Data Compression of Generalized Biosignals in the Heart and Muscle (December 2001)

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Abstract — **This paper presents the development of a compression method scheme for an ECG signal. The physiological basis of cardiac signals is discussed, followed by analysis of our chosen compression algorithm using sample ECG waveforms. Using sample signals, the system was tested to produce output with an average compression ratio of 46x and a composite PRD ~5%.**

Index Terms — **Biosignals, ECG, EMG, Compression**

I. Introduction

ECG activity, also known as *electrocardiographic activity* or *aggregate cardiopotential activity*, is the change of electrical potential that occurs during the contraction of the heart. Electric current is created from the change in electric potential, which can then be recorded based on the echoes from the constant series of waves that reflect the electrical activity of the heart. An electrocardiogram is the graphic line tracing of the electrical activity of the heart, which is then used by physicians to diagnose any abnormalities.

Each heartbeat is caused by a section of the heart generating an electrical signal, which then conducts through specialized pathways to all parts of the heart. These electrical signals also get transmitted through the chest to the skin where they can be recorded. The ECG is performed by placing 12 recording leads at certain specific locations on the body that record the heart's electrical activity. The ECG is the oldest heart test that is still in routine use today.

In order to extract meaningful information from the ECG signal, the signal must be digitized and the digital information must be stored. Although technically the signal can be sampled at as little as 300 Hz, the researchers and physicians would optimally like to sample at 5000 Hz, with 12 bits per channel. The full ECG of 12 channels would thus generate 720 kbits of data every second.

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This is feasible for powerful desktop computer systems, but patients can elicit physiological changes when they know they are being monitored. Many cardiac arrhythmias are also active only when the heart is exercising or under stress. In order for a physician to really obtain the information they need to not miss any diagnosis, an ambulatory ECG is required.

Such a device could fit comfortably under a patient's clothes and should be unnoticeable under normal conditions. A doctor could monitor the patient's rhythms with the heart undergoing everyday activity and could collect 24, 48, or 72 hours worth of recordings. However, it is not currently possible to manufacture such a device. Current memory uses too much power relative to current battery technology. This means that doctors and engineers must compromise- however, by introducing data compression into the picture, the amount they must compromise becomes much less. The key feature in any data compression scheme is that one can use knowledge of the nature of the signal to develop powerful compression algorithms.

Characteristics of the ECG Signal [2,3]

Cardiac Depolarization and *Repolarization* occur in a normal sequence to produce characteristic features of an ECG signal.

1. Sinoatrial (SA) node

2. Atrioventricular (AV) node

3. Atrioventricular bundle

4. Left and Right Bundles of His

5. Purkinje Fibres

6. Branch of left bundle branch

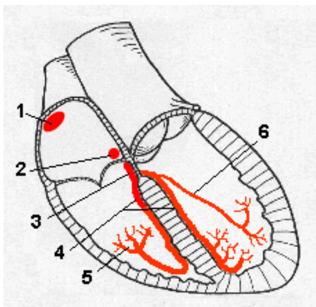

Figure 1. The electrical system of the heart.

P wave

The impulse starts at the SA node (located in the top corner of the right atrium) and a depolarization wave spreads throughout the right atrium towards the AV node. P waves are the first part of an ECG signal. They represent atrial contraction.

Q wave
After a small delay at the AV node, the depolarization wave continues into the atrioventricular bundle and into the Bundle of His. The Bundle of His then branches to form the left and right bundles of His and eventually form branches called Purkinje Fibers.

R wave
The large upward positive deflection in lead I (R wave) results from the depolarization of the top portion of the ventricular myocardium.

S wave
The depolarization wave continues to the ventricles.

ST segment
Finally, the heart is fully depolarized. For a short period, there is no electrical activity and this is represented by the flatness of this segment.

T wave
Repolarization starts from the endocardium to the epicardium. After this entire sequence is over, a period of no electrical activity exists until another impulse begins at the SA node.

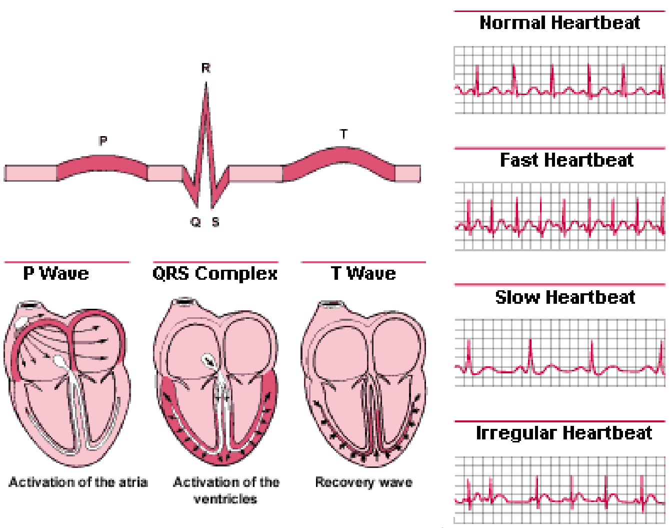

Figure 2: The features of a normal ECG signal.[1]

Key Abnormal features of an ECG signal [2,4]

P wave abnormalities:

A pointed P wave is a sign of right atrial hypertrophy.
An m-shaped P wave is a sign of left atrial abnormalities (hypertrophy or dilation).

Hyperkalaemia, a condition caused by high levels of potassium in the bloodstream, may be indicated by the following changes in the ECG: small or absent P waves**,** wide QRS, shortened or absent ST segment, and wide, tall and tented T waves.

Another condition signified by a P wave variation is the *Multifocal Atrial Tachycardia (MAT)*. This is due to fast heart beat and results in atrial rates higher than 100 beats per minute and irregular ventricular rhythm.

When an ECG of identical P waves occurs with a vanishing baseline, this is indicative of *atrial flutter*. In this case, one out of two or three or even four atrial depolarizations make it to the AV node.

In the case of the *Premature Atrial Beat*, the AV node fires earlier than normal. Thus, an ECG of this condition would contain early "different morphology" p-waves followed by a normal QRS complex.

For a *Premature Ventricular Contraction (PVC)*, the entire waveform is wide and varying from the normal ECG. This is a condition caused by anything that prevents oxygen from getting to the heart. Several can things occur: the purkinje fibers system is not being used, the left or right ventricle depolarizes early, and the resulting ECG has a short followed by a long R to R interval and a larger QRS complex. If the ECG shows that PVCs just happen to occur over the latter half of the T wave, ventricular flutter and ultimately ventricular fibrillation will result.

A Large Q wave is a sign of a previous heart attack.

A normal PR interval is 0.12 to 0.2 seconds. A short PR interval may indicate a problem with the conduction between the atria and ventricles. There may also be a problem of focused depolarization surrounding the AV node. An extended PR interval can be due to a delay between the atrial depolarization and ventricular depolarization, in which case a heart block may be present. This condition is not necessarily important but may be a sign of the following disorders: electrolyte disturbance, coronary artery disease, acute rheumatic carditis, or digitalis toxicity.

An increase in the width of the QRS complex on the ECG trace may be a sign of a bundle branch block. This occurs when there is a blockage in the normal conduction pathway between the AV node and the ventricles. This abnormality increases the time for the ventricles to contract. As a result, the QRS wave complex becomes wider because of a depolarization wave caused by a ventricular impulse.

Other long term problems can be detected by the ECG. In patients with high blood pressure, the left side of the heart increases to compensate. In lead II, the QRS complex widens at the base and its height increases (3 or 4 divisions higher). It is possible for re-stimulation to occur, when the impulse hits part of the heart wall again, as shown in the descending part of the T wave. This may cause fibrillation and possibly death.

An elevated or depressed ST segment can represent a cardiac infarct, meaning the muscle is not working properly. Causes of elevation include acute myocardial infarction (e.g. anterior, inferior), left bundle branch block (notching of R waves), normal variants (e.g. athletic heart, Edeiken pattern, high-take off), and acute pericarditis. Causes of depression include myocardial ischaemia, digoxin effect, ventricular hypertrophy, acute posterior myocardial infarction, pulmonary embolus, and left bundle branch block.

Finally, an inverted T wave is the sign of a past heart attack. Tall T waves can have several causes, including hyperkalaemia, hyperacute myocardial infarction, and left bundle branch block. A small, flattened or inverted T wave may be due to ischaemia, age, race, hyperventilation, anxiety, drinking iced water, Left Ventricular Hypertrophy, drugs (e.g. digoxin), pericarditis, Pulmonary Embolus, intraventricular conduction delay (e.g. Right Bundle Branch Block) or electrolyte disturbance. In RBBB, the conduction in the right bundle is lost. Consequently, the left bundle will beat quickly while the right side is waiting and conduction is slowed down. A really slow and delayed S portion of the ECG wave signifies this condition.

II. Design of Compression Scheme

The compression scheme aims to achieve the highest possible compression ratio without visually distorting the waveform to a degree that would cause a trained doctor to make an incorrect diagnosis. Three cascading compression techniques were used rather than a single technique because combining different techniques can combine the benefits of each.

The signal is sampled at 360 Hz, so it can stand to be downsampled without losing too much information. However, the QRS wave is only a few samples wide, and random downsampling could destroy valuable peak information. Therefore, the Turning Point algorithm was used to preserve slope changes. The algorithm was run with one pass.

At the back end of the run, Huffman coding was a natural choice. Because Huffman coding produces a bit-stream that does not resemble the original ECG and can no longer be compressed, Huffman coding must be the last component of our pathway. This also works well because Huffman coding is lossless, so the errors of the first two waveforms can be considered the total error. A new coding table was made for every signal as this gave the best compression ratio.

Choosing the middle algorithm to use was more challenging. It had to be something that would not be adversely affected by using a signal that had passed from Turning Point, and it should fit nicely into Huffman. We took advantage of the fact that there is a large time lag between beats. If this lag can be encoded as a line, there can be significant compression gain here without much distortion of the more important waveforms. Cortes and Aztec both feed extremely well into Huffman, because their horizontal lines produce many samples of the same value. The less random the distribution of values is, the better Huffman coding performs. To gain the power of the AZTEC algorithm with the slope saving power of turning point, we used the Cortes algorithm.

Errors were not directly calculated for our chosen scheme because composite error from many runs cannot simply be calculated in EMAP. However, our two chosen methods each had PRD values ~3-4%.

MIT/BIH Sample	Turning Point CR	Cortes CR	Huffman CR	Composite CR
C105fi	2	4.878	6.052	59.04
C105i	2	3.146	5.128	32.27
D207i	2	5.499	6.698	73.66
F108i	2	4.811	6.819	65.61
C105fi	2	2.143	3.380	14.48
Average	**2**	**4.09**	**5.61**	**45.93**

Table 1. Performance of three-tier coding scheme on 5 MIT/BIH Data Records.

Alternate Compression Methods

Several other compression methods were tested, and the results are chronicled in the following table. The parameters are listed from left to right. Many tests were performed, but the tabulated information is given only for the C105fi record. Moving average filters improved some methods (AZTEC) but not significantly enough to justify including that method in our final compression pathway. The biggest problem with these methods is their high PRD value. In general, a PRD >5% was taken to be unacceptable.

Method	Parameter	Compression Ratio	PRD%
TP	2,0,0,0	4	9.46
AZTEC	10,0,0,0	6.7	18.00
AZTEC	20,0,0,0	10.83	15.39
FAN	10,0,0,0	7.643	8.43
FAN	20,0,0,0	12.360	20.070
DPCM	[1],linear,0,0	2.750	5.35
DPCM	[2],linear,0,0	3.667	7.175
DPCM	[2],quad,0,0	3.667	11.06
LPC	Adapt,0,0,0	18.269	14.10
LPC	fix,0,0,0	16.073	10.59
LPC	both,0,0,0	16.073	10.727

Table 2. Alternate Compression Schemes Attempted.
1= [-50 -35 -25 -15 -5 5 15 25 35 50 75 100 150 200 300]
2- [-50 -25 -5 5 25 50 100 300]

Extension to EMG Signals

The compression pathway should work well on EMG signals as well, especially since muscle recordings can have long periods of silence between contractions. The compression scheme performs very well on constant values, but due to file format problems, no tests were undertaken.

III. Results

Figures 3 through 12 show the results of data compression on the five MIT/BIH signals. For each signal, the first figure is the original signal, followed by the reconstructed signal after Turning Point compression. The third graph in that figure shows difference between the two signals. The second figure shows the results of running the Cortes algorithm on the reconstructed Turning Point signal and the error associated in doing so. Since Huffman coding is lossless, no figures including this compression method were shown.

To compare the original signal with the final output for each record, the top waveform in the first figure and the middle waveform in the second figure should be analyzed. It is important to note the lack of any major signal distortions, which could cause misclassification of any of the anomalies listed above. For example, a widened QRS complex can indicate a PVC and if the compression scheme tended to shorten the QRS interval, then a doctor might read a normal heartbeat when in fact there could be a serious, underlying problem. The figures show that this error is avoided by our compression scheme.

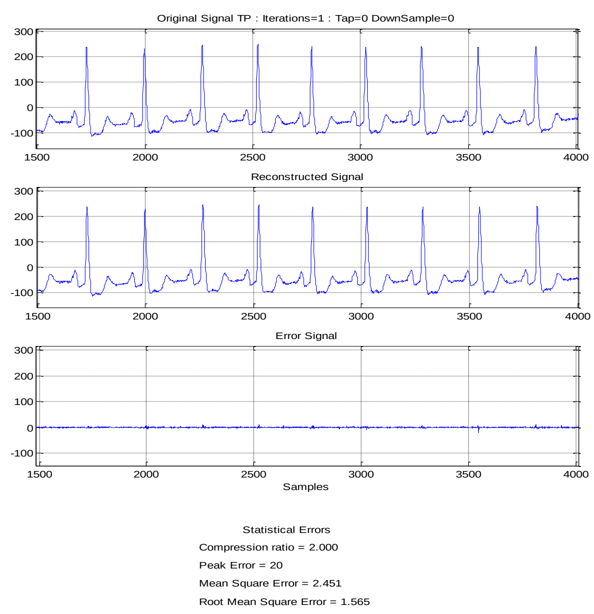

Fig 3. C105fi – Turning Point Compression

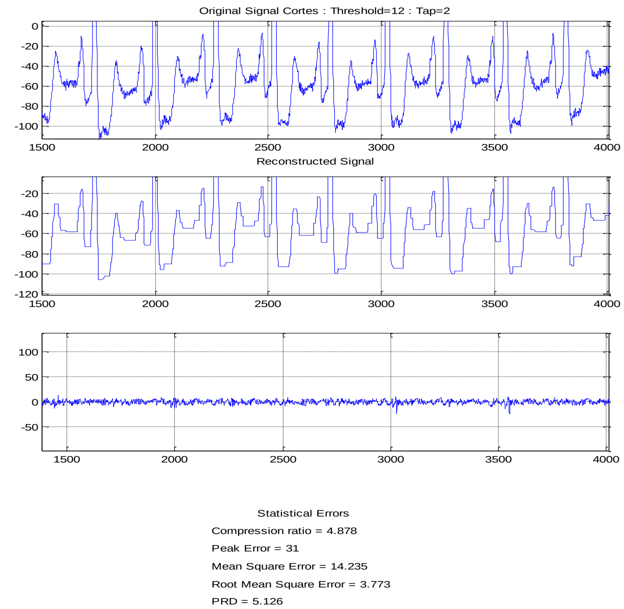

Fig 4. C105fi – Cortes Compression

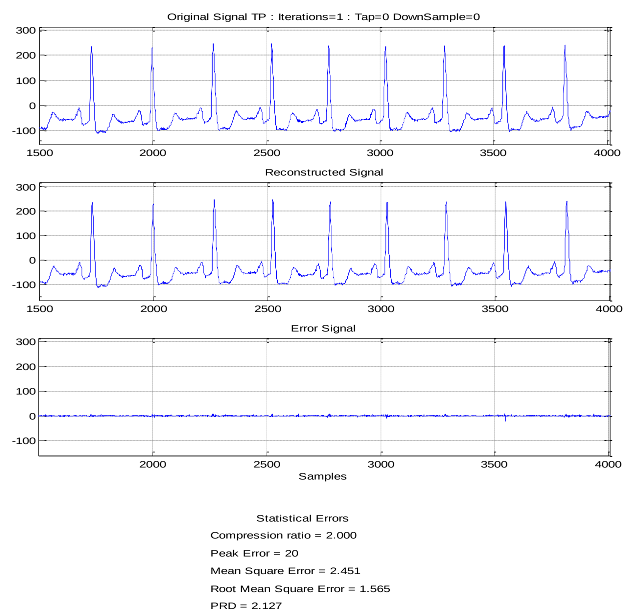

Fig 5. C105i – Turning Point Compression

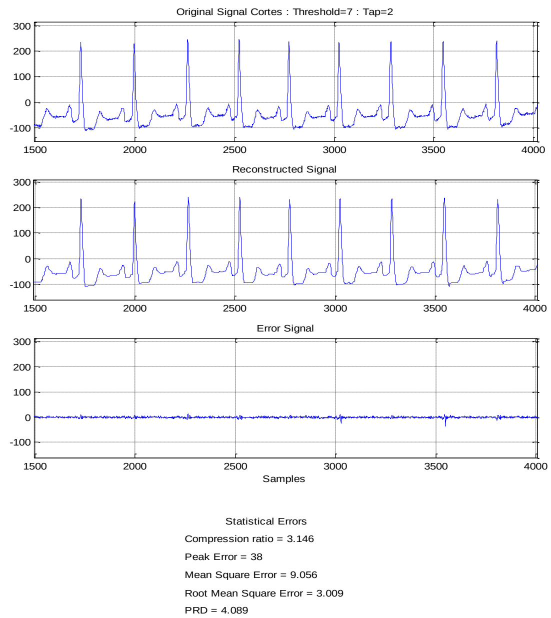

Fig 6. C105i – Cortes Compression

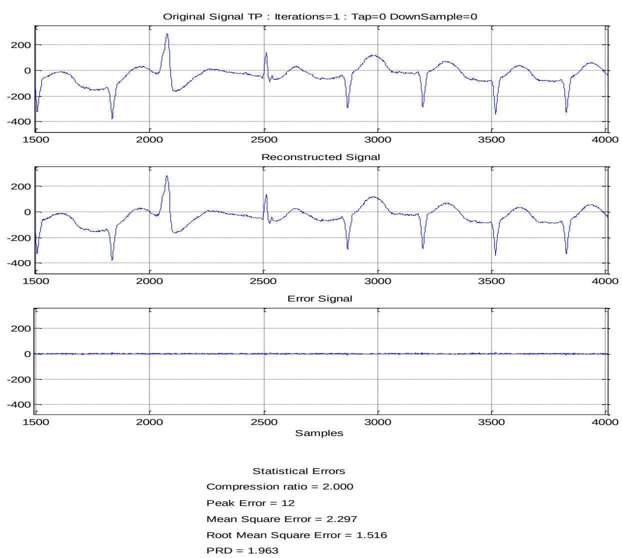

Fig 7. D207i – Turning Point Compression

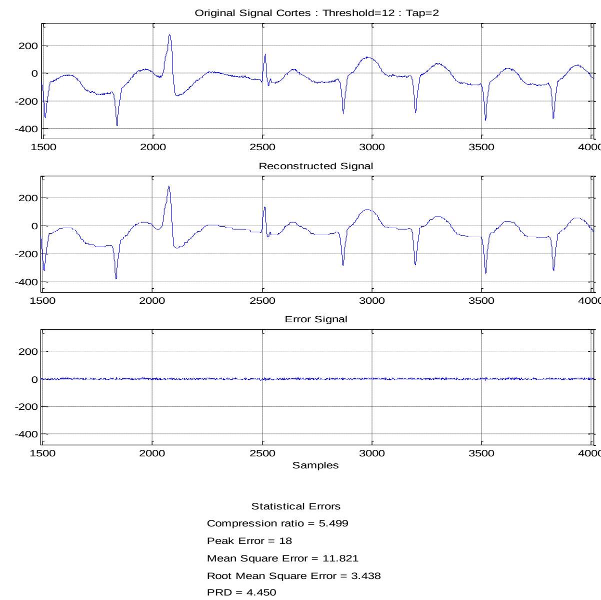

Fig 8. D207i – Cortes Compression

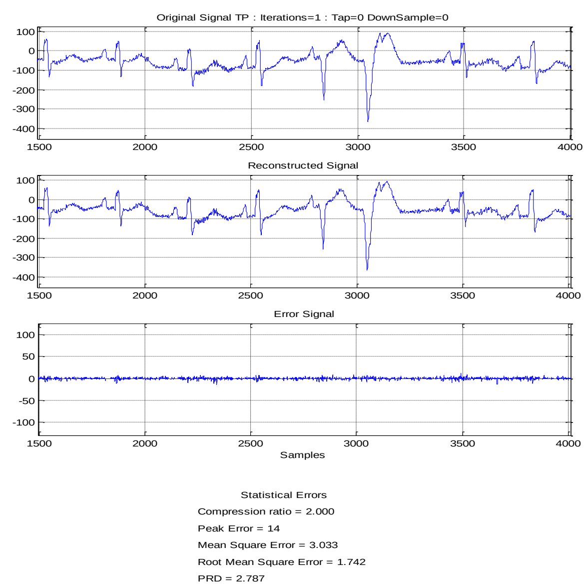

Fig 9. F108i – Turning Point Compression

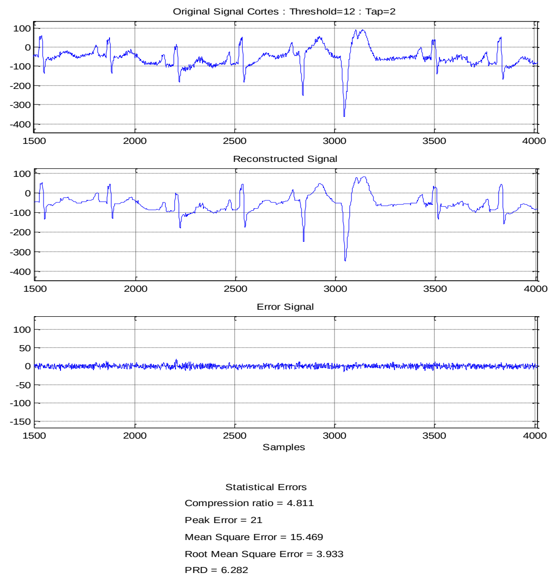

Fig 10. F108i – Cortes Compression

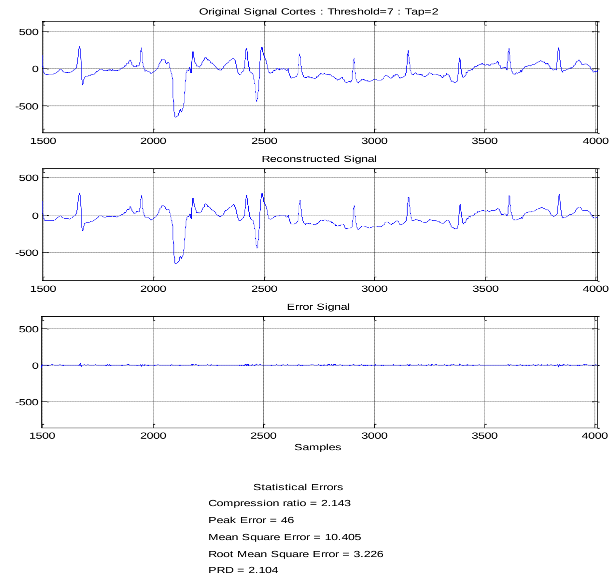

Fig 12. N105i – Cortes Compression

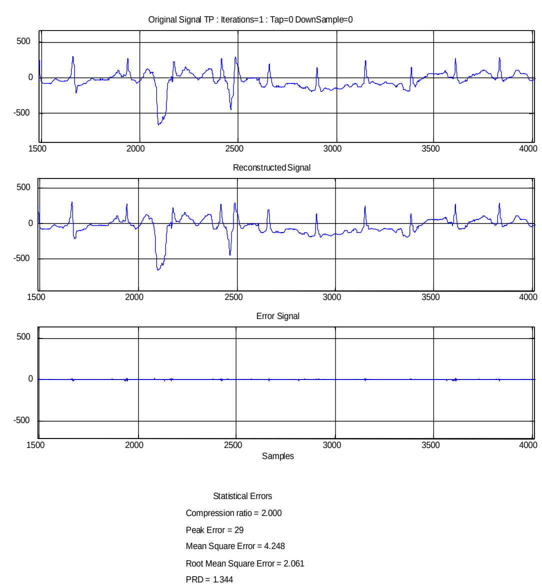

Fig 11. N105i – Turning Point Compression

IV. CONCLUSION

The designed compression scheme can provide a 46x compression ratio on the average, without significantly disrupting the waveform to cause a doctor to misdiagnose a patient. This compression design can greatly aid the manufacturers of an ambulatory ECG system.

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