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A Microwave Dosimetry System for Measured Sampled Integral-Dose Rate

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Abstract—**An interface has been developed to allow the measurement of sampled integral-dose rate, defined as the change in integral dose during a particular time interval divided by that interval, absorbed by test animals as they are exposed in a waveguide to 2450-MHz CW microwave energy. The purpose of this investigation is to quantify the variations in sampled integral-dose rate as a result of the animal movements and to compare different irradiation procedures with respect to variations in sampled integral-dose rate.**

NOMENCLATURE

Integral dose ϵ	Total electromagnetic energy absorbed by the test animal.
Integral-dose rate $\dot{\epsilon}$	The time rate of absorption of total electromagnetic energy.
Sampled integral-dose rate $\dot{\epsilon}_i$*	The measured change in total electromagnetic energy absorbed during the ith time interval divided by the value of that interval.
Distributed dose D	The electromagnetic energy absorbed by a macroscopic element of mass within the test animal divided by the value of that mass.

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INTRODUCTION

CURRENTLY, animals in microwave biological-effects experiments are irradiated by a variety of exposure-field configurations. Some of the irradiating apparatus include plane wave, focused field, aperture source, stripline, and waveguide. For some of these apparatus, the dosimetry is quantified in terms of external-field measurements using detectors that respond to the electric field squared. The results of the field measurements are presented in terms of power density (milliwatts/square centimeter) assuming a far-field relationship between the electric and magnetic fields. Biological effects, however, are related to the induced internal electromagnetic field in the biological body. It has been reported [1]–[3] that the induced electromagnetic field and hence the energy absorbed (proportional to the electric field squared) in a biological body depends on the size, geometry, and composition of the biological body. The energy absorption also depends on the type of exposure field, the source frequency [4]–[6], and the orientation of the biological body with respect to the exposure field. In an effort to quantify the microwave energy absorbed by small experimental animals, a waveguide system has been constructed and was reported previously [7]. The environmentally controlled microwave-waveguide irradiation facility operating at 2450 MHz allows for the measurement of the integral dose absorbed by a test animal during a given

irradiation period. During a typical exposure with this facility, the test animal is not anesthetized or restrained, but is restricted to a 10.9- × 11.4- × 5.5-cm volume in the waveguide. As a result of its freedom of movement, it is found that the integral-dose rate absorbed by the animal varies with time. This variation is expected since the energy absorption depends in part on the orientation of the animal with respect to the exposure field. The purpose of this investigation is to quantify the variations in integral-dose rate as a result of the animal movements and to compare different irradiation procedures with respect to variations in sampled integral-dose rate.

INSTRUMENTATION

Fig. 1 shows a block diagram of the waveguide irradiation apparatus and the interfaces for measuring sampled integral-dose rate. Detailed discussion of the waveguide irradiation apparatus has been presented in a previous paper [7]. Fig. 2 is a picture of the waveguide apparatus. Microwave energy is delivered by the 2450-MHz CW source into the animal chamber. The power fed into P_f, reflected from P_r, and transmitted through P_t the animal are measured by the power meters through the directional couplers. Electronic signals representing the respective power readings are fed into the voltage integrator. A voltage-integrator data-acquisition interface has been developed which transfers the accumulated counts from the voltage integrator to a digital cassette tape recorder at predetermined intervals. The system allows the adjustment of the sample period from 1 to 1000 s. The data stored on the cassette tape can be read, through the terminal modem interface, into Call/OS, a time-shared computer operating system which runs on an IBM 370/155 computer. A software package was developed which calculates the sampled integral-dose rate in watts as well as the integral dose in joules. The softwave package also allows these two quantities to be plotted as a function of time on a Tektronix Graphics Display Terminal.

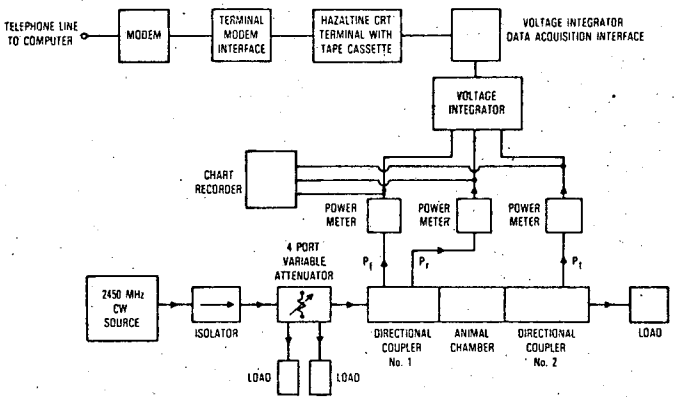

Fig. 1. Block diagram of waveguide irradiation apparatus.

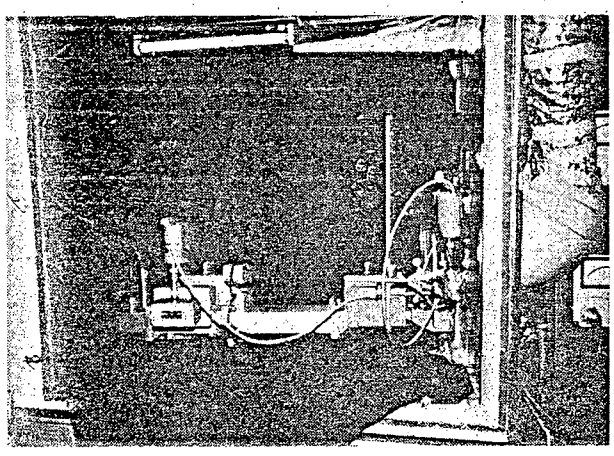

Fig. 2. Picture of waveguide apparatus.

MEASUREMENT OF SAMPLED INTEGRAL-DOSE RATE

Integral dose absorbed by the animal is given by the following equation

$$\epsilon = \int_0^T P_f\,dt - \left[\int_0^T P_r\,dt + \int_0^T P_t\,dt\right] \text{J} \qquad (1)$$

where ϵ is the integral dose and T is the exposure time in seconds. An analog signal for each of these power terms is applied to a separate channel of a voltage integrator. A digital count proportional to the integral of power with respect to time is produced for each channel. Equation (1) can be converted to

$$\epsilon = S_f C_f - [S_r C_r + S_t C_t]\,\text{J} \qquad (2)$$

where S_f, S_r, and S_t are scale factors for the forward, reflected, and transmitted channel, respectively; and C_f, C_r, and C_t are the counts in the forward, reflected, and transmitted channel, respectively.

During each sampling interval, data from the voltage integrator are transferred into the digital cassette tape recorder in the form of one digital word consisting of two digits each for the forward channel, the reflected channel, and the transmitted channel. After the data have been read from the cassette tape recorder into Call/OS, the sampled integral-dose rate can be calculated.

The first step is to reconstruct the cumulative counts for each channel. The integral dose can then be determined for each sample point collected, using (2). The sampled integral-dose rate is given by

$$\dot{\epsilon}_i^* = \frac{\epsilon_i - \epsilon_{i-1}}{\Delta t}\,\text{W} \qquad (3)$$

where $\dot{\epsilon}_i^*$ is the sampled integral-dose rate for the ith sampling interval; ϵ_i and ϵ_{i-1} are the integral doses during the ith and $(i-1)$th sampling interval, respectively; and Δt is the value of the sampling interval in seconds.

The interface is only capable of transferring an integer number of counts to the tape cassette. There is an uncertainty between the measured sampled integral-dose rate and the actual sampled integral-dose rate which can be attributed to neglecting the fractional portion of the counts when calculating the measured value. This difference can be accounted for by assuming that the actual sampled integral-dose rate is within a range of values

TABLE I
MEASUREMENT OF SAMPLED INTEGRAL-DOSE RATE FOR ANIMALS RESTRICTED TO A VOLUME IN THE WAVEGUIDE

Animal Number	Weight (Grams)	Integral Dose (Joules)	Mean of Sampled Integral Dose Rate (Watts)	Percentage of Observations greater than T_H[a] (%)	Percentage of Observations less than T_L[b] (%)
1	32.4	299.4	0.499	12.7	1.3
2	36.8	177.4	0.296	25.0	29.5
3	30.8	254.0	0.424	19.4	22.4
4	28.3	246.1	0.408	28.3	26.4
5	24.7	254.2	0.424	1.5	6.0
6	24.4	265.1	0.442	24.5	22.6
7	16.6	189.7	0.316	13.2	11.3
8	29.7	234.6	0.392	24.5	26.4
9	30.3	246.7	0.411	17.8	20.0
10	14.0	147.8	0.246	13.3	13.3
11	36.3	298.7	0.498	17.9	14.9
12[c]	27.7	151.6	0.253	0.0	0.0

Exposure Conditions

Frequency	2450 MHz
Exposure Time	10 mins
Temperature	24°C
Relative Humidity	50%
Air Flow	38 liters/min

[a] T_H equals 1.15 times the mean of the sampled integral-dose rate.
[b] T_L equals 0.85 times the mean of the sampled integral-dose rate.
[c] Dead animal.

which can be represented by $\Delta\dot{\epsilon}_i^*$, the percent deviation from the measured sampled integral-dose rate during the ith sample interval. A worst case analysis, in which the fractional portion of the count for each channel was allowed to assume the value zero or one, was performed which supplied a technique for calculating the upper and lower values for $\Delta\dot{\epsilon}_i^*$. This technique involves calculating the minimum and maximum values for the integral dose during each sampling interval using the following equations:

$$\epsilon_{i\,\min} = S_f C_f - S_r(C_r + 1) - S_t(C_t + 1)\ \text{J} \quad (4)$$

$$\epsilon_{i\,\max} = S_f(C_f + 1) - S_r C_r - S_t C_t\ \text{J} \quad (5)$$

where $\epsilon_{i\,\min}$ is the calculated minimum integral dose during the ith sampling interval and $\epsilon_{i\,\max}$ is the calculated maximum integral dose during the ith sampling interval. Equations (4) and (5) are used to calculate the minimum and maximum values for the sampled integral-dose rate using the following equations:

$$\dot{\epsilon}_{i\,\min}^* = \frac{\epsilon_{i\,\min} - \epsilon_{i-1\,\max}}{\Delta t}\ \text{W} \quad (6)$$

$$\dot{\epsilon}_{i\,\max}^* = \frac{\epsilon_{i\,\max} - \epsilon_{i-1\,\min}}{\Delta t}\ \text{W} \quad (7)$$

where $\dot{\epsilon}_{i\,\min}^*$ is the minimum value of the sampled integral-dose rate during the ith sampling interval and $\dot{\epsilon}_{i\,\max}^*$ is the maximum value of the sampled integral-dose rate during the ith sampling interval. The computer program calculates $\Delta\dot{\epsilon}_i^*$ for each sample interval and allows selection of different sample intervals for analyzing the data. As the sample interval increases, $\Delta\dot{\epsilon}_i^*$ decreases. The criterion used to select the optimum sample interval was to choose the solution using the shortest sample interval which reduces $\Delta\dot{\epsilon}_i^*$ to less than ± 4.0 percent. The software used for plotting allows the simultaneous display of $\dot{\epsilon}_{i\,\max}^*$, $\dot{\epsilon}_i^*$, and $\dot{\epsilon}_{i\,\min}^*$.

RESULTS

The results obtained by exposing twelve CF1 mice restricted to a 10.9- × 11.4- × 5.5-cm volume to 2450-MHz CW microwave energy are presented in Table I. The sampled integral-dose rate was measured for each exposure and its mean is reported in the table. An arbitrary upper threshold T_H was established which was equal to 1.15 times the mean of the sampled integral-dose rate. The percentage of values of the sampled integral-dose rate which are greater than T_H is reported. Similarly, a lower threshold T_L was established which was equal to 0.85 times the mean of the sampled integral-dose rate and was used to calculate the percentage of sampled integral-dose rate values which are less than T_L. By reporting the percentage of observations greater than T_H and the percentage of observations less than T_L, a comparison of differences in variation of sampled integral-dose rate about the mean can be made for each exposure. It should be pointed out that since each observation is not independent of the other observations, as qualitatively demonstrated by the cyclic appearance of the data, it is fundamentally incorrect to compare variation about the mean using standard deviation. Representative plots of the sampled integral-dose rate with respect to time are presented in Figs. 3–5. The integral doses and the means of the sampled integral-dose rate are approximately equal for these three exposures, although their sampled integral-dose rates are different.

The measurement system was tested for fluctuations in sampled integral-dose rate which are caused by param-

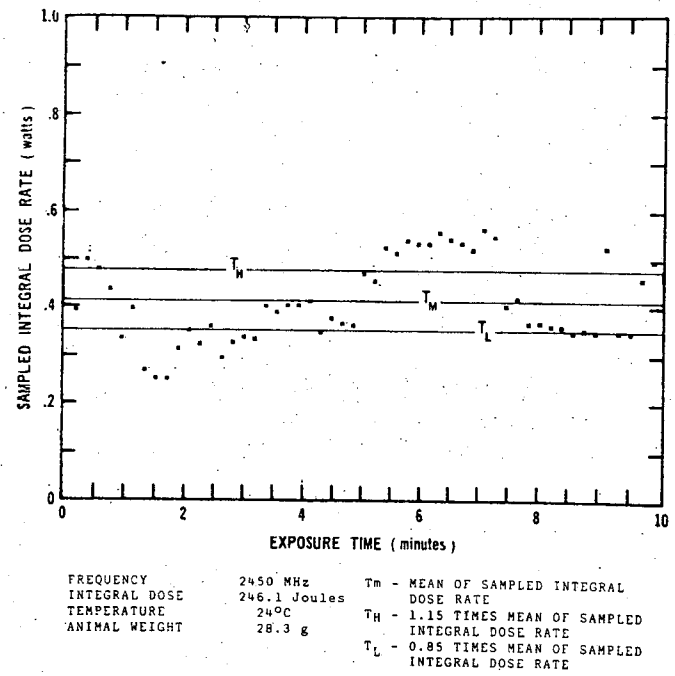

Fig. 3. Variation of sampled integral-dose rate with time for animal 4 which was restricted to a volume in the waveguide.

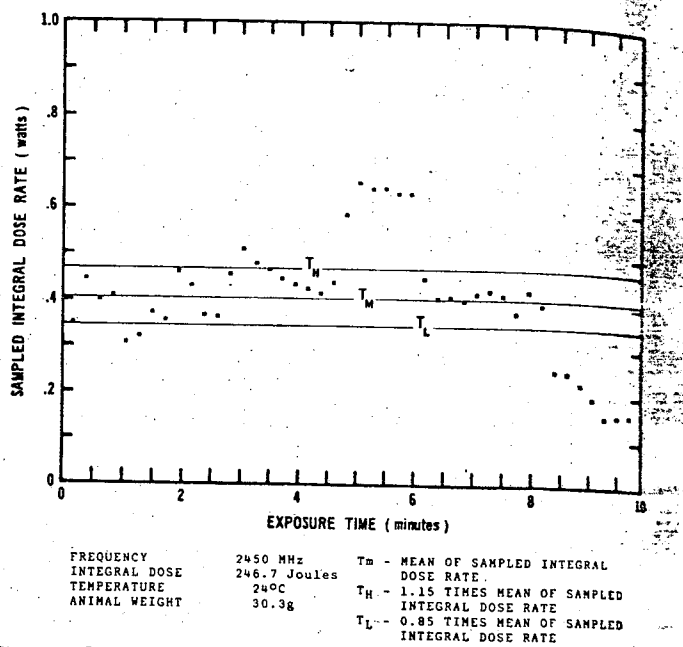

Fig. 5. Variation of sampled integral-dose rate with time for animal 9 which was restricted to a volume in the waveguide.

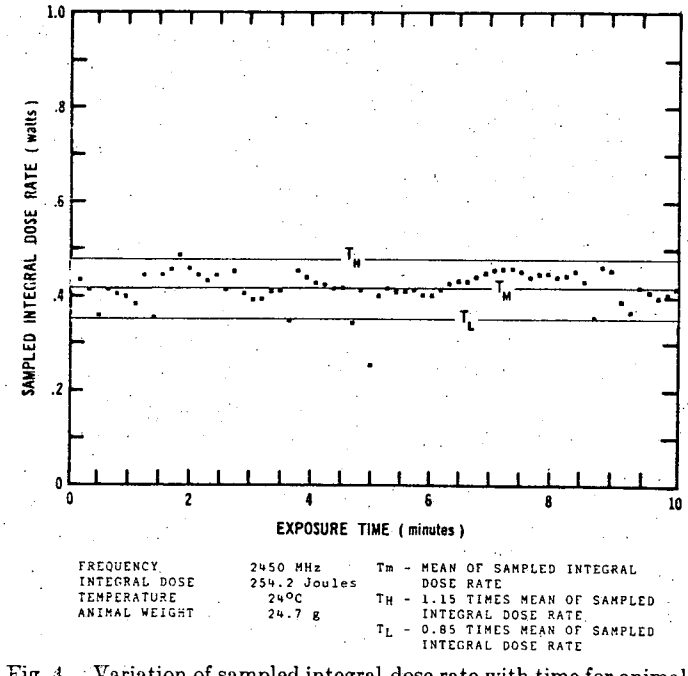

Fig. 4. Variation of sampled integral-dose rate with time for animal 5 which was restricted to a volume in the waveguide.

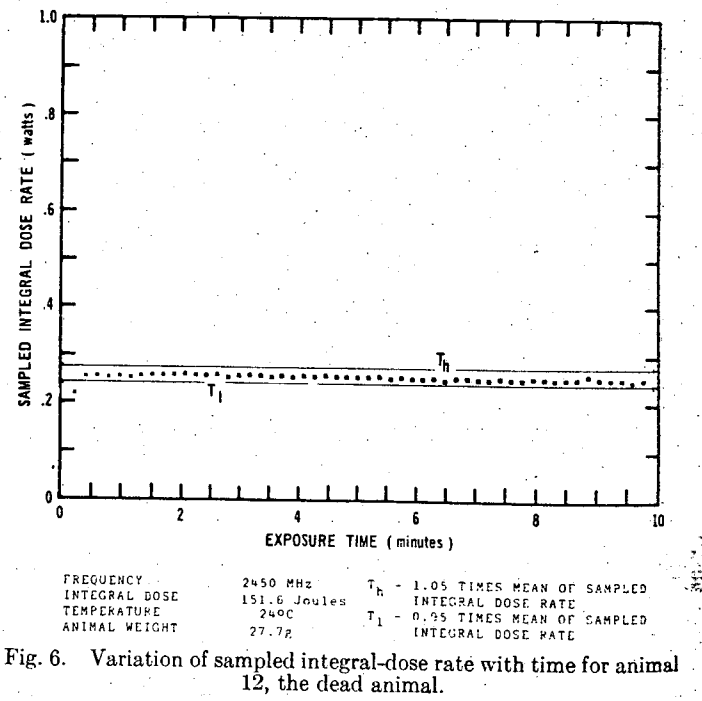

Fig. 6. Variation of sampled integral-dose rate with time for animal 12, the dead animal.

eters other than animal movement by exposing a dead animal. The results of this exposure are summarized in Table I for animal 12, the dead animal, and a comparative plot is shown in Fig. 6. The sampled integral-dose rate was constant within the normal variation inherent with the measuring technique. This exposure used as a control demonstrates that the variation in sampled integral-dose rate, shown in Figs. 3–5, is due to animal movement.

The results obtained by exposing four CF1 mice to 2450-MHz CW microwave energy which were anesthetized using 10-percent sodium pentobarbital are presented in Table II. The sampled integral-dose rate was recorded for each exposure and its mean is reported in the table. An upper threshold T_h and a lower threshold T_l are used to compare differences in variation of sampled integral-dose rate about the mean for each exposure. T_h equals 1.05 times the mean of the sampled integral-dose rate and T_l equals 0.95 times the mean of the sampled integral-dose rate. The percentage of sampled integral-dose rate values which are greater than T_h and the percentage of sampled integral-dose rate values less than T_l are tabulated. A plot of the sampled integral-dose rate with time for an anesthetized animal is presented in Fig. 7. The animal which was used for this exposure was orientated in the

TABLE II

MEASUREMENT OF SAMPLED INTEGRAL-DOSE RATE FOR ANESTHETIZED ANIMALS AND ANIMALS IN SMALL TUBES

	Animal Number	Weight (grams)	Integral Dose (Joules)	Mean of Sampled Integral Dose Rate (Watts)	Percentage of Observations greater than T_h [a] (%)	Percentage of Observations less than T_l [b] (%)
Anesthetized Animals						
	13	34.0	173.2	0.292	1.5	1.5
	14	39.3	145.0	0.244	0.0	1.9
	15	29.2	154.3	0.260	0.0	1.5
	16	35.9	141.0	0.237	0.0	1.9
	16 [c]	35.9	207.0	0.349	0.0	1.5
Animals in Small Tubes	17	28.9	157.7	0.264	15.1	15.1
	18	24.9	155.1	0.261	15.1	15.1
	19	24.7	230.1	0.383	1.5	1.5
	20	22.6	205.4	0.346	3.0	9.1

Exposure Conditions

Frequency	2450 MHz
Exposure Time	10 mins
Temperature	24°C
Relative Humidity	50%
Air Flow	38 liters/min

[a] T_h equals 1.05 times the mean of the sampled integral-dose rate.
[b] T_l equals 0.95 times the mean of the sampled integral-dose rate.
[c] z-axis orientation (see Fig. 10).

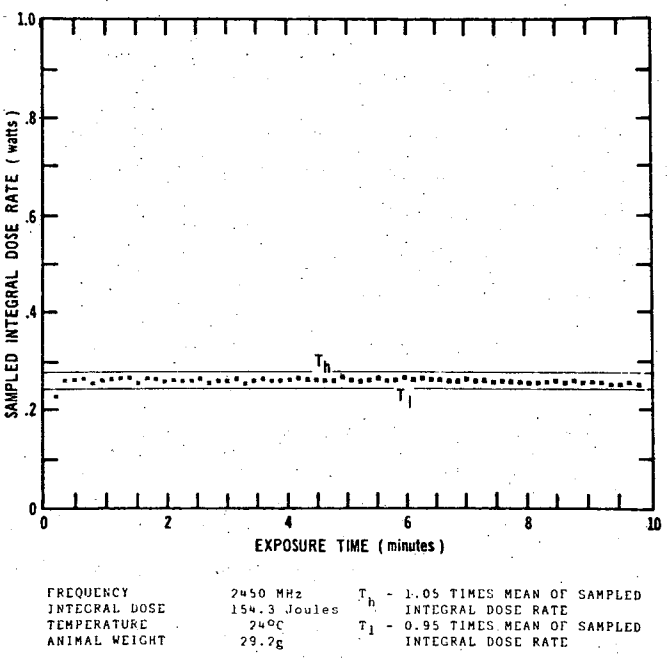

Fig. 7. Variation of sampled integral-dose rate with time for animal 15 which was anesthetized.

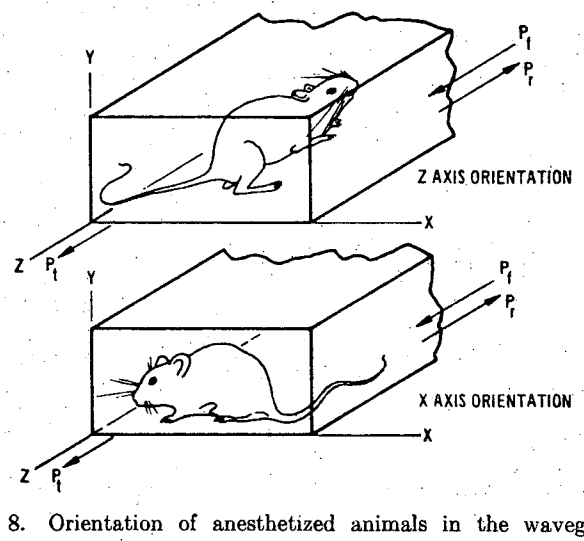

Fig. 8. Orientation of anesthetized animals in the waveguide.

waveguide along the x axis as shown in Fig. 8. One mouse, animal 16, was exposed twice; once while being orientated along the x axis and once while being orientated along the z axis.

The results obtained by exposing each of four CF1 mice in a small polypropolene tube (2.5-cm ID by 10-cm length) to 2450-MHz CW microwave energy also are presented in Table II. The tail of the test animal protruded through an opening in the cap of the tube preventing the animal from reversing its head and tail positions. The movements of the animal were greatly reduced due to its confinement. A picture of the restraining tube which shows its orientation in the waveguide during the exposure is shown in Fig. 9. A plot of the sampled integral-dose rate with time for one of the animals is presented in Fig. 10. The integral doses and the means of the sampled integral-dose rate are approximately equal for the exposures of a dead animal, an anesthetized animal, and a restrained animal which are represented by the plots shown in Figs. 6, 7, and 10, respectively.

DISCUSSION

A system for measuring the sampled integral-dose rate has been built and tested. Data have been collected for the irradiation of several CF1 mice and show that the sampled integral-dose rate varies with time due to movements of the animals. Comparative exposures were performed using a dead mouse, anesthetized mice, and mice in small tubes which demonstrate that variations in the

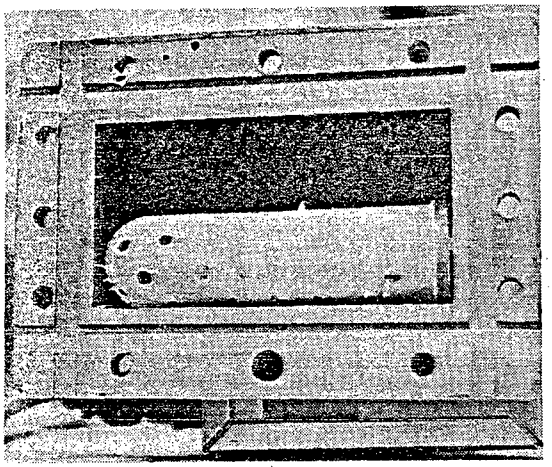

Fig. 9. Orientation of an animal in a small tube in the waveguide.

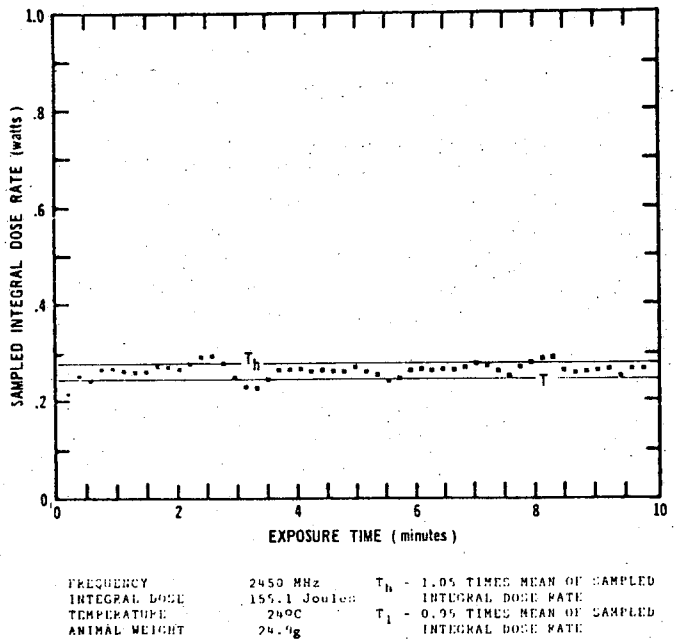

Fig. 10. Variation of sampled integral-dose rate with time for animal 18 which was placed in a small tube.

sampled integral-dose rate are reduced when animal movement is limited. The data also show that the variation in sampled integral-dose rate for anesthetized animals is approximately the same as the variation recorded for a dead animal. The variation in sampled integral-dose rate for animals in small tubes is greater than the variation observed for anesthetized animals, although it was significantly less than the variation observed for animals restricted to a volume in the waveguide.

If the integral dose absorbed by the animal is the only factor which determines the biological effect produced by microwaves, animal movement will not affect the results of experiments in which integral dose is measured. On the other hand, if the biological effect is dependent upon integral-dose rate, animal movement may affect the results of animal experiments. It is also expected that the distribution of absorbed microwave energy (distributed dose) in the animal also changes with its movement. As a result, dosimetric quantification in terms of integral dose alone, though a drastic improvement over exposure-field quantification, may not give sufficient dosimetric information. The variation of integral-dose rate as well as the distributed-dose rate may need to be quantified, especially if these variables affect the biological outcome. It also should be pointed out that the variations of integral- and distributed-dose rates are consequences of the movements and geometry of the animal and, therefore, apply to all irradiation apparatus which allow the animal to move.

Additional work is planned to investigate the effect of animal movement on distributed dose. Both the effects of variations in integral-dose rate and variations in distributed dose can be minimized by anesthetizing or restricting movements of the animals and orientating them consistently in the waveguide. It should also be pointed out that restriction of animal movements, though it facilitates dosimetric quantification, may have significant adverse biological implications to the experiment. It seems that a compromise of mutually acceptable degrees of dosimetric quantification versus animal confinement should be worked out between the engineer and the biologist for each microwave biological-effects experiment.

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