECG compression especially on irregular period ECG. Dynamic Time Warping technique is applied in preprocessing process instead of Period Normalization. This technique can reduce the residual value. In consequence, the error between original signal and the reconstructed signal is enormously decreased. But there is some disadvantage of this technique which is the addition warp path producing from Dynamic Time Warping process. Since the size of warp path more than two times the size of compressed residual, that extremely reduces the compression ratio. To improve compression ratio, the threshold selection based on EPE is applied and the threshold value depends on contributed energy in each subband. The more varying period is the more energy in low sub-band, particularly in approximation coefficient. The high EPE value of approximation coefficient will be selected to keep the essential information and the low EPE value of detail coefficient will be chosen to increase the compression ratio while only small change of error occurs. Another advantage of this proposed method is the improving of the reconstructed signal especially around peak point which is the importance clinical information. This correctness arises from DTW process which pairs all peaks to peak of reference beat. Thereby, all peaks will al-

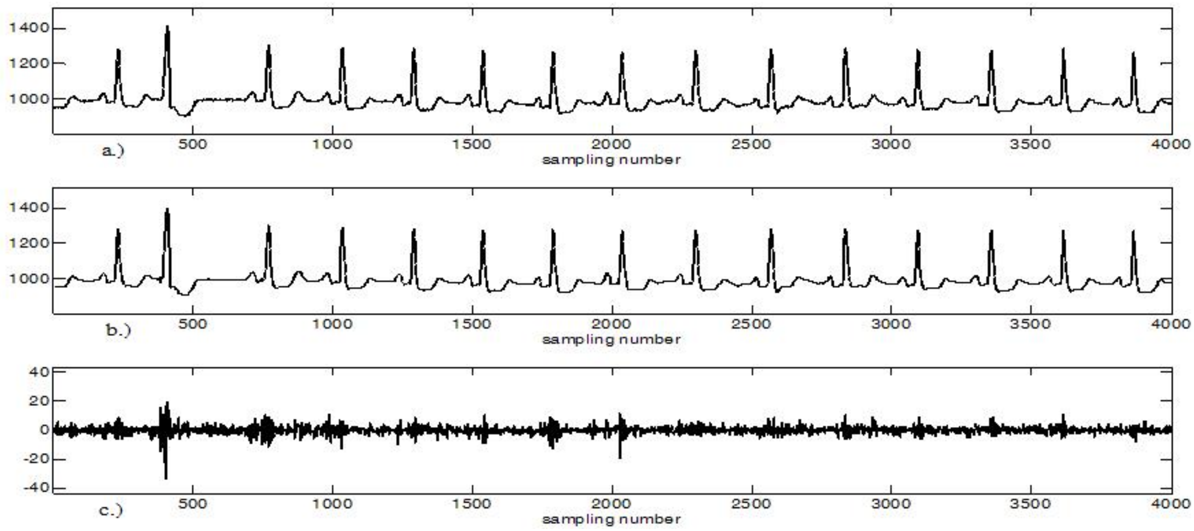

Fig.8: *Record 105 at* EPE_{AC} *=99% and* EPE_{DC} *=50% threshold setting a.) Original signal b.) Reconstructed signal c.) Error between (a) and (b).*

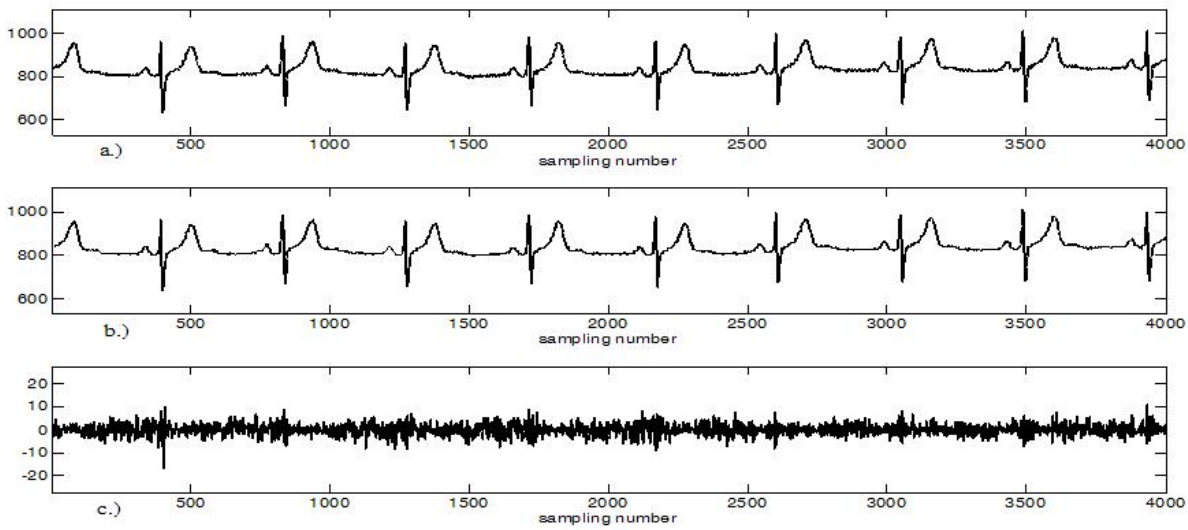

Fig.9: *Record 117 at* EPE_{AC} *=99% and* EPE_{DC} *=50% threshold setting a.) Original signal b.) Reconstructed signal c.) Error between (a) and (b).*

ways be reconstructed from reconstruction process. No matter to the regularity of signal period, the result from proposed method shows less distortion than other methods.

For further work, this research will keep on increasing the compression ratio by developing of algorithm which reducing the size of warp path to lower the total size of compressed signal and by developing algorithm for choosing the best threshold value based on Energy Packing Efficiency to receive the optimal value between compression ratio and error.

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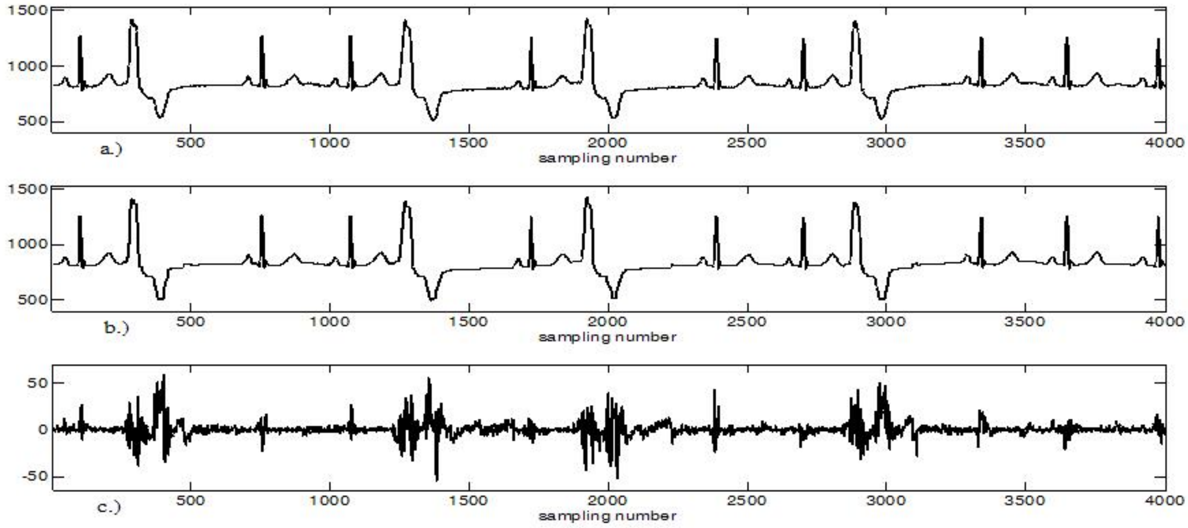

Fig.10: *Record 119 at* EPE_{AC} *=99% and* EPE_{DC} *=50% threshold setting a.) Original signal b.) Reconstructed signal c.) Error between (a) and (b).*

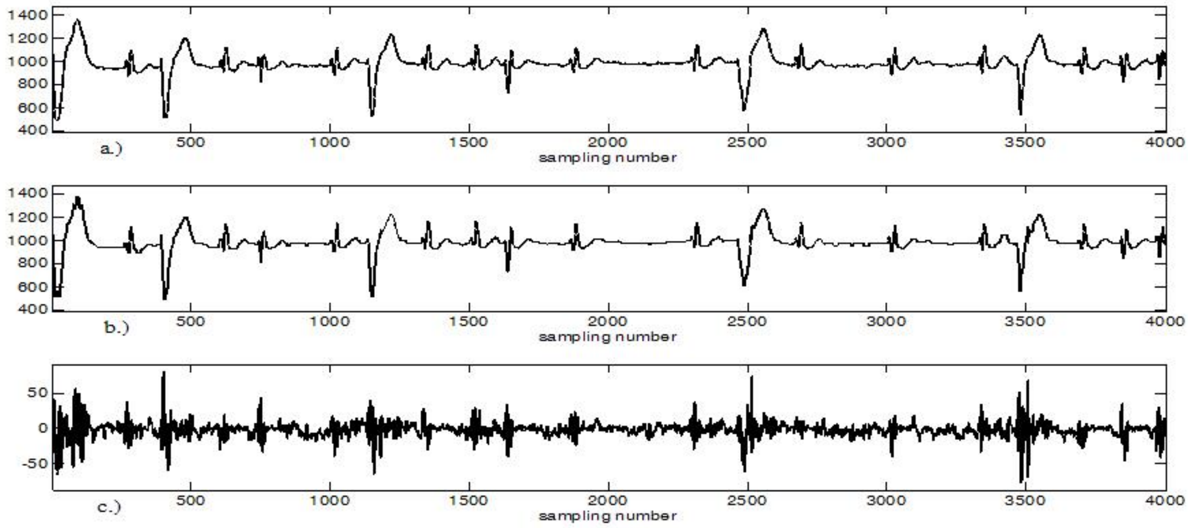

Fig.11: *Record 203 at* EPE_{AC} *=99% and* EPE_{DC} *=50% threshold setting a.) Original signal b.) Reconstructed signal c.) Error between (a) and (b).*

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