Study on Dental Diagnosis and Treatment Using Millimeter Waves

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***Abstract*—In order to diagnose dental caries noninvasively, transmission coefficient of the dental caries is measured and compared to that of a sound tooth. It has been revealed that dental caries are significantly lossy than a sound tooth in millimeter waves. The characteristic can be utilized in the new caries diagnosis. This paper also presents microwave and millimeter-wave heating for the lossy dental caries that can be used as a sterilization treatment. Temperature-distribution heated by microwave power has revealed that dental caries are easily heated. Furthermore, the results of the calculated specific absorption rate distribution using the finite-difference time-domain method indicate the possibility of caries treatment by millimeter-wave heating. It is concluded that millimeter waves can be used for dental medical diagnosis and treatment.**

***Index Terms*—Dental caries heating, dental diagnosis, dentistry, lenses, millimeter-wave diagnosis, millimeter-wave heating.**

I. Introduction

DENTAL CARIES have been conventionally diagnosed by a dentist's subjective judgement based on observation of change of color, odor, surface hardness, and clinical symptoms, such as pain. X-ray imaging provides a more objective diagnosis, but repeated X-ray radiation may cause biological damage to human tissues. In addition, such harmful X-ray diagnosis has the restriction that the initial stage of dental caries cannot be differentiated easily from the sound tissues. It has been revealed that the loss of dental caries is significantly higher than that of a sound tooth in microwave and millimeter-wave range [1]. The large attenuation of the caries in microwaves and millimeter waves suggests that the caries of a tooth can be detected easily by measuring the transmission coefficient using microwaves and millimeter waves. Higher resolution may be obtained by using millimeter waves.

To treat dental caries, a conventional technique is to remove the caries region using a high-speed rotary cutting apparatus. It is unavoidable that the peripheral sound area of the tooth is removed along with the decayed one, which are usually softened and infected. Attenuation of the caries in the region of microwaves and millimeter waves suggests that the caries can be heated easily by dielectric heating in order to kill the microorganisms, including bacteria and virus in the caries. It has been reported that some portion of dental caries become calcified on the condition that the caries keep sterilized [2]. From this point-of-view, this paper shows the application of millimeter waves to heat to sterilize caries for the new sterilization treatment. The result of specific absorption rate (SAR) simulation inside a caries model of a tooth using the finite-difference time-domain (FDTD) method will be shown and discussed in this paper.

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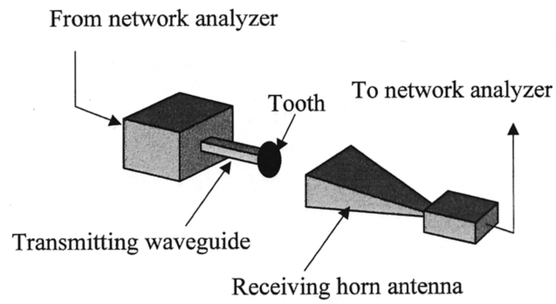

Fig. 1. Experimental setup.

II. Tooth Diagnosis Using Millimeter Waves

A. Measurement of Transmission Coefficient

In order to differentiate the dental caries from the sound tooth effectively, the complex permittivity of enamel, dentin, and the caries tooth has been obtained [1], [3]. From the results, it is found that the loss of caries is much higher than that of the sound part. To apply this characteristic in teeth diagnosis, a transmission coefficient was measured for the extracted caries teeth. An extracted and bisected adult's tooth was used for the sample. The experimental setup is shown in Fig. 1. As shown in Fig. 1, a sample tooth was irradiated by millimeter waves using a rectangular waveguide, which is directly contacted to the surface of the cutting plane of the tooth. The transmitted wave was received using a horn antenna, which is located on the other side and directed to the sample, and the transmission coefficient was obtained by a network analyzer (Anritsu–Wiltron 360B). The place where the waveguide is contacted on the flat backside is shown in Fig. 2. The transmission coefficient was measured over the frequency range from 33 to 110 GHz. Three types of waveguide applicators were used. From 33 to 50 GHz, the aperture size of the waveguide was 5.69×2.84 mm^2 (WR 22). From 50 to 75 GHz, the aperture size of waveguide was 3.76×1.88 mm^2 (WR 15). From 75 to 110 GHz, the aperture size of the waveguide was 2.54×1.27 mm^2 (WR 10). Since the aperture size of waveguide becomes smaller as the frequency band becomes higher, it becomes possible to measure the transmitted wave of

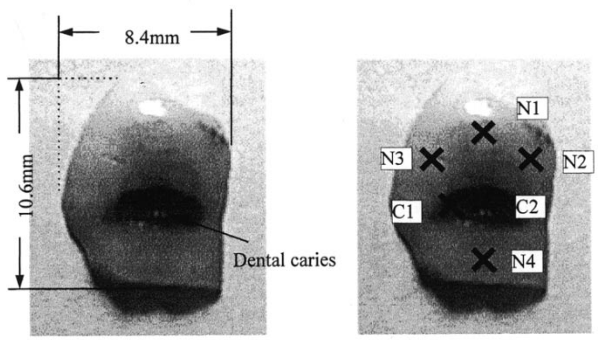

Fig. 2. Photo of tooth.

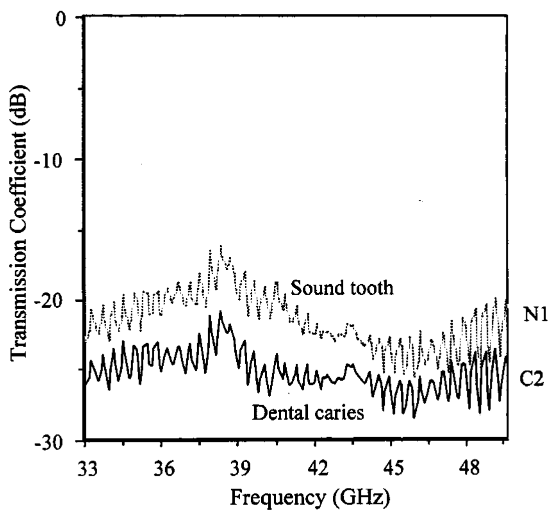

Fig. 3. Transmission coefficient of millimeter waves (33–50 GHz).

the part of the dental caries and that of the sound tooth separately.

B. Experimental Results

The experimental results for the measurement of the transmission coefficient of the extracted and bisected tooth are shown in Figs. 3–5. As shown in Fig. 3, in the frequency range from 33 to 50 GHz, the value for the dental caries is about 4 dB lower than that for the sound tooth. This difference of the transmission coefficient originates in the loss of water, which is contained in the dental caries [1]. In this frequency range, the aperture size of the waveguide is large for the extracted tooth, and it is then difficult to effectively differentiate the dental caries from the sound tooth. The difference of the transmission coefficient between the sound and caries parts becomes increased as the aperture size becomes smaller. As shown in Fig. 4, there is about a 7-dB difference between the transmission coefficient of the dental caries and sound tooth. Furthermore, as shown in Fig. 5, the value for the center caries is about 10 dB lower than that for the sound tooth. Also, the value for the edge caries is about 5 dB lower than that for the sound tooth. These results reveal that higher resolution is attained when higher frequency, i.e., a smaller applicator, is applied.

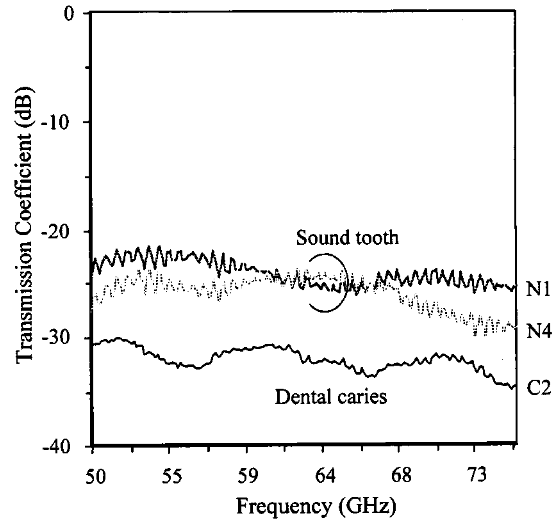

Fig. 4. Transmission coefficient of millimeter waves (50–75 GHz).

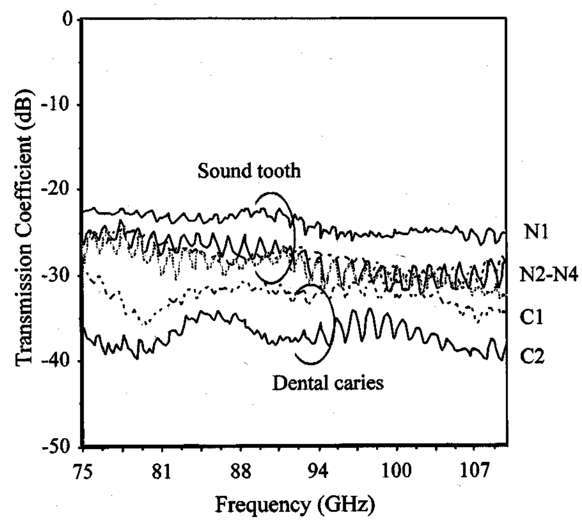

Fig. 5. Transmission coefficient of millimeter waves (75–110 GHz).

III. Caries Treatment by Microwave and Millimeter-Wave Heating

A. Heat Sensitivity of Bacteria in the Dental Caries

In order to apply microwave and millimeter-wave heating to dental-caries treatment, it is necessary to reveal the heat sensitivity of bacteria in the dental caries. Bacteria of *Streptococcus sobrinus* B13 was cultured and the survival rate versus time was obtained as a parameter of temperature. A microwave at 2.45 GHz was applied to heat the cultured bacteria. Water bath was also used to double check the survival rate of the bacteria. The colony method was applied for survival bacteria counting. The result is shown in Fig. 6. It is found that the temperature is higher than 50 °C, and that the survival rate of the bacteria is decreased. It has been reported that some portion of the dental caries become calcified and recovered on the condition that the caries are kept sterilized [2]. This characteristic can be applied to the dental-caries treatment using microwaves.

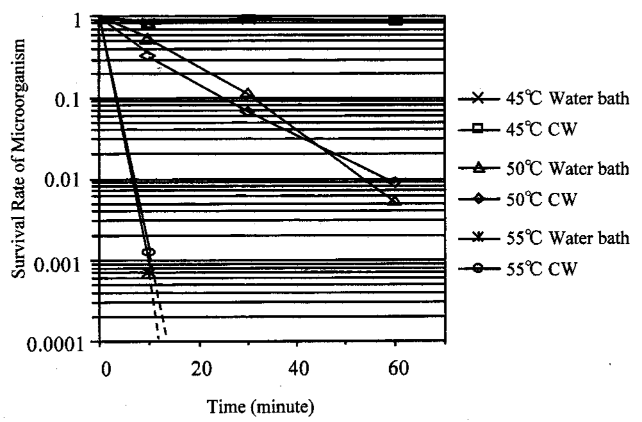

Fig. 6. Survival rate of microorganism versus time as a parameter of temperature (cultured bacteria: *streptococcus sobrinus* B13).

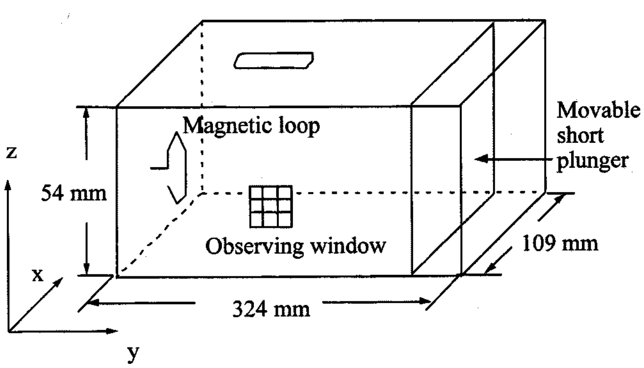

Fig. 7. Schematic of cavity resonator.

B. SAR Distribution in Tooth

As shown in Section II, dental caries are lossy compared to the sound part. Therefore, it is estimated that heat generation in the dental caries is higher than that of sound area. A 2.45-GHz microwave was applied to reveal the possibility of heating for the dental caries. Fig. 7 shows the TE_{103}-mode cavity resonator. The caries tooth was put in the cavity resonator, and the tooth was heated by microwave power. The maximum input power was 5 W. The surface temperature was measured from the window in the cavity wall by an infrared thermograph. The heating time was 10 s. The heating time is very short; therefore, the temperature can be considered in proportion to the SAR. The maximum temperature for the sample A is 47.8 °C and for the sample B is 43.7 °C. Fig. 8 shows the relative SAR distribution of the heated tooth. As shown in Fig. 8, caries denotes the highest SAR and the temperature becomes highest. From this result, it is found that the caries are easy to be heated by microwaves in comparison with the sound area. However, the tooth has a dental pulp in addition to enamel or dentin as normal tissue. Since dental pulp is made of watery and fairly sensitive tissues, it is necessary to avoid heating to the dental pulp. Furthermore, it is only necessary to heat dental caries to avoid side effects of heating on sound tissues. In order to heat only the microorganism in the caries, a millimeter wave is applied to selectively heat the caries.

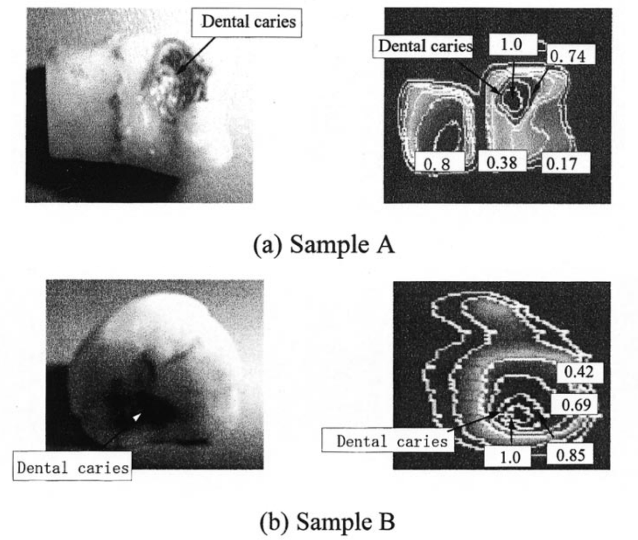

Fig. 8. Relative SAR distribution on a heated tooth at 2.45 GHz.

TABLE I
ELECTRICAL PROPERTIES AT 35 GHz AND DENSITY OF TISSUE IN THE TOOTH

	Sound tooth	Dental caries	Dental pulp
Relative permittivity	6.83	6.04	20.0
Conductivity [S/m]	0.039	5.06	40.0
Density (g/cc)	2.52	1.68	0.87

C. Heating of a Tooth Using Millimeter Waves

In order to reveal the heating characteristics of millimeter waves on a tooth including dental pulp, the distribution of the SAR [3] inside a tooth model is presented in this section. The SAR is defined as

$$\mathrm{SAR} = \frac{\sigma}{2\rho}|E|^2 \tag{1}$$

where E is the electric field, ρ is the density, and σ is the conductivity of the tissue. The simulation was made at 35 GHz because the wavelength was small enough relative to the tooth size and the energy might be focused on the caries area. It is not realistic to discuss this in higher frequency because it is still very difficult and expensive to develop a high-power generator in higher frequency.

The electrical properties of tissue at 35 GHz and density are listed in Table I. The density of the dental pulp is the value of rabbit's one. Relative permittivity and conductivity of the dental pulp are the value of blood [4]. To obtain the SAR distribution, E was calculated using the FDTD method [5], [6] at 35 GHz. The FDTD method was chosen because of its flexibility and efficiency in solving complex heterogeneous geometry. In order to simplify the computations, the boundary conditions were solved over a smaller area [7], [8]. The model that was to be heated by

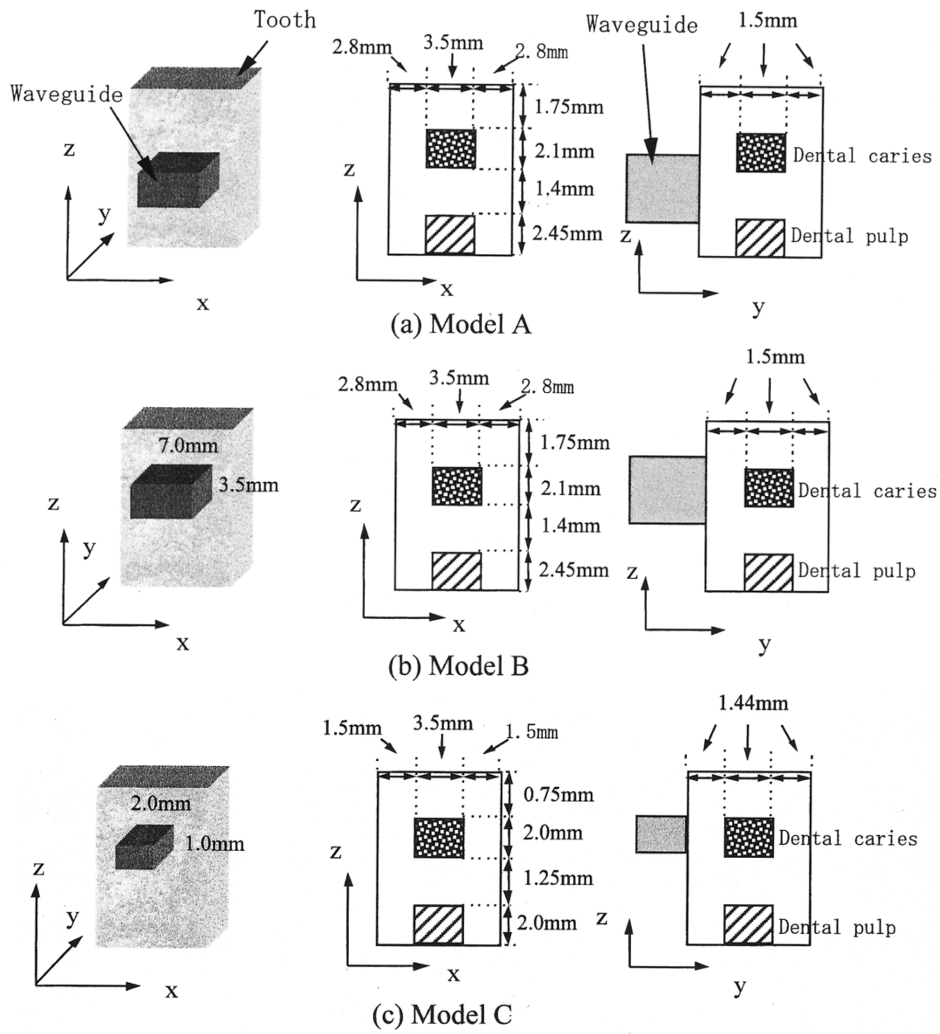

Fig. 9. Analysis model.

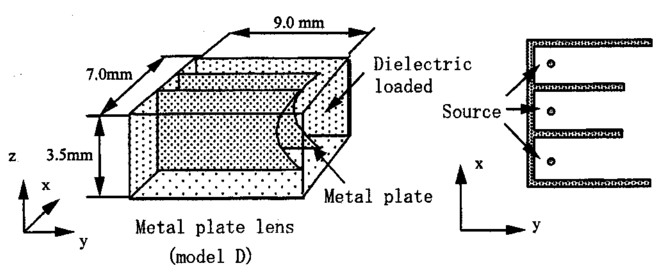

Fig. 10. Schematic of metal-plate lens (model D).

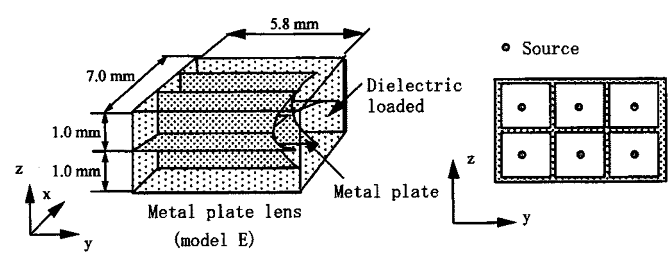

Fig. 11. Schematic of metal-plate lens (model E).

waveguide is shown in Fig. 9. To heat the caries selectively, a metal-plate lens is considered for the heating applicator, which is shown as models D and E [9], [10]. Models D and E are shown in Figs. 10 and 11, respectively. Millimeter waves were directly irradiated to the tooth from a direct contact waveguide. The size of the calculated region was $30 \times 55 \times 22$ in models A and B, and $26 \times 46 \times 24$ in models C, D, and E. The time step Δt of the FDTD calculation was 0.2 ps in models A and B, and 0.3 ps in models C, D, and E. Table II shows the cell size of each medium.

As shown in Fig. 9, all tooth models include dental caries and dental pulp. In models D and E, tooth models were the same as shown in Fig. 9. In model A, the waveguide is located the same distance from dental pulp and caries. In models B, C, D, and E, the waveguide is located in the front of the caries. In model C, the aperture size of waveguide is smaller than that of model B because the waveguide is filled with dielectric material that has the same permittivity with the sound tooth. The lens applicators are also filled with dielectric material that has the same permittivity with the sound tooth.

TABLE II
CELL SIZE IN ANALYSIS MODEL

	Δx (mm)	Δy (mm)	Δz (mm)
Model A, B	0.35	0.3	0.35
Model C, D, E	0.25	0.24	0.25

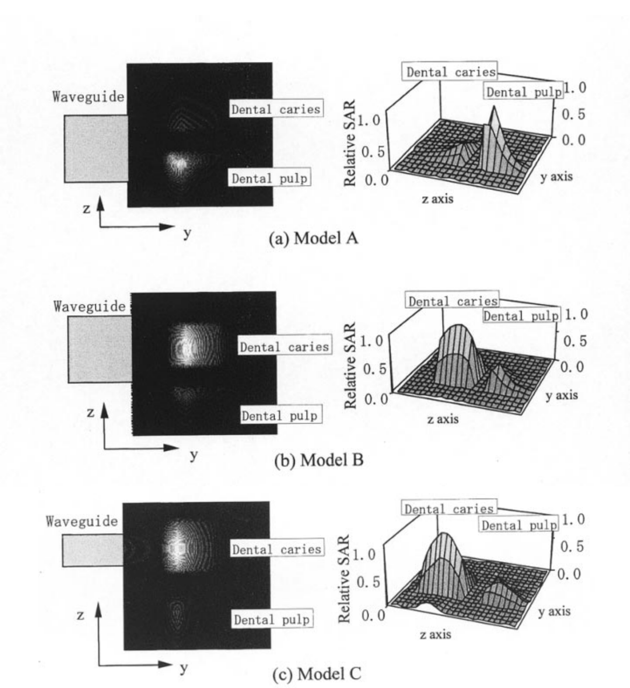

Fig. 12. SAR distribution in analysis model.

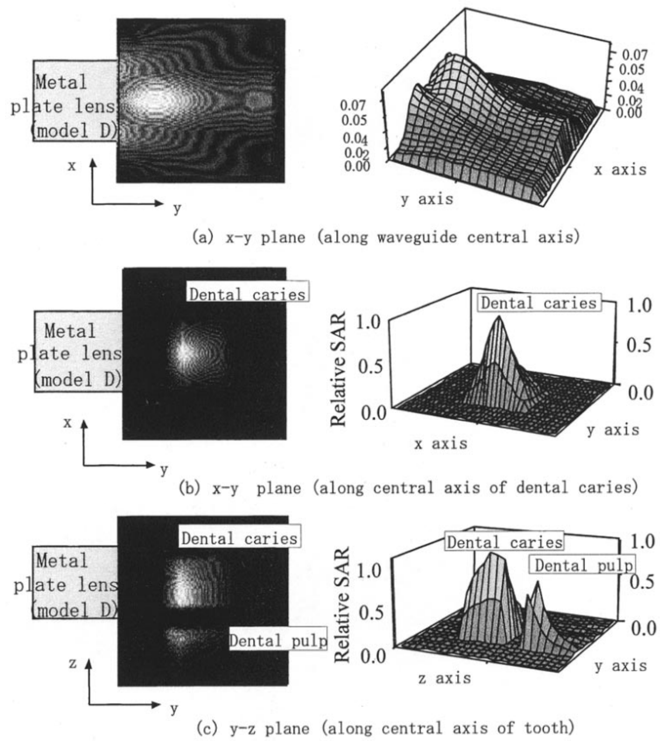

Fig. 13. SAR distribution in the tooth heating by metal-plate lens (model D).

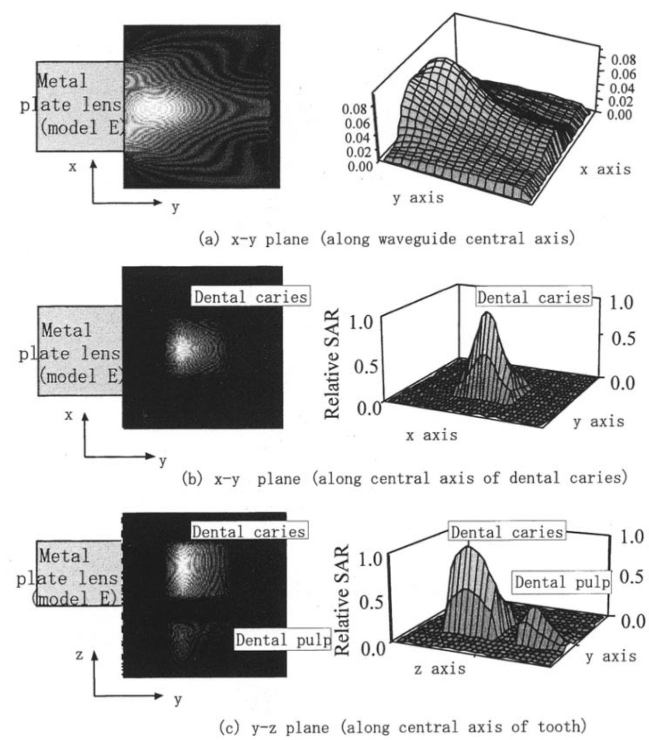

Fig. 14. SAR distribution in the tooth heating by metal-plate lens (model E).

D. Simulation Results

Fig. 12 shows the relative SAR distributions in models A, B, and C. Figs. 13 and 14 show the relative SAR distribution in models D and E, respectively. From the result of model A, it is found when the waveguide is located at the same distance from the dental pulp and caries, the dental pulp is heated stronger in comparison with the caries. However, from the result of models B, C, D, and E, it is found when the waveguide is located in front of the caries; it is possible to reduce the influence of millimeter-waves on the dental pulp. To evaluate the results, R_{cp} and R_{cc} are defined as

$$R_{cp} = \frac{\text{Max SAR in caries}}{\text{Max SAR in dental pulp}} \quad (2)$$

$$R_{cc} = \frac{\text{SAR in caries center}}{\text{Max SAR in caries peripheral}}. \quad (3)$$

The results are shown in Table III. From Table III, it is found that R_{cp} is largest when the applicator of model B is applied. This means if the applicator of model B is applied, the minimum heating of the dental pulp can be realized. If the lens applicator of model D is applied, maximum R_{cc} is obtained. This means if the applicator of model D is applied, maximum selective heating can be realized. Nevertheless, in this case, the heating of the dental pulp is not the least. The aperture size of the lens applicator is relatively large in comparison to the tooth size, and the energy is leaked to the area of the dental pulp. In such a case, the length between the dental pulp and applicator should be separated as far as possible.

TABLE III
EVALUATION OF HEATING

	Waveguide model B	Waveguide model C	Metal lens model D	Metal lens model E
R_{cp}	2.28	3.03	1.36	2.46
R_{cc}	1.8	3.57	3.86	2.4

IV. CONCLUSIONS

In this paper, the transmission coefficient of the dental caries is measured and compared to the sound area in millimeter waves up to 110 GHz. The attenuation of the caries area is very high compared to that of the sound area. It will be used for noninvasive dental-caries detection. In this case, a smaller applicator using higher frequency is more sensitive for the small caries detection. By the method proposed in this paper, more scientific and objective diagnosis for the caries will be realized.

In addition, the results of this paper show the possibility of utilization of millimeter-wave power to treat dental caries. In the basic microwave heating to dental caries at 2.45 GHz, 10 s of 5-W heating of caries make the maximum temperature of 47.8 °C. Though it depends on the heating volume and needed temperature rise, radiated power of smaller than 5 W is enough to heat dental caries in millimeter waves at 35 GHz. Caries can be sterilized by high temperature. Local heating by a millimeter wave may sterilize the caries. Sterilization may stop the progress of caries, and some portion of the caries may be calcified and cured by the remaining recovering mechanism of the tooth. Further research is needed to study the differences in absorption power of the tooth both *in vitro* and *in vivo*.

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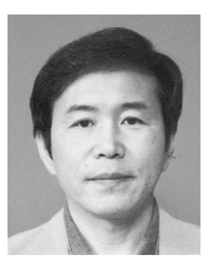

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