PAPER *Special Section on ECG Data Compression*

Performance Evaluation of ECG Compression Algorithms by Reconstruction Error and Diagnostic Response

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SUMMARY An electrocardiogram (ECG) data compression algorithm using a polygonal approximation and the template beat variation method (TBV) has been evaluated by reconstruction error and automatic interpretation. The algorithm combining SAPA3 with TBV (SAPA3/TBV) has superior compression performance in PRD and compression ratio. The reconstruction errors, defined as the difference of the amplitude and the time duration between the original ECG and the reconstructed one, are large at waves with small amplitude and/or gradual slopes such as the P wave. Tracing rebuilt from the compressed ECG has been analysed using the automatic interpretative program, and the diagnostic answers with the related measurements have been compared with the results obtained on the original ECG. The data compression algorithms (SAPA3 and SAPA3/TBV) have been tested on 100 cases in the data base produced by CSE. The reconstruction errors are related to the diagnostic errors. The TBV method suppresses these errors and more than 90% of diagnostic agreements at the error limit of 15 μV can be obtained.

key words: *data compression, electrocardiogram, SAPA, automatic interpretation, template*

1. Introduction

There are two types of data compression techniques, reversible and irreversible algorithms. A great variety of algorithms and methods of these two types for compression of electrocardiogram (ECG) signals have been reported [1]-[9] in order to minimize the transmission time in telephone networks, the capacity of data files and the memory size of recording devices. The reversible methods are used when diagnostic signals are requested; however the compression ratios of these algorithms are poor. If a greater compression ratio is required to minimize the memory size or the transmission time, the irreversible data compression methods must be used.

In the irreversible methods, two types of orthogonal transforms and direct transformation have been presented. The former approximates the original signals with limited numbers of coefficients expanded in the known functions. The latter approximates the original signals with polygons drawn within the upper and lower error limits of the signal curves. The polygonal approximation method is superior to orthogonal transforms, because it requires less calculation time and is able to accomplish compression manipulation in real time. In addition, the compression ratio can be controlled by the error limit. However, the larger the error limit is, the smaller the compressed data volume will be, and the lower the fidelity of the reconstructed signals becomes.

The evaluation parameters normally used for assessing a compression algorithm are visual comparison, root mean square (RMS) error, percent RMS difference (PRD) and correlation coefficient (CC). Visual comparison does not have universality. Although RMS, PRD and CC are quantitative means of evaluation, they are not sufficient enough to estimate the quality of the reconstructed ECG when measurements and diagnoses are executed on the basis of pattern recognitions and analyses of beat rhythm.

We have evaluated the compressed and decompressed ECG using the reconstruction error defined as the deviation of the amplitude and the time duration of each wave between the original ECG and the reconstructed one [10]. The results show that the reconstruction error does not necessarily relate to PRD or CC and fluctuates in spite of the constant value of PRD and CC.

Bedini et al. evaluated compression algorithms of polygonal approximation using diagnostic responses obtained by means of automatic interpretative software and by the cardiologist [11]. The results show that the degree of agreement of diagnostic response before and after compression manipulation depends upon the compression algorithms. In this report, details of the relationship between the compression ratio and diagnostic response and the contents of the diagnostic errors are not presented.

In the present paper, a new method has been adopted together with PRD for the performance evaluation of compression algorithms. It is based not only on reconstruction errors and diagnostic responses presented by an automatic interpretative program, but also on the disclosure of the relationship between the compression ratio and the disagreement in diagnosis,

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and details of changes in diagnostic findings. The compression algorithms of SAPA3 and SAPA3/TBV were evaluated.

2. TBV Method

The compression methods of ECG using a template have been proposed, in which an amplitude variation between neighbouring beats is compressed by a reduction of bit length [12] or a polygonal approximation (BBV) [13]. The compression ratio of the former is small, and in the latter the amplitude error is compounded and is not insured to remain within the error limit. The TBV method improves these faults. As shown in Fig. 1, a template of average wave of one ECG beat is prepared before compression manipulation, and the deviation wave between the template and each ECG beat is compressed by means of a polygonal approximation method such as TOMEK [4] or SAPA [6]. In the reconstruction (decompression) step, the ECG waves are retrieved with the template and the compressed data.

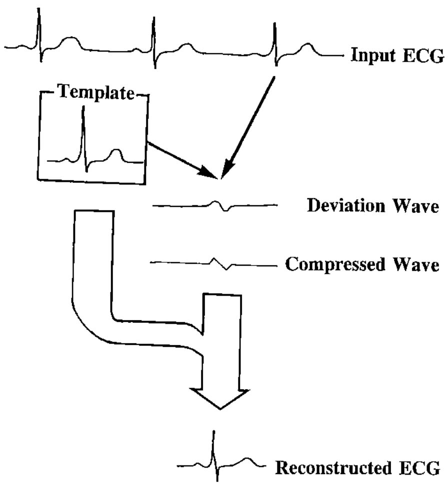

Fig. 1 Compression and decompression by TBV method.

If the length of the template is different from the duration of the beats, the compression is manipulated as shown in Fig. 2(a). When the template length is shorter than the beat interval, the part being over the template length is compressed without TBV method. In a reverse case, the section of the preceding template being overlapped by the following one is eliminated and the compression is manipulated with the reduced template.

When the similarity between the template and each beat is obscured by premature ventricular contruction or artifacts, compression manipulation is adopted for the original wave as shown in Fig. 2(b). The degree of similarity is judged by an integration value of the amplitude error between the template and each beat. This method needs less calculation time compared with calculation of CC or PRD. If the pattern of the ECG changes with time and the mismatch between the template and each beat increases, and the compression ratio degrades, a new template made of the averaged wave of 20 beats just after the increase of mismach is exchanged for the old one.

An example of the relationship of PRD as a function of compression ratio of sampling points (the number of sampling points after compression divided by that before compression) is shown in Fig. 3. The compression methods are TOMEK, SAPA3 [6] modified SAPA and the combinations of TBV and TOMEK or SAPA3 (TOMEK/TBV, SAPA3/TBV). The numbers in the figure show the error limits used in each compression method. PRD is average values of 3000 continuous beats, which are converted to digital signals in a sampling period of 5 mS. The template used in the TBV method is the averaged wave of 20

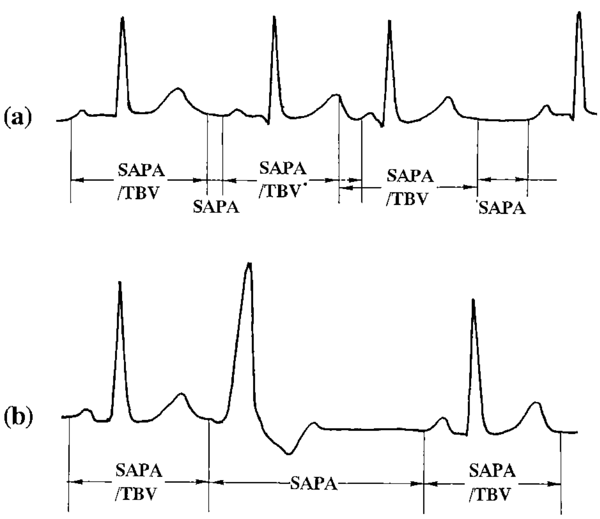

Fig. 2 Application of template to various waves, (a) variation of heartbeat duration, (b) premature ventricular contruction.

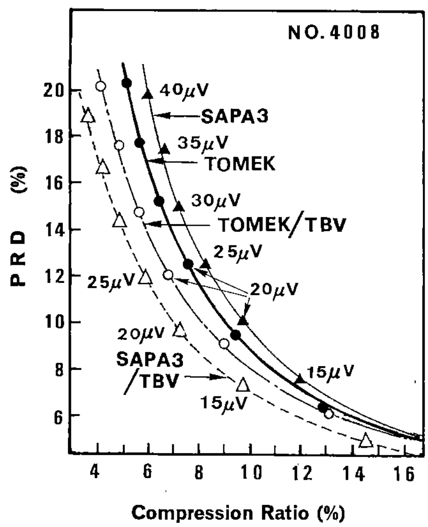

Fig. 3 Relationship between PRD and compression ratio in each algorithm.

beats from the top of the ECG.

TOMEK/TBV and SAPA3/TBV improve not only the compression ratio but also PRD in comparison with TOMEK and SAPA3. If the compression ratio is defined with the ratio of amplitude bit length, the TBV method shows a less compression ratio because of amplitude reduction of the stored signal. Although the compression performance of SAPA3 is inferior to TOMEK, SAPA3/TBV has the most superior compression performance in Fig. 3. The reason is that TOMEK/TBV has lower compression ratio effectiveness because the amplitude of signals is decreased by the TBV method. On the other hand, although SAPA3 requires more stored sampling points than TOMEK within the same error limit, SAPA3/TBV reduces the stored sampling points drastically and allows the compression ratio to improve about 30% with slight improvement of PRD. For this reason, evaluation of compression performance by automatic interpretation has been applied to the compressed and decompressed ECG using SAPA3 and SAPA3/TBV.

3. Evaluation of Algorithm by Automatic interpretation

Although measurements and diagnoses in ECG by means of automatic interpretation do not necessarily agree with those by cardiologists [14], [15], the reproducibility of the results is superior because the recognition algorithm of ECG waves and the diagnostic standard do not change. For this reason, it is useful to apply an automatic interpretative program to assess the accuracy of the reconstructed ECG. In this study, the automatic interpretative software supplied by Fukuda Denshi Co., Ltd. was used.

One hundred cases of ECG from the CSE (Common Standards for Quantitative Electrocardiography) data base were used for the evaluation of the compression algorithms. The files of the CSE data base (8 leads: I, II, V_1, V_2, V_3, V_4, V_5, V_6) are converted to the format of 12-bit dynamic range, sampling period 4 mS, and accuracy 4.9 μV/bit.

The sequence of the operation is as follows. All the formatted CSE files have been processed by each algorithm within the different error limits. The compressed files have been decompressed by the relative decompression program in the same format of the starting ones. The files of the compressed data bases have been processed by the automatic interpretative program and the results have been compared with the outputs obtained from the same original file by the same program.

As the file length of ECG in the CSE data base is 10 second, the template used in the TBV method has been prepared by summing and averaging all beats in the period except arrhythmia. Data compression has been performed on the deviation waves between the template and all beats existing in the period of 10 second. Since the template made of the average wave during 10 second contains almost of the feature of the ECG pattern, it seems that the performance evaluations of the long time ECG compression by the TBV method differs slightly from those obtained using the CSE data base unless the template mismatch is serious.

3. 1 Evaluation by Reconstruction Error

The deviation of a measurment value obtained by the automatic interpretation program in the original ECG and the reconstructed one is defined as a reconstruction error of amplitude and time duration. Averaged absolute values of reconstruction error for 100 cases have been calculated.

The reconstruction errors of amplitude by SAPA3 and SAPA3/TBV as a function of the error limit are shown in Fig. 4. P wave, R wave and ST are used to compare the degree of the amplitude error in V_5 lead. Figure 5 shows the reconstruction error of time duration of P, Q and R waves in V_5 lead as a function of the error limit.

With regard to the amplitude error, the average value by SAPA3 increase in the order of R wave, ST and P wave; this increase does not apply to ST below the error limit of 10 μV. On the other hand, those by

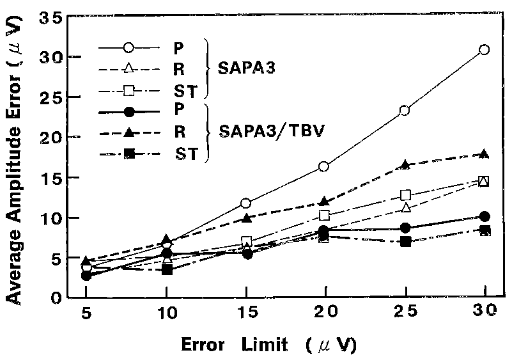

Fig. 4 Relationship between average amplitude error and error limit in P, R waves and ST.

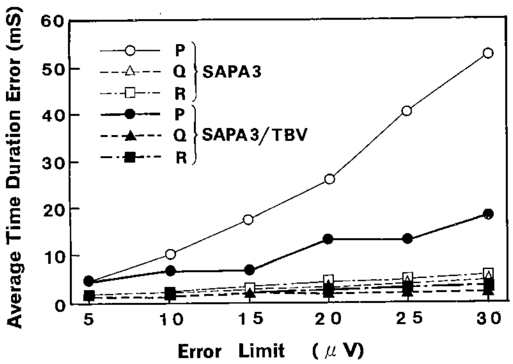

Fig. 5 Relationship between average time duration error and error limit in P, Q, R waves.

SAPA3/TBV increase in the order of ST, P wave and R wave, and all values except those for the R wave are smaller than those by SAPA3.

With regard to the time duration error, both Q wave and R wave have the average value below 5 mS using both compression methods. However, P wave has a large value of the time duration error, particularly in SAPA3.

Serious difference of the reconstruction error in the other leads was not observed except the amplitude error of Q wave in V_1 lead, which was about 10 times as large as those in the other leads at the error limit of 20 μV. The reason of the difference is that the amplitude of Q wave in V_1 lead is smaller than that in the other leads. The reconstruction errors by SAPA3/TBV are smaller than those by SAPA3 in all leads, except the R wave amplitude error.

From these results, in the polygonal approximation, the values of the reconstruction error differ in each wave of ECG even with the same error limit. These errors increase in ECG waves with small amplitude and gradual slopes. However, the TBV method suppresses the increase of these errors because the basic feature of ECG wave pattern is preserved in compression and is retrieved in decompression using a template.

3. 2 Evaluation by Diagnostic Response

A diagnostic response by the automatic interpretation is given by more than one diagnostic finding in a case. The definition of the equivalence ratio in diagnostic findings is the ratio of the sum of the same findings before and after compression to the total findings obtained in the original ECG of 100 cases. The classification of the diagnostic findings follows the above automatic interpretative program: ventricular hypertrophy (VH), atrioventricular conduction defects (AVCD), intraventricular conduction defects (IVCD), myocardial damage (MD), myocardial infarction (MI), axis deviation of QRS complex and other findings.

At first, the variation in the original ECG caused by either the fluctuation of ECG itself, respiration, body movement, artifacts or quantum noise of A/D conversion has been tested by exchanging a dominant beat. Figure 6 shows the average value of the equivalence ratio of diagnostic findings when the dominant beat has been exchanged three times. The equivalence ratios are distributed in the range of 82% to 97% except for the intraventricular conduction defects of 67%, and the averaged value of all the equivalence ratios is 84%.

The diagnostic responses by SAPA3 and SAPA3/TBV are depicted in Fig. 7 and Fig. 8, respectively. The classifications of diagnostic findings are the same as shown in Fig. 6. Although the equivalence ratios of findings are more than 90% at 5 μV of the error limit in SAPA3, they decrease in proportion to the increase of error limit. On the other hand, in SAPA3/TBV, the equivalence ratio of findings of more than 90% is achieved below 15 μV except atrioventricular conduc-

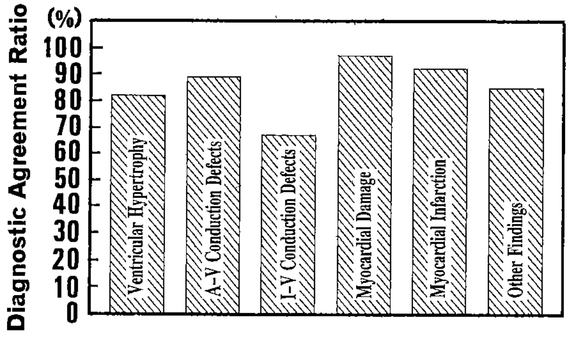

Fig. 6 Diagnostic response in dominant exchanges.

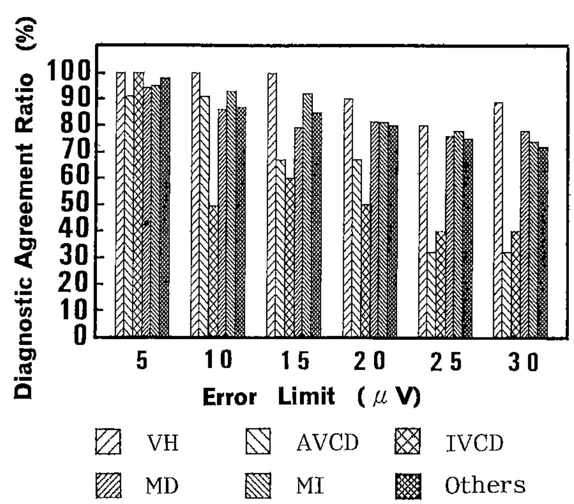

Fig. 7 Diagnostic response in compression and decompression manipulation using SAPA3.

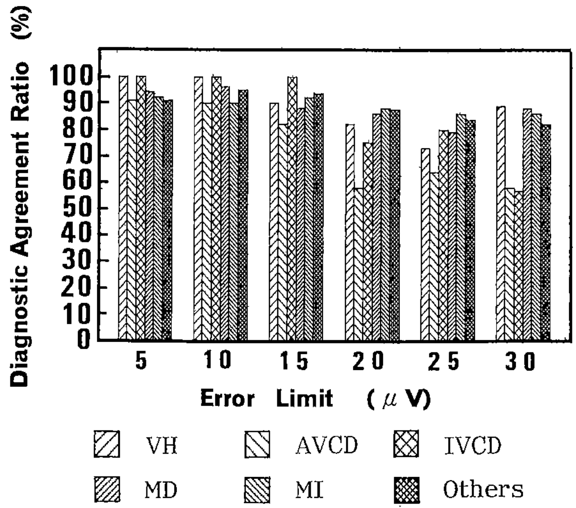

Fig. 8 Diagnostic response in compression and decompression manipulation using SAPA3/TBV.

Table 1 Atrioventricular conduction defects.

Original Diagnostic Finding	Finding of Reconstructed ECG(ε=15μV) SAPA3 Equivarent / Different	SAPA3/TBV Equivarent / Different
Short P-R Interval (SPRI)	0 / No Finding(1)	1 / WNL(1)
W-P-W Syndrome (WPW)	3 / 0	3 / 0
P-R Prolongation (PRP)	4 / No Finding(2)	5 / No Finding(1)
No Finding	/ WPW(1)	/ PRS(1)

Table 2 Myocardial damage.

Original Diagnostic Finding	Finding of Reconstructed ECG(ε=15μV) SAPA3 Equivarent / Different	SAPA3/TBV Equivarent / Different
Flat T (FT)	1 / 0	0 / NT(1)
Negative T (NT)	17 / No Finding(1) WNL(1), SSTTA(1)	18 / SSTTA(1), FT(1)
Suspect Slight ST-T Abnormality	0 / No Findng(1)	0 / STTA(1)
Slight ST-T Abnormality (SSTTA)	3 / NT(2)	3 / NT(2)
ST-T Abnormality (STTA)	21 / SSTTA(2)	23 / 0
No Finding	/ FT(2)	/ 0

tion defects of 82%. Since this value is superior to that obtained by the changes of dominant beats, SAPA3/TBV at the error limit of 15 μV seems to be practically suitable for the diagnostic use.

3.3 Details of Diagnostic Response

The details of the difference of diagnostic findings appearing in the reconstructed ECG from those in the original one are depicted in Table 1 to Table 4. The error limit (ε) is either 15 μV or 20 μV.

In the classification of atrioventricular conduction defects shown in Table 1, the different findings of 3 cases in SAPA3 and 2 cases in SAPA3/TBV related to P wave are shown. The change from no finding to WPW syndrome is observed in one case in SAPA3, and that to short P-R interval in SAPA3/TBV is also observed in one case. The different findings related to P wave are observed in both compression methods. The reason for the changes is that the time duration error caused by the compression and decompression operations is largest in the P wave, as shown in Fig. 5.

In the classification of myocardial damage depicted in Table 2, the changed findings related to flat T, negative T and ST-T abnormality are 10 cases in SAPA3 and 5 cases in SAPA3/TBV, respectively. However, all the findings of 23 cases related to ST-T abnormality in SAPA3/TBV agree with those of original ones. The different findings in SAPA3 being more than those in SAPA3/TBV are due to the feature of a polygonal approximation method, where the stored sampling points decrease and the amplitude errors increase at the region of a gradual slope such as the T wave and P wave, as shown in Fig. 4.

Table 3 Myocardial infarction.

Original Diagnostic Finding	Finding of Reconstructed ECG(ε=20μV) SAPA3 Equivarent / Different	SAPA3/TBV Equivarent / Different
Poor R Progression	3 / SASI(1)	4 / 0
Abnormal Q (AQ)	5 / 0	5 / 0
Suspect Anterior Inf. (SAI)	2 / 0	2 / 0
Possible Anterior Inf.	0 / AI(1), SAI(1), PASI(1)	1 / AI(1), PASI(1)
Anterior Inf. (AI)	6 / PASI(1)	5 / SAI(1), ASI(1)
Possible Anteroseptal Inf. (PASI)	0 / ASI(1)	1 / 0
Suspect Anteroseptal Inf. (SASI)	1 / 0	1 / 0
Anteroseptal Inf. (ASI)	11 / 0	11 / 0
Suspect Lateral Inf.	0 / No Finding(1)	1 / 0
Possible Lateral Inf.	2 / 0	2 / 0
Lateral Inf.	1 / 0	1 / 0
Suspect Inferior Inf. (SII)	0 / II(1)	1 / 0
Possible Inferior Inf. (PII)	10 / 0	10 / 0
Inferior Inf. (II)	10 / PII(1)	11 / 0
Possble High-Post Inf.	1 / 0	1 / 0
No Finding	/ AQ(1), PII(2)	/ AQ(1), SII(1), PII(1)

Table 4 Other findings.

Original Diagnostic Finding	Finding of Reconstructed ECG(ε=20μV) SAPA3 Equivarent / Different	SAPA3/TBV Equivarent / Different
Within Normal Limits (WNL)	19 / FT(1), SPRI(1) AQ(1), QTP(1)	19 / WPW(1), SII(1) SPRI(1),
Counterclockwise Rotation	9 / 0	9 / 0
Clockwise Rotation	5 / 0	5 / 0
Low Voltage(Limb Leads) (LVLL)	5 / 0	5 / 0
Low Voltage(Chest Leads)(LVCL)	5 / 0	5 / 0
QT Prolongation (QTP)	1 / 0	1 / 0
High T	1 / 0	1 / 0
ST Elevation (STE)	6 / No Finding(1)	5 / No Finding(2)
No Finding	/STE(3), QTP(3), LVLL(1)	/STE(1)、QTP(1)

In the classification of myocardial infarction depicted in Table 3, 12 cases in SAPA3 and 7 cases in SAPA3/TBV change in the diagnostic findings. In anterior infarction, a total of 4 cases of changes of infarction grade and a change to anteroseptal infarction in both compression methods is observed. The cause of the changes to anteroseptal infarction seems to be that the small r wave has vanished through compression and decompression operations and the QRS complex has been recognized to be of the QS type. In SAPA3, a total of 5 changes is observed in the classification of poor R progression, anteroseptal infarction and inferior infarction. In SAPA3/TBV, other changes do not appear in these diagnostic findings.

In the classification of other findings depicted in Table 4, the diagnostic findings related to the time duration of P, Q, T waves and ST level change, and the total numbers of changes are 11 in SAPA3 and 6 in SAPA3/TBV. In the diagnoses defined using the amplitude of QRS complex, 19 cases do not change in each compression method except for one case in SAPA3.

4. Discussion

The polygonal approximation method combined with TBV improves the compression ratio and PRD. In particular, SAPA3/TBV has a better compression performance than TOMEK/TBV, and improves the compression ratio to about 30% with a slight improvement of PRD.

Reproduction errors of amplitude and time duration on the reconstructed ECG depend on the each portion of the wave; they are large such as in P wave and T wave with a small amplitude and a gradual slope. The TBV method suppresses these errors as the feature of the original ECG waveforms is retrieved.

Although agreements of diagnostic findings between the original ECG and the reconstructed one decrease in proportion to error limit, the degree of degradation differs among diagnostic categories. Most changes in findings appear in the diagnoses using the measured values of P wave, small Q wave, small T wave and ST level. However, SAPA3/TBV also improves the ratios of agreement among the diagnoses using these values.

SAPA3/TBV can achieve more than 90% of diagnostic agreement with a compression ratio of about 10% at the error limit of 15 μV.

The analysis in this paper is intended to evaluate the distortions of ECG waves caused by the irreversible compression algorithms from a clinical diagnostic stand of view. The final judgements on whether the waveform distortion and the diagnostic changes in the reconstructed ECG are fatal or negligible will be left to cardiologists in each case.

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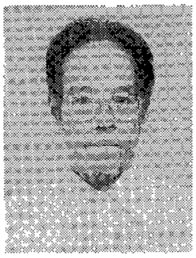

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