PAPER

Reduction of Electromagnetic Absorption in the Human Head for Portable Telephones by a Ferrite Sheet Attachment

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SUMMARY From the standpoint of reducing the electromagnetic (EM) absorption in the human head for portable telephones, a ferrite sheet is proposed to use as a protection attachment between the antenna and the head. By using an anatomically based head model and a realistic portable telephone model, the effects of the ferrite sheet on both the reduction of EM absorption and antenna radiation pattern are numerically analyzed by the finite-difference time-domain (FDTD) method. The results show that a ferrite sheet can result in a reduction over 13% for the spatial peak SAR averaged over one gram of tissue relative to a degradation below 0.6 dB for the antenna radiation pattern.
key words: *reduction of SAR, portable telephone, anatomically based head model, FDTD calculation, ferrite sheet*

1. Introduction

With the recent rapid increase in the use of portable telephones, public concern regarding potential health hazards due to the absorption of EM energy emitted by these telephones has been growing. Safety guidelines for protecting the human body from radio wave exposure have been issued in various countries. In these safety guidelines the basic safety limits applicable for portable telephones are defined in terms of the specific absorption rate (SAR). A spatial peak SAR value not exceeding 1.6 W/kg for a specified uncontrolled environment (ANSI/IEEE C95.1-1992 RF safety guidelines [1]) or 8 W/kg (RF protection guidelines issued by Telecommunications Technology Council of Japan [2]), as averaged over any 1 gram of tissue, should be acceptable. A number of studies have been conducted to evaluate the SAR and compliance with the safety guidelines using anatomically realistic models of the head for some typical antennas used for these telephones [3]–[9]. Some results have implied that as a portable telephone is brought extremely close to the head a spatial SAR averaged over one gram may exceed 1.6 W/kg [4],[9]. So it is necessary to do an effort for reducing the EM absorption by the human head in the design stage of telephones. An effective means is to set up a lossy material layer between the antenna and the human head. The lossy material layer should satisfy the following requirement: reducing the SAR in the human head but less affecting the antenna performance.

In this paper, a lossy magnetic material or ferrite is considered for this use. A ferrite sheet is proposed to cover an area close to the antenna feed point of portable telephones. The FDTD method is used to investigate the possibility in this study because of its flexibility and efficiency in solving complex heterogeneous geometries. An anatomically based model of the human head and a monopole antenna on a dielectric covered metal box are assumed. The effects of the ferrite sheet on the SAR, absorbed power and antenna radiation pattern are numerically analyzed for different sizes and thickness of the ferrite sheet at 940 MHz and 1500 MHz. A comparison to a metal sheet is also given.

2. Head and Telephone Model

Figure 1 shows the human head and portable telephone model for the present study.

The head model was constructed by our groups on the basis of an anatomical chart of a Japanese adult head [10]. It consists of 273 108 cubical cells with a resolution of 2.5 × 2.5 × 2.5 mm. Seven types of tissues, i.e., bone, brain, muscle, eyeball, fat, skin and lens, are involved in this head model. Their dielectric properties at 940 MHz and 1500 MHz are given in Table 1 in which ε_r and σ are the relative permittivity and conductivity, respectively [11]. The mass density of each of tissues was assumed to be 1000 kg/m^3.

The portable telephone was modeled by a $\lambda/4$ monopole antenna mounted on a dielectric covered rectangular metal box. The monopole had a radius of 0.5 mm. The metal box was covered with a dielectric insulator of 2.5 mm thickness and $\varepsilon_r = 2.0$. The dimensions of the portable telephone were 12(length) × 4(width) × 2.5 (depth) cm. The monopole was located at the top of the telephone, in the center of the 4 cm side and 2 cm far from the edge of the 2.5 cm side. Because of the proximity of the hand to the telephone, it is essential to also model the hand. For the present study, the hand was modeled by 2/3 muscle-equivalent material (its ε_r and σ values are two-thirds muscle's ones) being 10 cm wide and 2 cm thick and wrapped around three sides of the lower part of the portable telephone.

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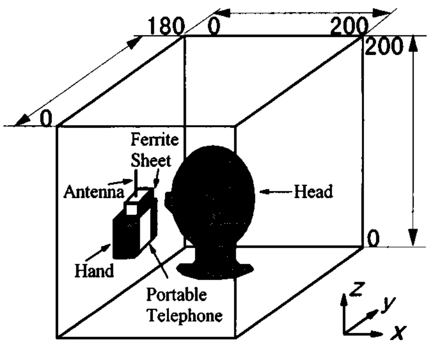
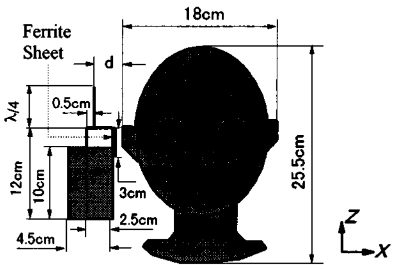


(a) Head-telephone model and calculation region



(b) Front view of head-telephone model

Fig. 1 Geometry of the head-telephone model for calculation.

Table 1 Dielectric properties of tissues.

	940 MHz		1500 MHz	
Tissue	ε_r	σ [S/m]	ε_r	σ [S/m]
Bone	17.4	0.19	16.1	0.32
Brain	44.1	0.89	42.8	1.08
Muscle	51.8	1.11	50.2	1.39
Eyeball	74.3	1.97	73.9	2.21
Fat	10.0	0.17	9.7	0.20
Skin	39.5	0.69	39.1	0.86
Lens	44.0	0.80	43.0	1.10

Table 2 Properties of the ferrite sheet.

	940 MHz	1500 MHz
ε'_r	7.00	6.98
ε''_r	0.58	1.18
μ'_r	2.83	2.02
μ''_r	3.25	3.64

A commercially available ferrite sheet was chosen as a candidate for reducing the EM absorption in the human head. The material properties, supplied by Nihon Cresta Co., Ltd., are given in Table 2 in which $\varepsilon'_r - j\varepsilon''_r$ and $\mu'_r - j\mu''_r$ are the complex relative permittivity and permeability, respectively. Three sizes of the ferrite sheet, named as Type A, B and C, respectively, as shown in Fig. 2, were considered. Type A imaged the case where a portable telephone is inserted in a thin dielectric case including a ferrite sheet of 4 × 3 cm in the area above the antenna feed point. Type B imaged the case for a ferrite sheet of 4 × 3 cm covering one part of the portable telephone below the antenna feed point.

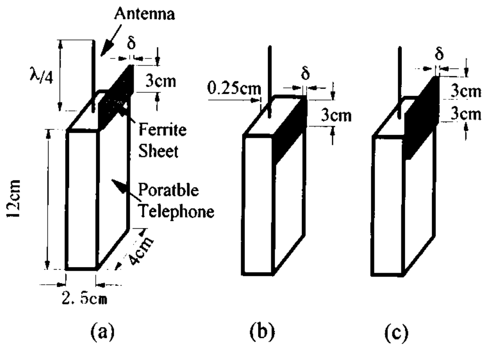


Fig. 2 Portable telephones with ferrite sheets. (a) Type A, (b) Type B, (c) Type C.

Type C had a size twice as large as Type A or B.

3. Method of Analysis

3.1 FDTD Implementation

The FDTD method was used for the analysis. This method was first described by Yee and further details about the method can be found in [12] and [13]. For the present study, the Yee-cell and rectangular computational grid were used. The FDTD formulations were derived from the following Maxwell's time-domain equations,

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu_0 \mu'_r}(\nabla \times E) - \frac{\sigma^*}{\mu_0 \mu'_r} H \qquad (1)$$

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon_0 \varepsilon'_r}(\nabla \times H) - \frac{\sigma}{\varepsilon_0 \varepsilon'_r} E \qquad (2)$$

where $\sigma^* = \omega\mu_0\mu''_r$ and $\sigma = \omega\varepsilon_0\varepsilon''_r$ were added for treating magnetically and electrically lossy materials, respectively. The parameters for our FDTD calculations were as follows. A space domain enclosing the human head and the portable telephone had 200 × 180 × 200 cells. The cells had a size $u = 2.5$ mm. The time step was set to $u/\sqrt{3}c$, where c is the speed of light, to ensure the numerical stability. The time-stepping was performed for about seven sinusoidal cycles in order to reach a stead state. To absorb the outgoing scattered waves, the second order Mur absorbing boundaries [13] acting on electric fields were used. The boundary was placed at least 45 cells from the nearest feature of the telephone or the head.

The following attentions have been paid in the FDTD calculations. (1) Since one should specify material properties (ϵ_r, σ, μ_r and σ^*) at the field locations within a Yee cell, an averaged value of the material properties of the cells was specified if the cells including the field location were not the same material. (2) For an observing cell, the electric field E and magnetic field H of this cell were ones in the center of the cell, which were obtained from the averages of relevant field

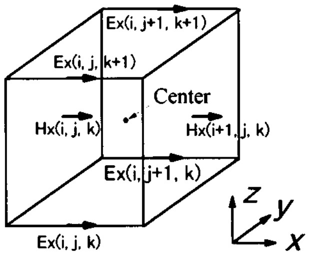


Fig. 3 View of calculation for E and H in the center of the cell.

components in this cell. For example, E_x and H_x components in the center of the cell (i,j,k) as shown in Fig. 3 were calculated as follows:

$$E_x(i_c,j_c,k_c) = [E_x(i,j,k) + E_x(i,j,k+1) + E_x(i,j+1,k+1) + E_x(i,j+1,k)]/4 \quad (3)$$

$$H_x(i_c,j_c,k_c) = [H_x(i,j,k) + H_x(i+1,j,k)]/2 \quad (4)$$

The monopole antenna was approached by thin-wire approximation which includes the effects of a wire with radius smaller than the FDTD cell dimensions. An antenna excitation was introduced by specifying a voltage with complex amplitude V across the 1-cell gap between the monopole and the top surface of the metal box. The input impedance of antenna was calculated using $Z_{in} = V/I$ where I is the complex amplitude of the current flowing through the voltage source gap which can be obtained from Ampere's law on a small curve around the gap. The input power was calculated as $P_{in} = (1/2)Re\,(VI^*)$ where $*$ denotes the complex conjugate. The power absorbed in the head and hand was calculated as $P_{abs} = (1/2)\int_v \sigma|E|^2 dv$ and the SAR was calculated as $SAR = (1/2)\sigma|E|^2/\rho$ where ρ is the tissue density. The far-field radiation pattern was calculated by using a near-field to far-field transformation [12]. It employs the field equivalence principle to obtain the radiation pattern from calculated near-field electric and magnetic field vectors on a rectangular box enclosing the modeled structures.

3.2 Validation

To verify our FDTD code, a test run using the same telephone-head model as previously used by J. Toftgard et al. [3] was first conducted at 914 MHz. The telephone was modeled as a $\lambda/4$ monopole antenna on a metal box. The head was a sphere with a radius of 9 cm and the hand was modeled as being 10 cm wide and 2 cm thick. Both the head and hand had $\epsilon_r = 50.5$ and $\sigma = 1.2$ S/m. Figure 4 shows calculated input impedance and radiation pattern in ϕ-plane for $\theta = 90°$. Both of them are in good agreement with the results given in [3]. This gives confidence to our FDTD code.

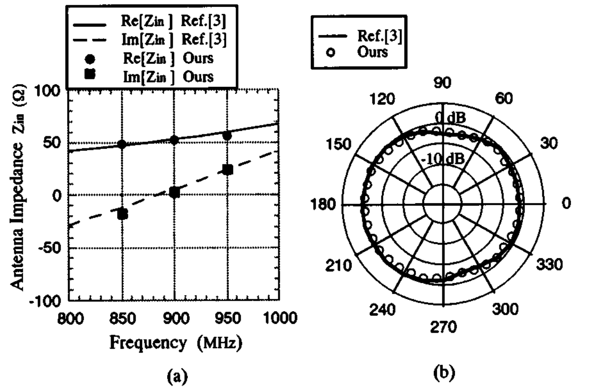


Fig. 4 Test results of our FDTD code. (a) Antenna impedance, (b) Radiation pattern in ϕ-plane.

Table 3 SAR and absorbed power. (P_{in} = 1 W, d = 2.5 cm)

	940 MHz	1500 MHz
Peak SAR_{1g} for head [W/kg]	2.18	2.93
Peak SAR_{1g} for brain [W/kg]	1.22	1.25
Average SAR for eyeball [W/kg]	0.015	0.012
Average SAR for head [W/kg]	0.063	0.047
P_{abs} by head [%]	26.8	20.0

4. Numerical Results and Discussions

4.1 Reduction of SAR

For the calculated results given in this section, the following conditions apply: (1) the anatomically based head model was used; (2) the input power P_{in} of the monopole antenna was 1 W; (3) the distance d between the monopole antenna and the closest head surface was 2.5 cm; (4) except for special indication, the sheet thickness δ was 2.5 mm. Table 3 gives calculated SAR values and absorbed power without the ferrite sheet. The peak SAR_{1g} denotes the spatial peak value of the SAR averaged over one gram of tissue (defined as a tissue volume in the shape of a cube). Since the spatial peak SAR for the head occurs in the ear which has an irregular shape, a tissue volume in the shape of a cube of, say, 1 × 1 × 1 cm may contain air cells and will therefore have a weight less than 1 g. For such a case of evaluation of the peak SAR_{1g}, Gandhi et al. claimed that at least 80 percent of the cube should be occupied by the tissues and no more than 20 percent of the cube should be in air [9]. In our calculations, the peak SAR_{1g} for the head was obtained from such a 1 × 1 × 1 cm cube as Gandhi et al. suggested. The results shown in Table 3 are similar to those reported elsewhere for both the peak SAR_{1g} and the absorbed power [4],[6],[8], while a complete agreement was not obtained because the computation conditions, such as the details of the head, telephone configurations and frequencies, were not the same. For example, with a vertical alignment of the portable telephone at the side of the head and d = 2 cm, Dimbylow and Mann have given a peak SAR_{1g} of 1.85 W/kg and

Table 4 Effects of ferrite sheets ($\delta = 2.5$ mm) on SAR reduction. ($P_{in} = 1$ W, $d = 2.5$ cm)

	ξ [%]					
	940 MHz			1500 MHz		
	Type A	Type B	Type C	Type A	Type B	Type C
Peak SAR_{1g} for head	14.1	13.6	23.2	15.4	15.2	25.7
Peak SAR_{1g} for brain	14.0	14.1	23.6	14.0	19.0	28.2
Average SAR for eyeball	0.9	2.2	2.9	4.6	10.1	13.9
Average SAR for head	9.2	9.0	15.4	11.5	13.3	21.1
P_{abs} by head	9.2	9.0	15.4	11.5	13.3	21.1

Table 5 Effect of sheet thickness δ [mm] on SAR reduction. (Type B, $P_{in} = 1$ W, $d = 2.5$ cm)

	940 MHz			1500 MHz		
	without ferrite	with ferrite $\delta = 2.5$	with ferrite $\delta = 5.0$	without ferrite	with ferrite $\delta = 2.5$	with ferrite $\delta = 5.0$
Peak SAR_{1g} for head [W/kg]	2.18	1.88	1.84	2.93	2.48	2.25
P_{abs} by head [%]	26.8	24.4	23.4	20.0	17.3	16.0

absorbed power of 28.2% at 900 MHz [4].

To evaluate the effect of the ferrite sheet as a protection layer on the reduction of EM absorption, we defined a relative reduction ratio ξ as

$$\xi = \frac{\Gamma_{without\ protection} - \Gamma_{with\ protection}}{\Gamma_{without\ protection}} \tag{5}$$

where Γ denotes the SAR or P_{abs}. It should be noticed that if $\xi > 0$ the SAR or P_{abs} is reduced and otherwise increased.

Table 4 gives the ξ calculated for the three types of ferrite sheet. It can be seen that all of the three ferrite sheets give a significant reduction of EM absorption at both 940 MHz and 1500 MHz. A reduction of 13%–15% on the peak SAR_{1g} can be obtained for Type A and B, and a reduction over 23% on the peak SAR_{1g} can be obtained for Type C. A double sheet size has not given a doubled reduction effect because the current on the monopole degrades with deviating from the antenna feed point. The numerical results for Type A and B also show that the ferrite sheets above and below the feed point have the same effect on the reduction of EM absorption provided they have the same size. This fact suggests that Type B is more realistic from a viewpoint of practical use. So in the following the numerical results and discussions are limited to Type B.

Since the ferrite material is an EM absorptive one, the thickness of ferrite sheet may be an important factor for the reduction of EM absorption. Table 5 shows the effect of the thickness of ferrite sheet on the EM absorption. It can be found that both the peak SAR_{1g} and the power absorbed by the head decrease with the increase of the thickness of ferrite sheet as expected. In the range of a realistic sheet thickness (say not thicker than 5 mm), the SAR reduction due to the increase of sheet thickness is slight at 940 MHz. However, at 1500 MHz, the SAR reduction is larger than that at 940 MHz. This may be due to the fact that the skin depth of the ferrite sheet at 1500 MHz is only half of that at 940 MHz.

Table 6 Effect of metal sheet on SAR reduction. (Type C-size, $\delta \to 0$, $d = 2.5$ cm)

	ξ [%]	
	940 MHz	1500 MHz
Peak SAR_{1g} for head	−12.8	−26.5
Peak SAR_{1g} for brain	−15.2	−26.1
Average SAR for eyeball	−10.4	−1.2
Average SAR for head	−4.6	−17.5
P_{abs} by head	−4.6	−17.5

It is known that a metal sheet covering the human body is effective in reducing the EM absorption due to the reflection characteristic of metal [14]. However, for the present case, a large size of metal sheet is not realistic. A numerical calculation has been done for investigating the possibility of using a metal sheet with a small size to reduce the EM absorption. The metal sheet was modeled as an infinitely thin perfect conductor with the same sizes as the ferrite sheets. ξ was still used to evaluate the effect on the reduction of EM absorption. The calculated results for ξ are given in Table 6 for Type C-sized metal sheet because it has the largest size in the three types and thus the largest reflection effect is expected. It should be noticed that the values of ξ are minus both at 940 MHz and 1500 MHz. Especially, at 1500 MHz, the absorbed power is increased by 17.5%. Table 6 implies that a metal sheet with a small size can not reduce the SAR in the human head. The results calculated for Type A and B-sized metal sheets also support this finding. The reason is considered as follows. Strong EM field can be induced in the neighbor of the edges of a metal sheet due to scattering. When the size of the metal sheet is small compared to the head, the head is exposed to the strong EM field and thus absorbs more EM energy. However, for a ferrite sheet, no strong EM field is induced in its neighbor because of its ability to absorb EM energy and transform it into heat. Therefore a ferrite sheet, not a metal sheet, has resulted in the reduction of EM absorption in the human head.

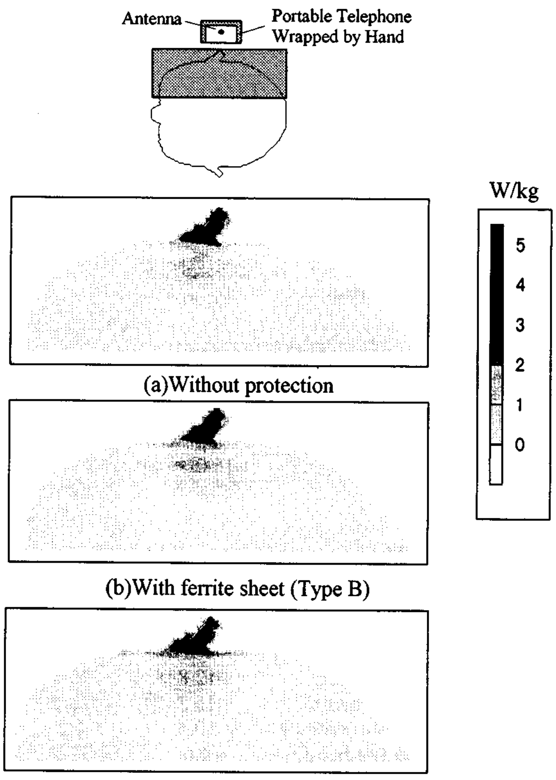


Fig. 5 SAR distributions in a horizontal cross section through the center of eyes. Only the shadow area is shown.

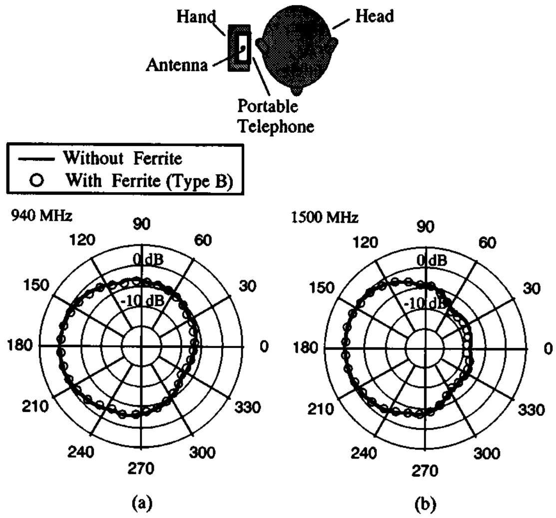


Fig. 6 Radiation patterns in ϕ-plane for a monopole antenna on a dielectric covered metal box for the anatomically based head model. (a) 940 MHz, (b) 1500 MHz.

Table 7 Far-field degradation [dB] due to ferrite sheet. (Type B, $\delta = 2.5$ mm, $d = 2.5$ cm)

ϕ	0°	90°	180°	270°
940 MHz	0.36	0.38	0.16	0.10
1500 MHz	0.60	0.12	0.06	0.04

Table 8 Antenna radiation efficiency. (Type B, $\delta = 2.5$ mm, $d = 2.5$ cm)

	η [%]	
	without ferrite	with ferrite
940 MHz	54.91	54.85
1500 MHz	61.52	61.31

To see this more clearly, the SAR distributions in a horizontal cross section through the eyes are shown in Fig. 5. The upper is the SAR distribution without the ferrite or metal sheet, the middle and the lower are ones with the ferrite (Type B) and metal sheets (Type C-size), respectively. Only the SAR distributions close to the portable telephone are shown. From Fig. 5, it is obvious that the use of the ferrite sheet has resulted in a significant SAR reduction, especially at the higher SAR area, whereas the use of the metal sheet has resulted in a SAR increase rather than reduction.

4.2 Radiation Pattern

Another concerned point is whether the ferrite sheet less affects antenna radiation performance or not. This was investigated by calculating the antenna radiation pattern and antenna radiation efficiency. Figure 6 shows the radiation patterns for Type B (which is more realistic from a viewpoint of practical use as indicated above) in ϕ-plane for $\theta = 90°$ at 940 MHz and 1500 MHz, respectively. The degradation on radiation pattern resulted from the ferrite sheet is insignificant. Table 7 gives the decreased radiated far-field due to the ferrite sheet in four representative directions. It can be seen that the degradations of radiated far-field do not exceed 0.6 dB.

Moreover, the antenna radiation efficiency was calculated as

$$\eta = \frac{P_{in} - P_{abs}}{P_{in}} \quad (6)$$

where P_{abs} is the power absorbed by the head, hand and the ferrite sheet if it is attached to the telephone. The power absorbed by the ferrite sheet was calculated from $(1/2)\int_v (\sigma |E|^2 + \sigma^* |H|^2) dv$. Table 8 gives η at 940 MHz and 1500 MHz for Type B. It can be found that the degradations of antenna radiation efficiency due to the ferrite sheet are only 0.06 % at 940 MHz and 0.21 % at 1500 MHz, respectively. These values are relatively small compared to ξ. This means that the ferrite sheet does not almost decrease the radiated power.

5. Conclusions

The present study has been done as an effort for reducing the EM absorption in the human head for portable telephones. The study has used the FDTD method in conjunction with detailed models of the human head, hand and portable telephone. The SAR, absorbed power and antenna radiation pattern are numerically analyzed. A practical conclusion that can be drawn from the numerical results is that a ferrite sheet reduces the EM absorption in the human head and less affects the antenna radiation pattern. The numerical results revel that a ferrite sheet of 4×3 cm can result in a reduction over 13% for peak SAR_{1g} and 9% for absorbed power by head, respectively, relative to a degradation below 0.6 dB for the radiation pattern. Another important conclusion that can be drawn from this study is that a metal sheet with small size increases the EM absorption in the human head. Further works are required for experimental validation. Evaluation for more realistic human head and portable telephone models, such as tilting the portable telephone so as to make its mouthpiece close to the lower jaw and pressing the ear to the telephone, is also required.

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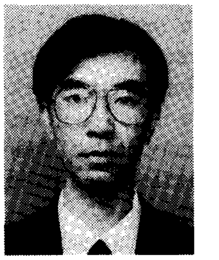

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