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Calibration of Mg_2SiO_4(Tb) Thermoluminescent Dosimeters for Use in Determining Diagnostic X-Ray Doses to Adult Health Study Participants

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1989年から，放射線影響研究所の業績報告書は，従来の日英両文を併記した方式では発行しない．主要な報告書については，今後も日英両文で印刷するが，それぞれ別に発行する．内容が高度に専門的であり，一般の関心が少ないと思われる報告書については英文のみとし，日本文の要約を添付する．

これにより，広島・長崎の原爆電離放射線被曝の人体に及ぼす晩発性生物学的影響に関する最近の知見を今までよりも速やかにお知らせできることと思う．

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財団法人　放射線影響研究所
業　績　報　告　書

RERF TR 11-89
研究課題　8-89

成人健康調査対象者の診断用X線被曝線量測定を目的としたMg_2SiO_4(Tb)熱蛍光線量計の校正[§]

Calibration of Mg_2SiO_4(Tb) Thermoluminescent Dosimeters for Use in Determining Diagnostic X-Ray Doses to Adult Health Study Participants

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要　約

成人健康調査受診者が診断用X線検査によって受ける線量を測定するための準備としてMg_2SiO_4(Tb)熱蛍光線量計(TLD)の性質を調べた．この線量計は小型で，低線量のX線に対して比較的高感度であるので，精密な線量測定に適している．その熱蛍光強度に基づいて線量を精密に測定するためには，強力な校正が必要である．その感度については，X線管電圧を種々に変えて線量を調べるとともに，方向依存性を見るために照射方向も変えて調べた．線量計の感度はフェーディング効果及び加熱板の劣化によって低下した．しかし，それらの好ましくない影響は少なくとも1.5時間線量計を保存した後に銀メッキされた新しい加熱板を使うことによって，避けることができる．本研究で感度が測定されたTLDは今後の診断用X線の線量測定に役立てられる．

[§]本報告にはこの要約以外に訳文はない．

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Calibration of Mg_2SiO_4(Tb) Thermoluminescent Dosimeters for Use in Determining Diagnostic X-Ray Doses to Adult Health Study Participants[§]

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Summary

Characteristics of Mg_2SiO_4(Tb) thermoluminescent dosimeters (TLD) were ascertained preparatory to measuring dose from diagnostic X-ray examinations received by Adult Health Study participants. These detectors are small, relatively sensitive to low-dose X rays, and are appropriate for precise dosimetry. Extensive calibration is necessary for precisely determining doses according to their thermoluminescent intensities. Their sensitivities were investigated, by dose according to X-ray tube voltage, and by exposure direction, to obtain directional dependence. Dosimeter sensitivity lessened due to the fading effect and diminution of the planchet. However, these adverse effects can be avoided by storing the dosimeters at least 1.5 hours and by using fresh silver-plated planchets. Thus, the TLDs, for which sensitivities were determined in this study, will be useful in subsequent diagnostic X-ray dosimetry.

Introduction

The contribution of diagnostic X-ray examinations to the total ionizing radiation exposure of Adult Health Study (AHS) subjects has been under consideration at RERF for many years. Although medical X-ray doses to active bone marrow and gonads have been estimated for many years,[1–5] the recently reported excess cancer incidence for organs such as the breast and lung[6,7] has stimulated interest in estimating the doses to other organs.

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§**The complete text of this report will not be available in Japanese.**

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For dosimetry using a phantom human, TLDs are considered ideal, because they are small and can be inserted at various sites. However, TLDs are neither air- nor tissue-equivalent, and thermoluminescent (TL) intensities must be carefully converted to doses.

TLDs consisting of Mg_2SiO_4(Tb) phosphor (MSO detectors) are widely used[8,9] due to their sensitivity to X rays, permitting dose measurements over a broad range.[10] The properties of these MSO detectors and other TLDs have been studied by Nakajima[10–12] and Driscoll.[13] Their studies focused mainly on the dosimetry of natural radiation and gamma rays used during radiation therapy. To measure doses incurred in diagnostic radiology, it was necessary to determine the detailed physical characteristics of MSO detectors, which indicated that diagnostic doses can be measured within a 5% range of accuracy.

Apparatus

An Alderson Rando phantom female human (Alderson Research Laboratories, Stamford, Conn, USA) was exposed by using a Toshiba radiography unit, with a DRX2603HD X-ray tube, a DC-15K controller, and a DG-15F transformer (Toshiba Medical Systems Co., Ltd., Tokyo). To determine daily alterations in the sensitivity of the MSO detectors, gamma-ray exposures were incurred by using a Shimadzu Isotron-21 cobalt gamma-ray exposure apparatus (3000 Ci,* Shimadzu Seisakusho Co., Ltd., Kyoto). The MSO detectors used were Kasei Optonix MSO (MSO-S) detectors (Kasei Optonix, Ltd., Odawara). Each was 1.5 mm ϕ in diameter and 1.3 cm in length. TL intensities were measured using a Harshaw thermoluminescence readout system, Model 2000A, and an automated integrating picoammeter, Model 2000B (Harshaw/Nuclear Systems, Cleveland, Ohio, USA). Each MSO detector was heated on a Harshaw silver-plated planchet. An Exradin A2 Shonka–Wyckoff chamber (Warrenville, Ill, USA) was used to measure X-ray exposures. The Shonka–Wyckoff chamber was calibrated at the Regional Calibration Laboratory, Memorial Sloan-Kettering Cancer Center, New York.

Experiments and Results

The Shonka–Wyckoff chamber was used as a standard dosimeter to observe the properties of the MSO detectors. The MSO detectors were heated to 250°C for 60 sec, and the TL intensities were integrated. The detectors were then annealed at 400°C in an electric oven for seven hours.

Thermoluminescence–exposure relationships

Six MSO detectors and the ionization chamber were placed on a styrofoam block. The central axes of the rods were perpendicular to the X-ray beam. The MSO detectors were positioned on a line crossing the anode–cathode axis. The "anode effect" was observed during our preliminary assessments. The dosimeters and chamber were exposed to X rays at a distance of 1 m from the focal spot

**Although current RERF technical reports employ the International System of Units, certain reports related to medical X-ray exposure retain traditional units, R and Ci, due to equipment calibrations.*

using a tube current of 100 mA, a tube voltage of 100 kVp, an added aluminum filter (2.5 mm thick), and a 20 cm × 20 cm irradiation field.

The results, shown in Table 1 and Figure 1, demonstrated that the detector sensitivities depended on their exposure in the low dose region. The sensitivity at 20 mR was about 10% greater than that at 100 mR. For doses greater than 100 mR, it was quite uniform within ±1%.

Energy dependence of TLD sensitivities

For the X-ray exposures, the tube voltage was altered in 20 kVp increments through a range from 40 to 140 kVp. Exposure times were adjusted so that the exposures were about 100 mR. Other experimental factors were the same as the experiment described above.

The results obtained are shown in Table 2 and Figure 2. The sensitivity of the MSO detectors used decreased linearly with increasing tube voltage from 60 to 140 kVp.

Fading effect of TLDs

The MSO detectors were exposed to 60 and 110 kVp X rays and to ^{60}Co gamma rays. TL intensities were measured at various times after ^{60}Co gamma-ray exposures of 308 mR. The central axis of the detector was perpendicular to the gamma rays. The conditions for the X-ray exposures were the same as those in the experiments described above, except for tube voltage.

Table 3 and Figure 3 show the TL intensity readings per 1 mR exposure. In all cases, no fading effect was observed from one hour until one day postirradiation.

Variations in TLD sensitivities

Numerous MSO detectors were placed on a thin acrylic supporting plate and exposed to 633 mR gamma rays from a ^{60}Co source. The same detectors were exposed to 100 kVp X rays, for a total exposure of about 100 mR. The sensitivities of the MSO detectors to gamma rays and to 100 kVp X rays were then examined.

Figure 4 shows the variations in sensitivity of the MSO detector to 100 kVp X rays. Each sensitivity to X rays was corrected according to the deviation from the mean value of the sensitivity to gamma rays. The standard deviations of the sensitivity to X rays before and after these corrections were 2.8% and 2.0%, respectively. Before the corrections, several TLDs showed relatively large deviations in sensitivity from the mean value as shown in Figure 4. However, the corrections facilitated the elimination of measurement errors exceeding 4%.

Sensitivity of TLDs on the Rando phantom

The Rando phantom was placed in the supine position on the X-ray examination table and was irradiated with the MSO detectors and the Shonka–Wyckoff chamber on the phantom's surface. The exposures simulated chest radiography

Table 1. X-ray exposure and sensitivity of the Mg_2SiO_4(Tb) thermoluminescent dosimeters

Exposure time (sec)	Exposure* (mR)	Sensitivity (nC/mR)
0.05	17.3	10.56 (0.06)**
0.1	35.0	9.99 (0.19)
0.2	69.8	9.68 (0.12)
0.3	105.2	9.46 (0.10)
0.4	139.7	9.45 (0.21)
0.6	207.5	9.44 (0.19)

*Tube voltage: 100 kVp

**Standard deviation of six measured values is shown in parentheses.

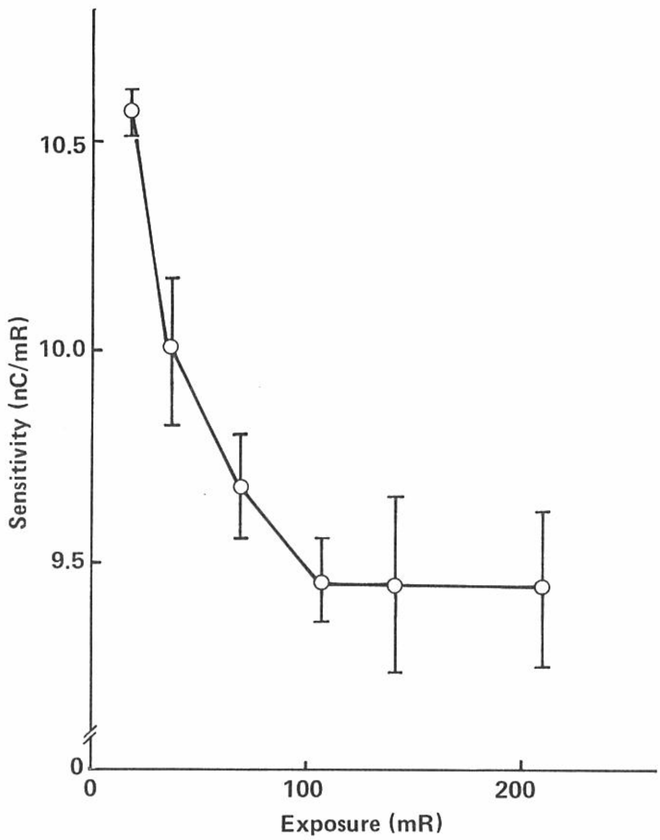

Figure 1. Sensitivity of the thermoluminescent dosimeters to various exposures

The Mg_2SiO_4(Tb) detectors on a styrofoam block were exposed to various low levels of X rays under the following conditions: Tube voltage, 100 kVp; filter, 2.5 mm Al; and field size, 20 x 20 cm. Error bars indicate the standard deviations.

Table 2. Correlations of $Mg_2SiO_4(Tb)$ thermoluminescent dosimeter sensitivity and tube voltages

Tube voltage (kVp)	Exposure time (sec)	Exposure (mR)	Sensitivity (nC/mR)
40	8	115.3	10.44 (0.11)*
60	1.2	105.5	10.35 (0.03)
80	0.5	104.5	9.87 (0.02)
100	0.3	104.2	9.50 (0.03)
120	0.2	98.8	9.05 (0.06)
140	0.16	95.1	8.73 (0.07)

*Standard deviation of six measured values is shown in parentheses.

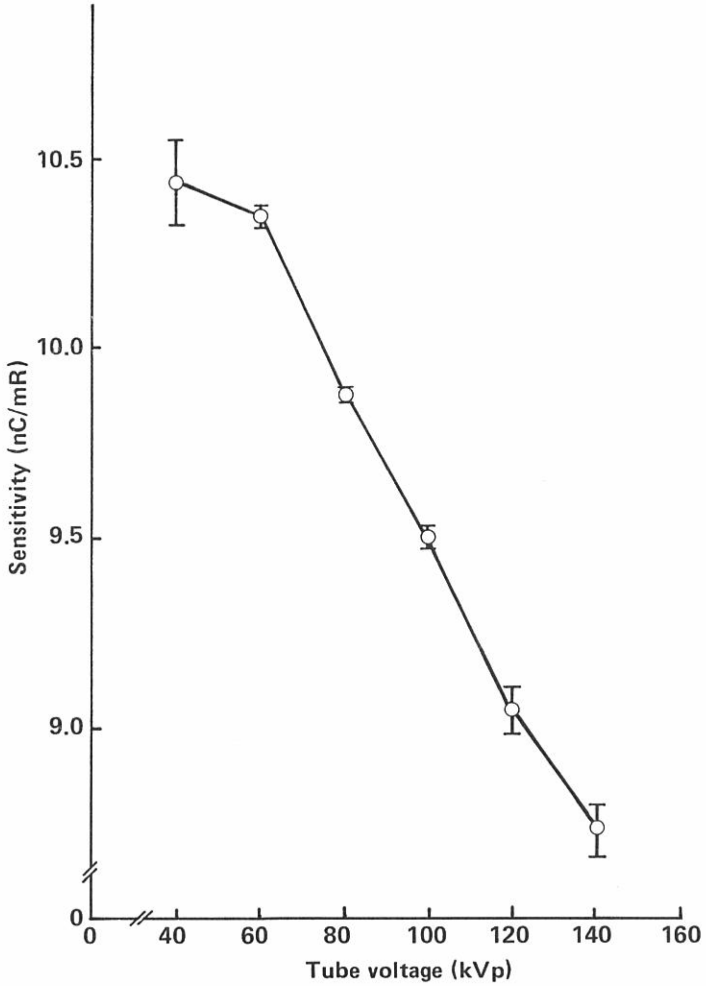

Figure 2. Sensitivity of the thermoluminescent dosimeters to tube voltages

Exposures were adjusted to nearly 100 mR. The conditions of exposure, excluding total exposures and tube voltage, were the same as those of Figure 1. Error bars indicate the standard deviations.

Table 3. Fading effect of the Mg_2SiO_4(Tb) thermoluminescent dosimeters

Time (hour)	Sensitivity (nC/mR)
60 kVp X ray	
1	10.0 (0.3)*
4.5	10.2 (0.3)
24	9.6 (0.2)
110 kVp X ray	
1.5	9.6 (0.3)
19.5	9.6 (0.3)
20.5	9.4 (0.3)
^{60}Co gamma ray	
1	5.02 (0.04)
2	5.18 (0.11)
4	5.18 (0.09)
23	5.04 (0.06)
30	4.97 (0.15)

*Standard deviation of six measured values is shown in parentheses.

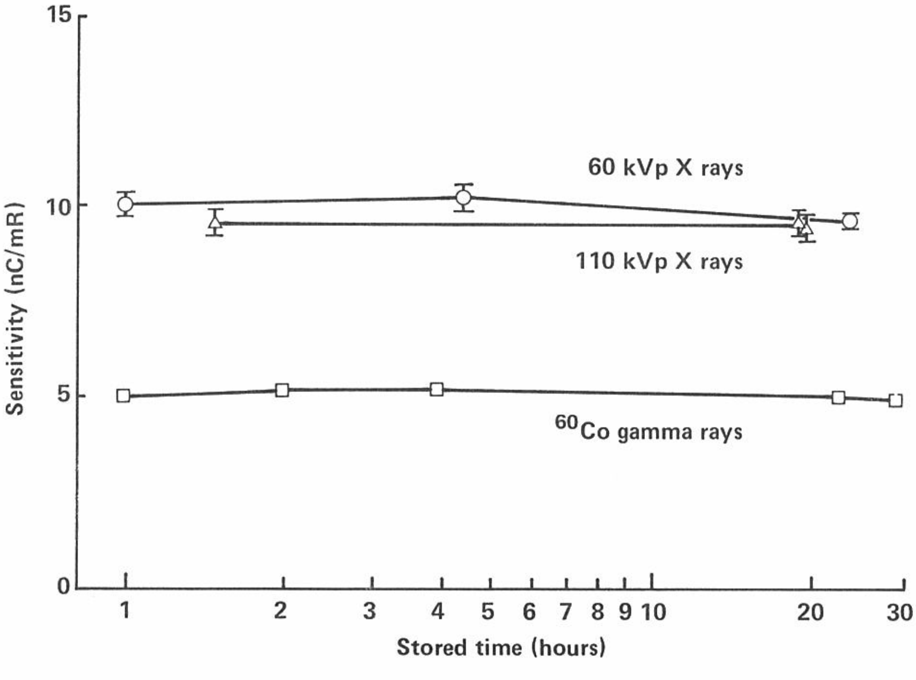

Figure 3. Fading effect of the thermoluminescent dosimeters

The thermoluminescence readings were made several hours (storage time) after exposure to X rays and gamma rays. Error bars indicate the standard deviations.

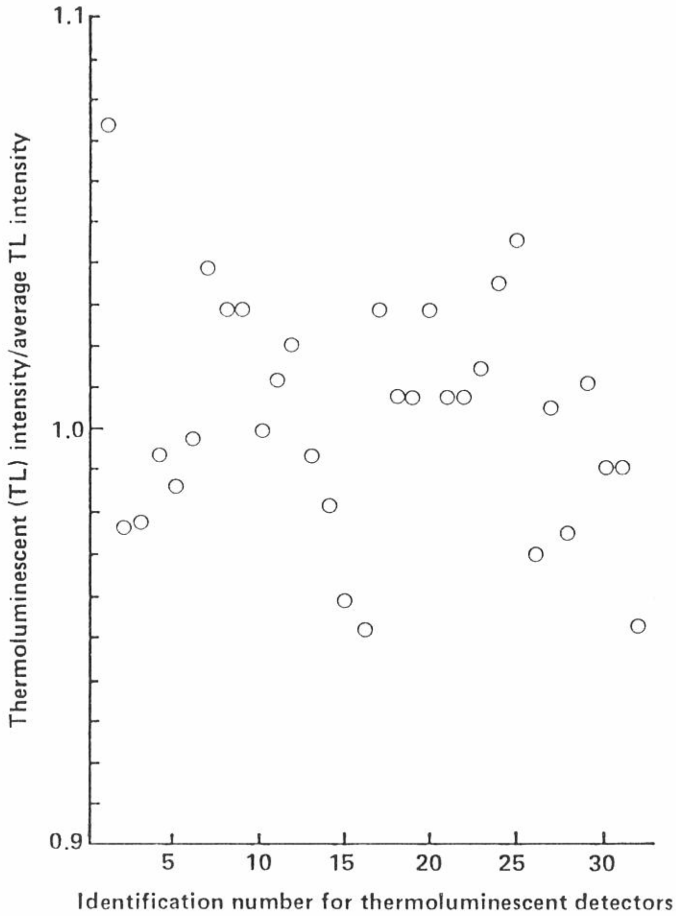

Figure 4. Variations in sensitivity of the thermoluminescent dosimeters

The Mg_2SiO_4(Tb) detectors were placed on a styrofoam block and were exposed to 100 kVp X rays. Intensities were divided by the average intensity.

in the anteroposterior (AP) projection. The exposure factors were 1) 100 cm focus-to-chamber distance, 2) 20 cm × 20 cm field size, 3) 100 kVp tube voltage, 4) 2.5 mm of total aluminum equivalent filtration, and 5) 100 mA tube current. Each set of MSO detectors on a styrofoam block was then exposed to X rays by using the exposure factors described above.

Figure 5 shows the sensitivity of the MSO detectors on the Rando phantom and on the styrofoam block. In general, the sensitivity of the MSO detectors on the Rando phantom was coincident with their sensitivity on the styrofoam block, within the 95% confidence level.

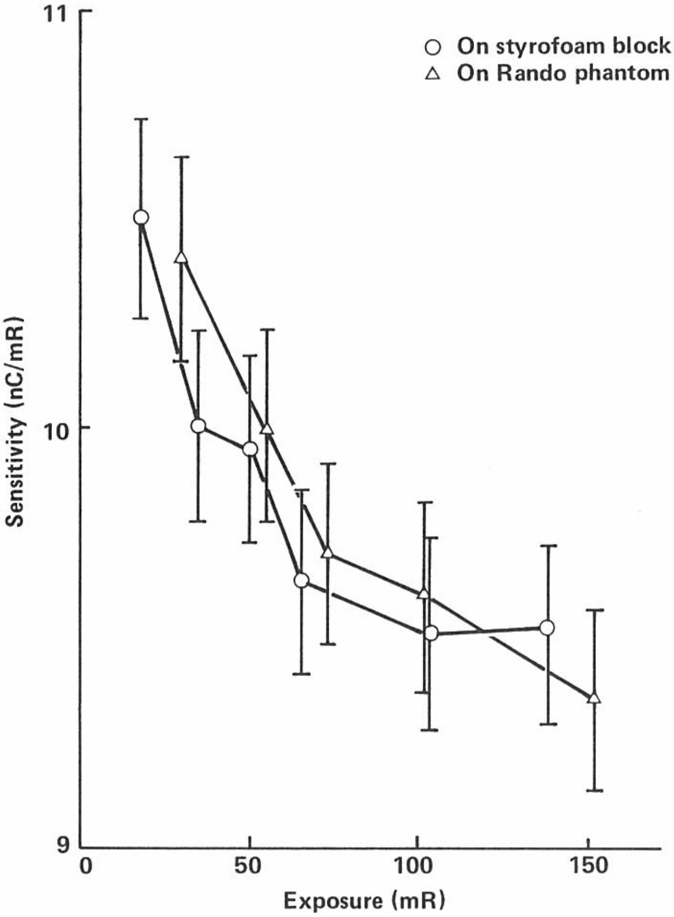

Figure 5. Sensitivity of the thermoluminescent dosimeters (TLD) in air and on a Rando phantom

The Mg_2SiO_4 detectors were exposed to 100 kVp X rays on a styrofoam block and also on a Rando phantom. Error bars indicate the standard errors estimated from the variation of the TLD sensitivities and the reproducibility of the Shonka–Wyckoff chamber.

Directional dependence of TLD rods

The Shonka–Wyckoff chamber and the MSO detectors were placed on the Rando phantom. The conditions for X-ray exposure were the same as in the experiment for determining the sensitivity on the Rando phantom. Exposures were for detectors whose central axes were perpendicular to and parallel with the X-ray beam.

Figure 6 shows the sensitivity of the MSO detectors. Those parallel to the X-ray beam were clearly less sensitive than those perpendicular to the X-ray beam.

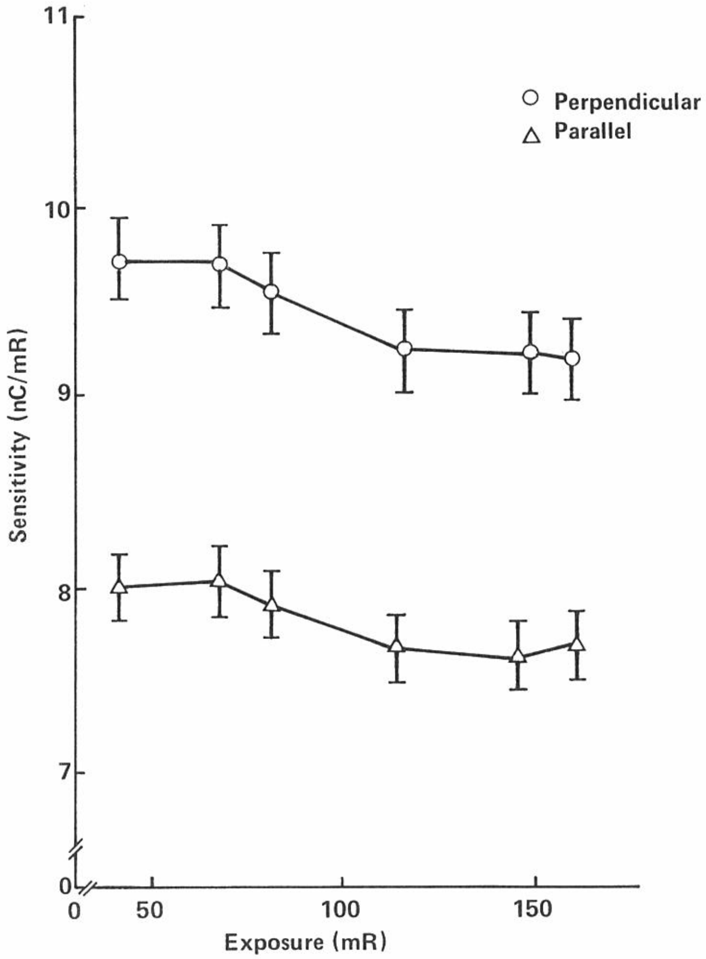

Figure 6. Thermoluminescent sensitivity for 100 kVp X rays parallel with and perpendicular to the central axes of the cylindrical Mg_2SiO_4(Tb) detectors.

Error bars indicate the standard errors estimated from the variation of the thermoluminescent dosimeter sensitivity and the reproducibility of the Shonka–Wyckoff chamber.

Age of the planchet

A set of MSO detectors was exposed to 100 kVp X rays and ^{60}Co gamma rays. Using new and old planchets, TL intensity was measured with the Harshaw TLD readout equipment. The old planchet had been used about 100 times prior to this experiment.

TL intensity was measured using a new planchet, and the results were compared with the intensity measured using the old planchet. The ratio of the former to the latter is shown in Table 4. This ratio depended neither on the X-ray exposure nor on the type of radiation.

Table 4. Heating plate effect on the sensitivity of the $Mg_2SiO_4(Tb)$ thermoluminescent dosimeters

Radiation	Exposure (mR)	Ratio*
X ray	35	1.13 (0.03)**
X ray	70	1.12 (0.04)
X ray	104	1.12 (0.04)
X ray	139	1.13 (0.03)
Gamma ray	633	1.12 (0.01)

*Ratio of TLD sensitivities obtained using a new heating plate to those obtained using an old heating plate

**Standard deviation of three measured values is shown in parentheses.

Discussion

The MSO detector, $Mg_2SiO_4(Tb)$ phosphor, is more sensitive than are other phosphors, such as LiF and $CaSO_4(Tm)$. As shown in Figure 1, linearity of response to exposures could not be obtained in exposure regions lower than 100 mR. However, the chamber did retain its linearity of sensitivity throughout a wide dose range (at least, 10 mR – 10 R) with sufficient accuracy (the relative error is less than 3%). Moreover, the sensitivity of the MSO detectors depended on the direction of the X-ray beam. The MSO detectors are superior to the chamber for phantom dosimetry, owing to their small size. However, they require more careful calibration than does the chamber.

If the sensitivity of the MSO detectors is not precisely determined, relatively large errors will be introduced into doses determined by TLD. For example, the average sensitivity factor provided by the following simple experiment cannot always be used: the chamber and detectors are exposed to 100 mR X rays using a 100 kVp tube voltage, when the direction of the X rays is perpendicular to the central axis of each detector. The doses evaluated by the TL intensity may have involved several systematic errors, such as i) +12% when the exposure was 20 mR (Figure 1), ii) +10% when 40 to 50 kVp tube voltage was used (Figure 2), iii) ±7% for a relatively sensitive or insensitive detector (Figure 4), iv) –20% for the X-ray beams in parallel with the central axis of each detector (Figure 6), and v) ±12% when the heating plate is different from that used for determining the average response value (Table 4).

Proper determination of the sensitivity factors for each detector is therefore necessary to minimize these systematic errors.

In addition to the errors mentioned above, several sources of error relate to the sensitivity, but these are negligible. Some of them were assessed as follows: The sensitivity of MSO detectors to X rays decreased following numerous experiments; however, no change in sensitivity was observed until the detectors had been used about 50 times. In this experiment, the time from annealing to measurement was less than two days and the exposures to be measured were adjusted to greater than 20 mR. The fading effect was negligible as shown in Table 3 and Figure 3. The background after two days was consistently less than 20 nC, corresponding to about 2 mR. The background was always measured and subtracted, but the subtraction never resulted in large errors. Nakajima[11] reported that MSO phosphors are sensitive to visible light. Therefore, during the present dosimetry assessment, the MSO phosphors were stored in plastic cases and shielded from visible light sources. Thus, no corrections for illumination effects were required. Although the energy distribution of X rays may be altered due to scattered X rays, the difference in sensitivity caused by backscattered X rays was relatively small, as shown in Figure 5. Diagnostic X rays are produced using lower X-ray tube voltages, compared with therapeutic X rays. Scattering of diagnostic X rays scarcely altered the original energy distribution.

This study concerned only diagnostic X-ray dosimetry. The MSO detectors calibrated in this study were considered suitable for that purpose. In the low dose region (20 to 100 mR), we confirmed that the sensitivity of the MSO detectors was not constant for 100 kVp X-rays. This characteristic is important for precise measurements of diagnostic X-ray doses. Yamamoto and Kaga[14] also measured the sensitivities to X-rays and gamma rays. Since their thermoluminescence readout system and standard ionization chamber were different from those we used, the characteristics of MSO detectors they studied differed from those reported here.

We have not studied the characteristics of MSO detectors for high-energy X rays and gamma rays. They have already been assessed by Higashida et al,[15] who measured the sensitivities of a set of MSO detectors to high-energy X rays (250 kVp) in a high exposure range (2.5 to 170 R). They showed that the MSO detectors are also suitable for measuring doses during radiation therapy.

Our results indicate that these detectors are advantageous, especially for measuring absorbed doses from diagnostic X-ray exposures, since they permit measurements in the low dose range from 0.2 to 50 mGy. Their sensitivities depend on photon energy, but the energy of the scattered X rays scarcely differs from that of direct diagnostic X rays. The TLD responses are closely reproducible; for example, the standard deviation of TLD readings for gamma-ray exposures by a ^{60}Co source was consistently less than 3%. This reproducibility is better than that of the output of the X-ray equipment used, the relative deviation of which sometimes exceeded 5%. Thus, the error in the exposures evaluated can be controlled well, provided the sensitivity of each detector to X rays is determined while controlling the exposure range, tube voltage, the anode effect of the X-ray apparatus, the direction of the X-ray beam, and the condition of the planchet.

In the future, the radiation doses to several human organs during diagnostic X-ray examinations will be estimated using the MSO detectors evaluated in the present study.

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