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PAPER Special Section on ECG Data Compression

Electrocardiogram Data Compression by the Oslo Algorithm and DP Matching

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SUMMARY We use the B spline function and apply the Oslo algorithm to minimize the number of control points in electrocardiogram (ECG) waveform compression under the limitation of evaluation indexes. This method is based on dynamic programming matching to transfer the control points of a reference ECG waveform to the succeeding ECG waveforms. This reduces the execution time for beat-to-beat processing. We also reduced the processing time at several compression stages. When the difference percent normalized root mean square difference is around 10, our method gives the highest compression ratio at a sampling frequency of 250 Hz.

key words: compression, ECG, B spline, DP matching

1. Introduction

With the popularity of electrocardiogram data in clinical applications, there has been a strong demand for methods of compressing the huge volume of electrocardiogram (ECG) for storage and transmission. Various compression methods have been proposed in terms of several stages including sampling, redundancy rejection, and encoding. AZTEC [1] and SAPA [2] offer excellent algorithmic ease and a high compression rate. However, they do not always reproduce the details of the ECG waveform.

We have proposed a compression method based on reducing the number of control points that are extracted after approximating the ECG waveform by the B spline function. The B spline curve gives less vibration than other polynomial approximations and is Considered locally a reasonable approximation [3]. Therefore, it is used for representing the curve and the curved surface. We studied the Oslo algorithm [4] which varies the number of control points without degenerating the reproduced waveform. The inverse Oslo algorithm is used to compress the figure pattern data because it can represent the pattern by fewer control points. However, the Oslo algorithm requires a long execution time if it is applied to the ECG waveform of each beat. Thus, direct implementation of the Oslo algorithm is not practical for real-time processing of long term ECG data.

To overcome the difficulties in real-time processing, we use dynamic programming (DP) matching [5] to transfer the control points previously estimated from the initial ECG waveform to the succeeding beats. We call the initial ECG waveform a reference ECG waveform. This method achieves several improvements in processing time of the control point adjustment and in the long term ECG processing stage. As a result, the processing time becomes practical.

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2. Adjustment of Control Points

2.1 Third-Order B Spline Function

The third-order B spline curve is composed of curve segments $C_i(t)$ determined by the control point series Q_j. For example, using four consecutive control points, Q_j for $j=1, \cdots, 4$, $C_i(t)$ is defined by:

$$C_i(t)=N_0(t)Q_{i-1}+N_1(t)Q_i+N_2(t)Q_{i+1}+N_4(t)Q_{i+2} \quad (1)$$

where $N_j(t)$ is the normalized B spline function and is determined by the knots consisting of a specific time series. The joint points of adjusting curve segments, $\{P_i\}$, are the node points which are determined by the knot series.

2.2 Oslo Algorithm

The Oslo algorithm is known as a method of increasing the number of control points without changing the curve profile by inserting knots (Fig. 1). Assuming the original control point series Q_j for $j=0, \cdots, n$, and its knot series T_j, a new control point D_j with an extra m knots Φ_j, $j=0, \cdots, n+m$, is given by

$$D_j=\sum \alpha_i(j)Q_i, \quad m>n, \quad (2)$$

where the coefficients, α_i, depend on the relationship between T_j and Φ_j without depending on the curve profile.

The inverse-Oslo algorithm decreases the number of control points without changing the curve profile. The matrix expression of (2) is

$$\boldsymbol{D}=\boldsymbol{A}\boldsymbol{Q}, \tag{3}$$

so the reduction of control points is given by

$$\boldsymbol{Q}=\boldsymbol{A}^{-1}\boldsymbol{D}, \tag{4}$$

where the number of knots for $\boldsymbol{D}$ is larger than that for $\boldsymbol{Q}$. This simultaneous equation has a larger number of conditions than required. We used the singular value decomposition to obtain an approximate of $\boldsymbol{Q}$ by the general inverse matrix of $\boldsymbol{A}$.

2. 3 Evaluation Indexes

We evaluated the waveform reproducibility as a function of the compression ratio (CR), using the correlation coefficient (CC) and difference percent normal-

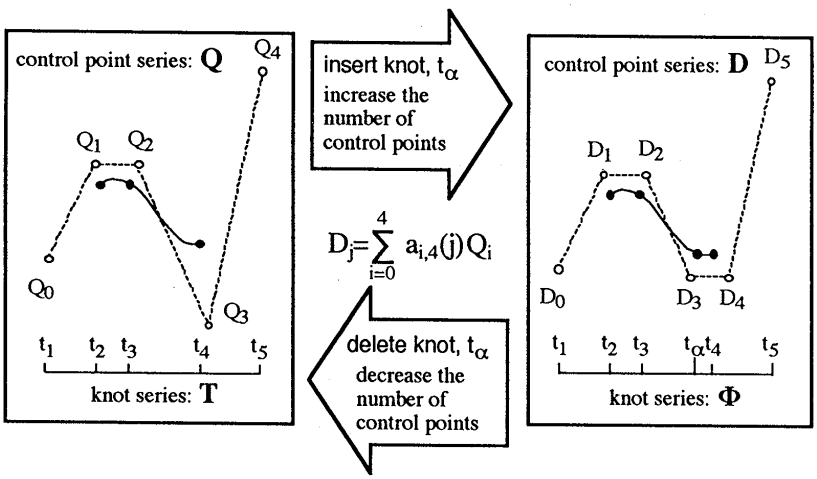

Fig. 1 Adjustment of the number of control points by the Oslo and the inverse Oslo algorithms.

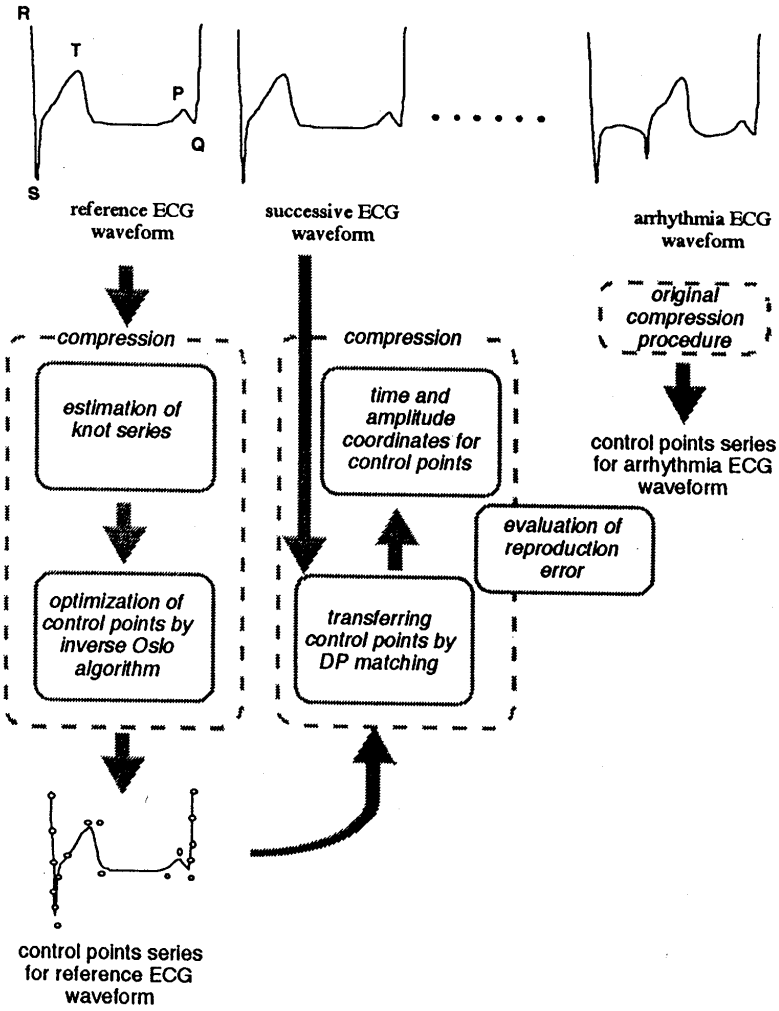

Fig. 2 Overview of the compression procedure.

ized root mean square difference (PRD) as follows:

$$\mathrm{CR}=(\text{number of control points})/(\text{number of original points}); \quad (5)$$

$$\mathrm{CC}=E_t[(o-\hat{o})(e-\hat{e})]/\{E_t[(o-\hat{o})^2]E_t[(e-\hat{e})^2]\}^{1/2}; \quad (6)$$

$$\hat{o}=E_t[o],\ \hat{e}=E_t[e]; \quad (7)$$

$$\mathrm{PRD}=\{E_t[((o-\hat{o})-(e-\hat{e}))^2]/E_t[(e-\hat{e})^2]\}^{1/2}100; \quad (8)$$

where o is the original waveform and e is the estimates. $E_t[\cdot]$ means an expectation procedure in time domain. CC indicates whether the reproduced waveform is similar to the original waveform. Moreover, the PRD evaluates the variance of the reproduction error. CC takes a value from -1.0 to 1.0. PRD takes a value of more than zero. Good reproducibility is achieved when CC and PRD are near 1.0 and 0.0, respectively.

3. Compression

3.1 Overview

Figure 2 shows the flow chart of the entire procedure of our method. First, a reference ECG waveform of one beat, which is the average pattern of three beats of consecutive ECG waveforms, is calculated. Next, the reference control points are adjusted for the reference ECG waveform by the reduction procedure including the Oslo algorithm. Afterwards, the reference control points are transferred by DP matching for successive beats.

The ECG waveform is reconstructed by the transferred control points and the B spline function. This reconstructed ECG waveform is in turn compared with the original ECG waveform at each beat. A set of compression data is stored while monitoring the CC or PRD to check, if the CC or PRD terminates within a permission level. If the evaluation index is too larger, the original reduction procedure to estimate the reference control points is repeated from the beginning. This will occur in case of an arrhythmia beat.

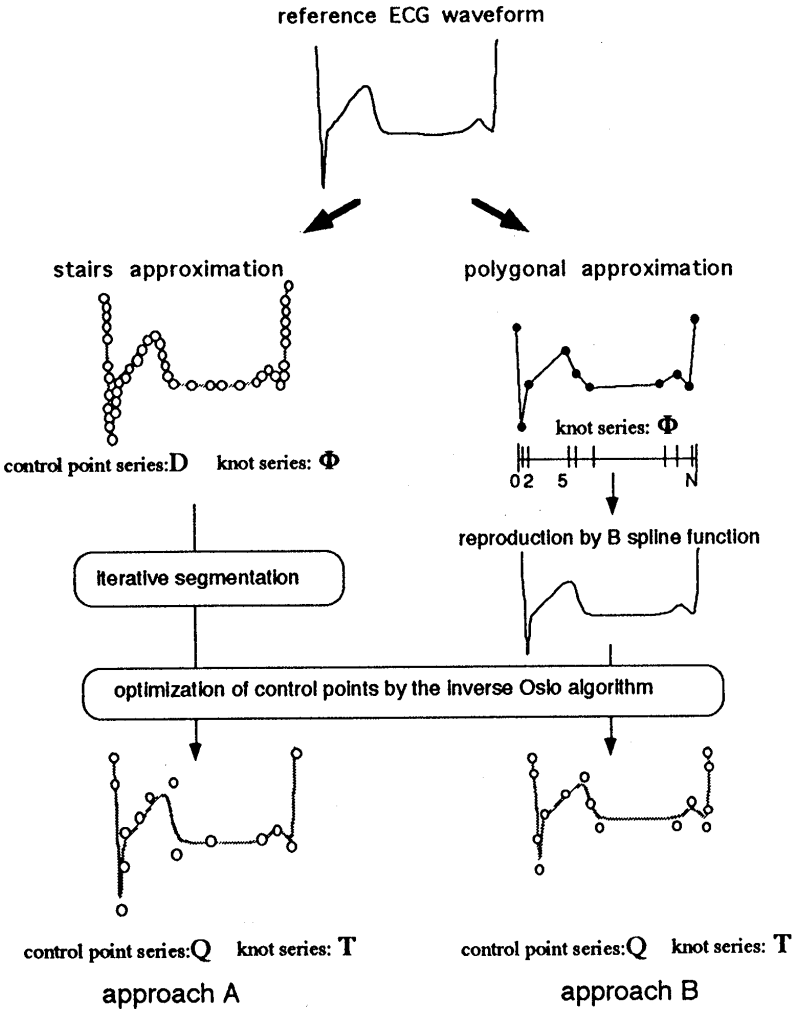

Fig. 3 Reference control point searching procedure.

3.2 Reference Control Points

In the first compression of approach A (Fig. 3), the B spline curve of a reference ECG waveform is differentiated to obtain the stairs approximation. This procedure eliminates the redundancy in the ECG that changes gradually in time. The second compression is carried out referring to the obtained knot series; the series of control points is optimized by the inverse Oslo algorithm. We start with five control points and then estimate $\boldsymbol{T}$. Next, $\boldsymbol{Q}$ is calculated by Eq. (4). Finally, the B spline curve is generated from $\boldsymbol{Q}$ to reproduce the ECG waveform. One knot is increased if the error between the reconstructed ECG waveform and its original one exceeds the permission level. Increasing the number of control points by iterative fractionation, we estimate an appropriate knot series. Iterative fractionation is a method of dividing one segment with the maximum mean square error into two parts. The reproduced ECG waveform approaches its original waveform when we specify knots for this coupling point one-by-one. This procedure is continued until the error is reduced to below the permission level.

Since a matrix operation is required with every increase in knots, approach A takes a long time. As an alternative, we tried to prepare a larger number of knots than optimally required, applying a polygonal approximation to the ECG waveform (approach B). The second procedure was done in the same manner.

3.3 Control Point Transfer by DP Matching

The computational cost can be reduced if the control points of a reference ECG waveform are transferred for successive beats. To carry out the transformation, the time scaling factor should be treated as time-varying due to the fluctuation of R-R intervals. Since the time scaling factor is varying even at every points in a R-R interval, we applied DP matching to the control points (control point-DP matching) and the knots (knot-DP matching). The DP matching determines a time warping function between the reference ECG waveform and successive ECG waveforms.

In the control point-DP matching, the time coordinates of reference control points are transferred to the successive ECG waveform by referring to the time warping function. After the time coordinates of control points have been determined for the successive beats, the associated amplitude coordinates are calculated as:

$$\Delta = r(q_x) - y(s_x) \tag{9}$$

$$s_y = q_y - \Delta \tag{10}$$

where

$r(t)$: reference ECG waveform,

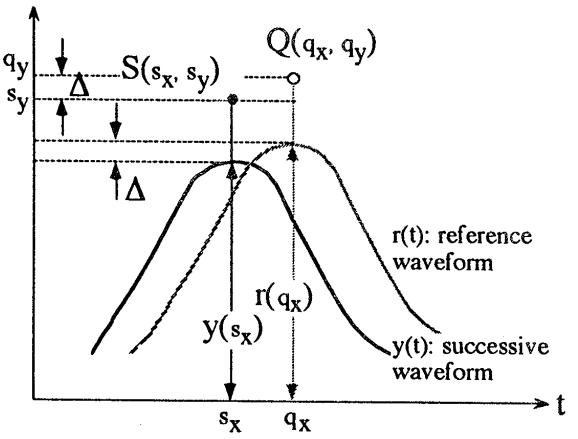

Fig. 4 Calculation of the amplitude coordinate, s_y, in the process of transferring reference control points.

$y(t)$: consecutive ECG waveform,

$Q(q_x, q_y)$: control point coordinates of reference ECG waveform, and

$S(s_x, s_y)$: control point coordinates of succeeding ECG waveform.

This procedure is shown in Fig. 4. That is, Δ is the difference between the reference ECG waveform and a succeeding one in terms of amplitude value at a pair of control point time instants, q_x and s_x. The amplitude coordinate of a succeeding ECG waveform is then determined by Eq. (10).

In this method, the amplitude warping between reference and subsequent ECG waveforms is not taken into account. To overcome this shortcoming, we transferred the knots instead of control points. In the knot-DP matching, the knot series of a reference ECG waveform is transferred to the subsequent ECG waveform. Then the coordinates of control points are directly estimated from the knots by the Oslo algorithm. The knot-DP matching incurred a high computational cost, but it achieved better reproducibility because the control points were correctly determined at each beat. It should be noted that the computational cost of the knot-DP matching is less than the direct control points estimation procedure for succeeding beats.

4. Results

4.1 Reference ECG

We used the MIT/BIH arrhythmia Database (MIT100, 101, 102, 103, and 104). ECG waveforms were sampled at a rate of 360 Hz with 11 bits resolution. Table 1 compares reproducibility and processing times for compression of one beat.

The CR in the first compression stage was 0.5 and the PRD in the second compression stage was less than 10, which show that good reproducibility was achieved for normal and abnormal ECG data (Fig. 5). It

Table 1 Comparison of reproducibility and the processing time: approaches are listed in Fig. 3.

	approach	CR	CC	PRD	processed time
MIT100	approach A	29 / 291	0.996	9.23	11.0 [sec]
	approach B	29 / 291	0.996	9.29	2.2
MIT101	approach A	20 / 317	0.996	9.79	5.2
	approach B	21 / 317	0.996	9.12	1.4
MIT102	approach A	23 / 292	0.995	9.89	6.8
	approach B	23 / 292	0.996	9.09	5.1
MIT103	approach A	21 / 306	0.996	9.30	5.5
	approach B	21 / 306	0.997	8.28	1.3
MIT104	approach A	19 / 295	0.996	9.86	4.6
	approach B	19 / 295	0.995	9.81	1.2

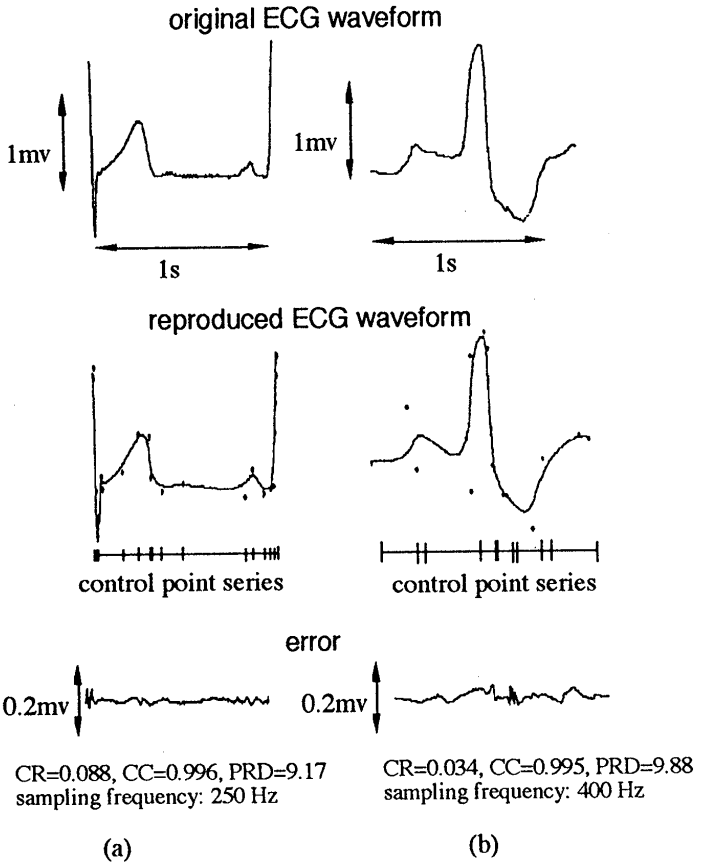

Fig. 5 Reproducibility for (a) normal and (b) abnormal ECG by the approach A.

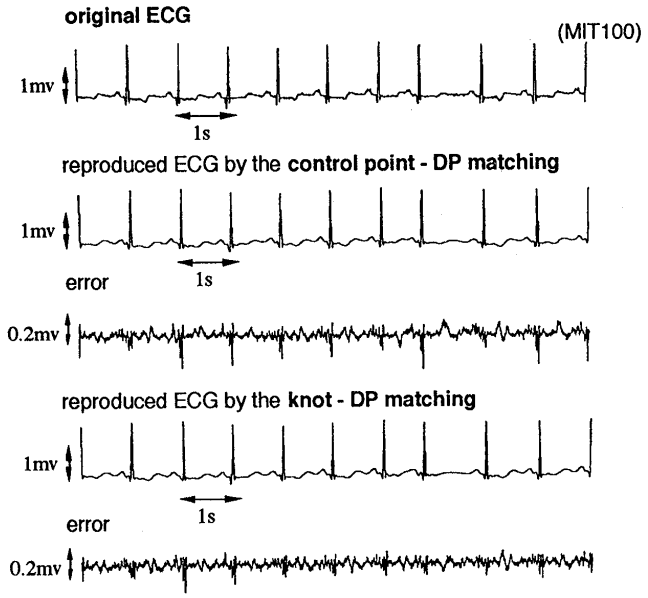

Fig. 6 Comparison of reproducibility between the control point-DP matching and the knot-DP matching.

should be noted that the CR in Fig. 5 was reduced to around one-tenth due to the second compression by the inverse Oslo algorithm. No degeneration was found around the R-wave, because the peak of the R-wave, for which the compression was executed, is sharp and has a high amplitude. The P-wave amplitude is quite small, so the reproduced P-wave was slightly distorted. Poor reproducibility was found around the QRS-wave, because it contains high frequencies and thus control points are insufficient. Setting the CR from 0.3 to 0.8 in the first compression for approach A, we compared the results. For CR of 0.3 and 0.4, a lot of points were extracted around the QRS wave, but the number of points around the T-wave was still insufficient. Enough points around the T-wave were extracted for CR of 0.5. The more CR decreased, the more CC decreased and PRD increased. When CR was 0.5, both CC and PRD showed excellent reproducibility for normal and abnormal ECG waveforms.

The difference in CR between the two compression approaches in the first stage was small. Approach B sometimes required one or two points fewer than approach A. Using a workstation SUN Sparc Station 2 (28.5 MIPS, 4.52 MFLOPS), it took 4.6–11.0 s for approach A, compared to only 1.2–2.2 s for approach B. Note that we executed the compression in the condition that PRD was less than 10.

4. 2 Long Term ECG

Figure 6 shows the results for the control point-DP matching and the knot-DP matching procedures for a long term ECG. We used 20 reference control points, setting the acceptable PRD of the reference ECG waveform as 10 or less. The differences between the original and reproduced ECGs was quite small. However, the knot-DP matching procedure achieved higher reproducibility around the QRS complex than the control point-DP matching procedure, according to the error. The knot-DP matching procedure requires a higher computational cost than the control point-DP matching procedure, due to the matrix computation to find the control points. Table 2 indicates the performance of DP matching and reproducibility for long term ECG of 30 min. Note that the reference control points were estimated by approach A.

The control point-DP matching procedure requires about 0.06 s to compress one beat of an ECG waveform, assuming that the heart rate is 70 beats per min. The control point-DP matching procedure seems sufficient to proceed onto real time compression. On the other hand, the knot-DP matching procedure takes about 0.9 s.

Table 2 Performance of DP matching and reproducibility for a long term ECG: approach C is the control point-DP matching; approach D is the knot-DP matching. Approach A was used for a reference ECG waveform.

	approach	CR	PRD: mean	PRD: variance	processed time
MIT100	approach C	0.10	15.3	4.3	133.9[s]
	approach D	0.10	10.7	1.3	3196.
MIT101	approach C	0.06	18.6	146.	128.9
	approach D	0.06	16.4	405.	1982.
MIT102	approach C	0.08	19.8	43.9	134.5
	approach D	0.08	11.3	17.3	2400.
MIT103	approach C	0.07	15.2	9.6	129.2
	approach D	0.07	13.2	1.5	2062.
MIT104	approach C	0.07	38.6	3300.	134.3
	approach D	0.07	53.1	163969.	1894.

4. 3 Various Types of ECGs

Figure 7 shows the result of an abnormal ECG waveform caused by the extrasystole. If such a waveform is found, then the control points are calculated again and in turn the reproducibility can be maintained at the same level as that for the reference ECG. Moreover, our procedure is not affected by the change in baseline in the time domain or the noise composed of high frequencies.

5. Discussion

5. 1 Compression of a Reference ECG

The low CR and the desirable reproduction would be

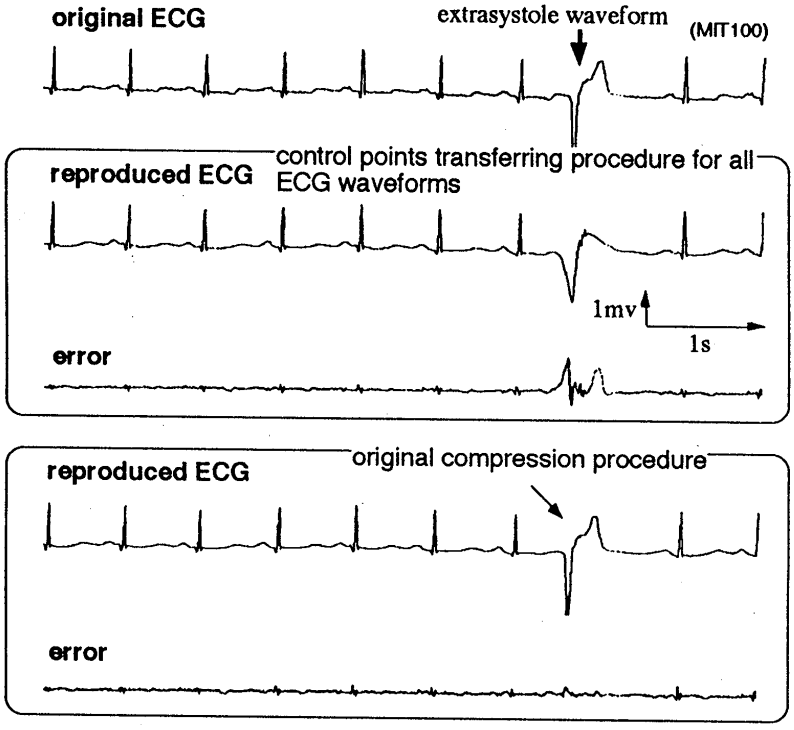

Fig. 7 Reproduced ECG waveform and error including extrasystole waveform.

completed, if the Oslo algorithm could be applied to all the samples of the ECG waveform. However, the computational cost increases with the second power of the matrix rank. Thus the first compression stage, in which the number of the knots was limited, was done before the inverse Oslo algorithm operation. The result using the third differentiation of the B spline curve (approach A) shows no difference between an original ECG and the reproduced ECG, where the desired CR was 0.5 in the first compression stage and the evaluation indexes, CC and PRD, were more than 0.999 and less than 5.0, respectively. Note that approach B, the polygonal approximation, achieved a shorter processing time than approach A with no degeneration in CR.

Even if the control points were fixed, the reproduced waveform would depend on the individual control points accompanying the time and the amplitude. In general, this problem is a nonlinear least-squares problem that has several solutions. In practice, it is difficult to find an optimum solution. The one-by-one fractionation is a method to obtain the quasi-optimum solution in a relatively short time, that is, it reduces the errors one-by-one. Therefore, the one-by-one fractionation is effective for selecting the knot series for control point reduction.

Our method requires a lot of time for estimating the coefficient matrix of the Oslo algorithm, the inverse-matrix operation, and the reproduction by the B spline function. We assessed the relationship between the number of initial control points and the processing time in the following conditions: the number of initial control points was from 4 to 50, and PRD was less than 10. As a result, a large number of initial control points should be estimated in advance to make it easier to select optimum control points for each beat.

5. 2 Compression of a Long Term ECG

Since the DP matching can transfer the control points of a reference ECG waveform to the succeeding ECG waveforms, compression is not required at every beat. This allows real time compression of long term ECGs. In terms of the reproducibility, however, this approach is slightly inferior to directly applying the Oslo algorithm to every beat.

The DP matching adjusted the time scales between the reference ECG and the succeeding ECGs, but not the amplitude scales between them. However, it should be noted that the B spline function depends on the amplitude of control points. Even if the amplitude at one control point doubles, the amplitude reproduced by the B spline function will not double in practice. In a clinical situation, such the nonlinearity may not obstruct the practical application of DP matching. The variance of the time instants of control points is considerably small within the periodical ECG waveform.

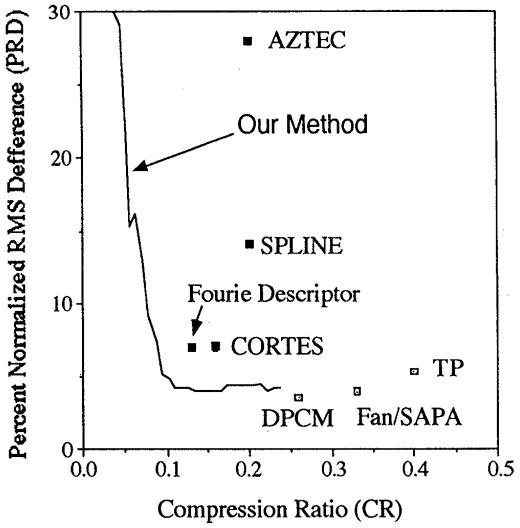

Fig. 8 Relationship between CR and PRD for each method.

5. 3 Comparison with Other Methods

A strict comparison with the conventional methods is difficult, because each method has its own strong points and different types of ECG data. For reference, we demonstrated the relationship between CR and PRD for our method, AZTEC, TP, CORTES, Fan/SAPA, SPLINE, DPCM, and Fourier Descriptors in Fig. 8, adjusting the sampling frequency to 250 Hz. The solid line indicates our data, which is obtained from one beat with approach A and the numerical value of other methods was quoted from Ref. [6]. When the PRD is around 10, our method gives the highest value of CR.

6. Conclusion

We propose a new ECG compression technique based on adjusting the control points of the B spline function by the Oslo algorithm for a one-beat ECG waveform and the dynamic programming (DP) matching to deal with beat-to-beat ECG waveforms. Within a difference percent normalized root square difference (PRD) level of 10, compression ratio (CR) of 0.08 with the correlation coefficient (CC) of more than 0.99 was achieved for a reference ECG waveform. Even for an extra-systole waveform, CR was 0.09 accompanied by a CC of more than 0.99.

DP matching procedure is effective to treat long term ECG data, because it is not necessary to estimate the control points of every beat. Finally, our method completed the compression in 5.0 s for a reference ECG and in 0.1 s for the succeeding ECG waveforms for every beat.

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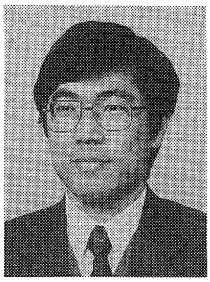

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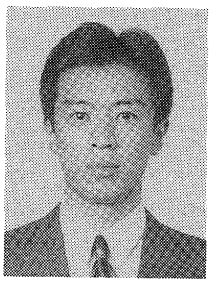

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