Evaluation of effective dose for a patient under Ga-67 nuclear examination using TLD, water phantom and a simplified model

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This study evaluated the effective dose of Ga-67 for a patient undergoing Ga-67 citrate nuclear examination by applying thermoluminescent dosimeter (TLD) technique and an indigenous water phantom. The Ga-67 radionuclide remaining in the body inevitably generated a measurable internal dose even though gamma camera scanning took only minutes to complete the clinical examination. For effective simulation of the cumulated effective dose for a patient undergoing examination, 150 TLDs were placed inside the water phantom for 6 days to monitor the gamma ray dose from the distributed Ga-67 citrate solution. The inserted TLDs represented internal organs, and the effective dose was calculated according to data in the ICRP-60 report. The water phantom was designed to model the body of a healthy human weighing 70 kg, and the water that was mixed with Ga-67 citrate solution was slowly replaced with fresh feed water to yield the required biological half life of the phantom. After continuously feeding in fresh water throughout the 6 days of TLD exposure, the TLDs were analyzed to determine the effective doses from the various biological half lives of the phantom. The derived effective dose of 185 MBq Ga-67 citrate solution for male/female (M/F) was 10.7/12.2, 10.7/12.0, 8.7/9.9 and 6.0/6.8 mSv, of biological half lives of 6.0, 4.5, 3.0 and 1.5 days, respectively. Although these experimental results correlated well with earlier empirical studies, they were lower than most calculated values. The cumulated uncertainty in the effective dose was 12.5–19.4%, which was acceptable in terms of both TLD counting statistic and reproducibility.

Keywords: water phantom; internal dose; TLD, transient equilibrium; dose verification

INTRODUCTION

To evaluate the effective dose of Ga-67 for a patient undergoing Ga-67 citrate nuclear examination, this study used an indigenous water phantom, the thermoluminescent dosimeter (TLD) technique and a simplified model. Unlike X-ray diagnosis, in which the patient is passively and only momentarily exposed to low-dose X-rays, gamma camera scintigraphy exposes the patient to a high internal dose. Patients who undergo nuclear examination are initially injected with a compound solution containing a specific radionuclide before being scanned with a gamma camera to obtain scintigraphy images for clinical diagnosis. Although nuclear examination requires only minutes for data acquisition, excretion of the radioactive solution may take days. Until it is eventually excreted by metabolic mechanisms, the radioactive solution remains in the bodies of patients after they undergo Ga-67 nuclear examination. Studies of this topic in recent decades have developed many theoretical simulations of the cumulative dose of radioactive nuclides since each nuclide has a unique radioactive fingerprint. Although most theoretical studies of this issue have applied the medical internal radiation dose (MIRD) calculation model, their conclusions are highly variable [1–10]. Practical studies of internal dose are rarely performed and their results are even more inconsistent.
The disagreements among both theoretical and practical investigations may result from incorrect research assumptions or oversimplifications.

The many radionuclides used for clinical diagnosis include the radiopharmaceutical $^{67}$Ga-citrate, which was originally developed for bone scintigraphy before later being applied in diagnosing malignant lymphomas, hepatic tumors and melanomas [16]. Patients who undergo routine nuclear examinations must wait 3 or 4 hours after receiving an initial injection of 185 MBq Ga-67 citrate solution so that the radio-labeled solution can adequately disperse in the body and enable data collection. Therefore, this study effectively simulated this unique situation by using an indigenous water phantom for precise modeling of the Ga-67 nuclear examination process. After sealing and placing several hundred well-calibrated TLD-100s in the phantom for several days to obtain the cumulative gamma ray dose in the represented organ locations, the ICRP-60 report is used to calculate the effective dose. The TLD is calibrated by either practical measurement or by theoretical computation in a preliminary study, since TLD in water must be specifically considered. A simple model based on the transient equilibrium in the radionuclide chain decay theorem is used to calculate the effective dose. The model assumes that the biological-half-life of the Ga-67 citrate solution determines the internal dose accumulation. That is, the model calculates the effective doses based on the biological half-lives of the Ga-67 radionuclide.

### EFFECTIVE DOSE

The ICRP committees have been quantifying personal radiation doses for many decades. In 1990, ICRP-60 [17] defined effective dose, $E$, as the quantity surveyed by personal dosimetry, which is calculated as

$$E = \sum \omega_T \times H_T$$

(1)

Where $\omega_T$ is a tissue or organ weighting factor and $H_T$ is the tissue or organ equivalent dose, which is given by:

$$H_T = \sum \omega_\gamma \times D_{T,\gamma}$$

(2)

Where $\omega_\gamma$ is the weighting factor of the incident radiation and $D_{T,\gamma}$ is the mean dose of incident radiation of type $\gamma$ absorbed by the organ or tissue $T$; that is, the effective dose can be determined directly by multiplying the equivalent dose for each organ or tissue by the corresponding weighting factors [Eq. 2].

In ICRP-26, $\omega_T$ values were specifically assigned to only six organs. For analytical purposes, the five organs that received the next highest dose equivalents were combined into a pseudo-organ called the ‘remainder’ [18]. In ICRP-60, the number of organs that were assigned $\omega_T$ values was much larger, and previous values of $\omega_T$ were updated as the understanding of cancer risk from exposure of these organs to radiation improved. The pseudo-organ, ‘remainder’, was also re-defined in ICRP-60 and defined as ten specific organs. Since the $\omega_T$ values of the various organs were independent of $H_T$ delivery, the ICRP-26 definition of $H_E$ can be extended to include updated values of ICRP-60 $\omega_T$, which increases accuracy when estimating $E$.

### EXPERIMENT

This work evaluated the effective dose, $E$, of Ga-67 citrate in a Ga-67 citrate nuclear examination of an adult patient of either gender. Each organ or tissue of interest was assigned a $\omega_T$ value based on three to five TLD-100s. The counts were then used to calculate the effective dose based on the equivalent dose for each organ or tissue (Eqs 1–2).

**Water phantom**

Figure 1 shows the graph (A) and the actual water phantom (B) used herein. The computerized plot shows the fine structure in a precise scale of the water phantom. The phantom, which was designed to model a 70-kg human body (including thoracic, abdominal and pelvic cavities) consisted of an elliptical acrylic (polymethylmethacrylate, PMMA) box (700 mm high, with a major elliptical axis of 200 and a minor axis of 100 mm) containing 44.0 kg of water (mass = $20 \times 10 \times 70 \times \pi \times 0.001 = 44.0$ [kg]). Figure 1 clearly shows that the feed water tube was inserted through the tube in the center of the top of the

Fig. 1. (A) The computerized plot of the water phantom, (B) the water phantom that was used herein. The phantom was an elliptical acrylic (polymethylmethacrylate, PMMA) box (700 mm high, with a major elliptical axis of 200 and a minor axis of 100 mm).
The overflow then flows from the drain tube on the top-tail of the box. The feed water can be adjusted to model various human metabolic mechanisms. For example, continuously filling the box with feed water at 5 cm³/min was equivalent to replacing half of the water phantom in 3.05 days \((22,000 \text{ cm}^3) / (5 \text{ cm}^3/\text{min.} \times 60 \text{ [min/h]} \times 24 \text{ [h/day]}) = 3.05 \text{ [day]}\). The feed water input must be precisely controlled because the residence time of radioactive Ga-67 citrate solution in the phantom determined the internal dose. Therefore, the feed water input to the phantom was precisely controlled with an automatic infusion device used for clinical intravenous infusion.

An actual gamma camera scan of a male body (76 kg, 172 cm, BMI = 25.7) was inspected to determine whether the indigenous water phantom could effectively simulate the human body undergoing nuclear examination. The image was obtained by a 10 min scan of a male patient performed 4 h after the patient had been injected with 148 MBq of Ga-67 citrate solution. Figure 2 clearly shows that the counts/pixels in the (0) stomach, (1) lumbar-spine, (2) liver and (3) whole body (regions of interest, ROI, 0, 1, 2 and 3) were (0) 10.2 \((3661/360 = 10.2)\), (1) 16.6 \((5960/360 = 16.6)\), (2) 21.5 \((7734/360 = 21.5)\) and (3) 11.4 \((580733/50720 = 11.4)\), respectively. The indigenous water phantom defined the body in terms of thoracic, abdominal and pelvic cavities. The variation in count/pixel values was negligible throughout the body even though the count/pixel was higher in a few critical organs than in other regions. However, the simplified model confirmed that the human body could still be represented as a homogenous body of water in which Ga-67 citrate solution was well distributed since large variations in the acquired count/pixel were limited to only a few regions and to a comparatively short time during the actual gamma camera scan.

**Preliminary survey of biological half life**

A preliminary survey was performed to evaluate the biological half-life of the Ga-67 radionuclide in six patients (2M/4F, ages 25–50 years). The Ga-67 citrate nuclear examination in each patient was performed by rapid screening with a gamma camera (SIEMENS E. CAM) at Chung Shan Medical University Hospital (CSMUH). The ROI in each patient was the neck to the thigh, and the counting protocol was a 10-min scan performed 30 min after injection with the Ga-67 citrate solution followed by 30-min scans every 12 h for 3 days. Therefore, six sets of counts/pixel data were obtained as a function of elapsed time. The biological half-life, \(T_B\), of the Ga-67 radionuclide in the whole body of each patient could thus be determined. The average \(T_B\) derived for the whole body (defined as ROI 3 in Fig. 2) was 1.86 ± 0.45 days (max \(T_B\): 2.63 days, min \(T_B\): 1.38 days). Additionally, Arsos et al. reported a 4.9-day biological half-life for intravenously injected Ga-67 citrate solution [19]. Another study of human metabolic mechanisms by Priest et al. reported a 4.7-day biological half life [20]. Thus, \(T_B\) was adjusted to 1.5, 3.0, 4.5 and 6.0 days, respectively, to obtain the practical effective dose in this work.

**TLD calibration**

Calibration was performed by placing 150 TLD-100s (LiF: Mg, Ti) \((3 \times 3 \times 0.9 \text{ mm}^3\), Harshaw) in the center of a spherical water tank (diameter, 40 cm) for 24 h and then recording radioactive emissions from the TLD readout system. The absorbed dose \(D_T\) of the TLD at that position after a fixed period, \(t\), was calculated by a simplified Eq. 3 [21] or by a theoretical simulation performed using MCNP code [22].

\[
D_T(t) = \sum_{i=1}^{n} \phi_i \times E_i \times I_i \times \left( \frac{\mu_i}{\rho} \right)_{abi} \times \frac{1 - e^{-\mu_i t}}{\mu_i} \times \frac{1 - e^{-\lambda t}}{\lambda} \quad (3)
\]

Where \(\Phi\) is the beam flux and \(E\) is the gamma ray energy of the Ga-67 radionuclide. The \(I_i\) is the branching ratio of
the specific gamma ray energy. The \((\mu/\rho)\) and \(\mu_i\) are the real mass absorption coefficient and linear attenuation coefficient of water, respectively, at a particular gamma ray energy. The decay constant \(\lambda\) is defined as the reciprocal of only the physical half-life of the Ga-67 radionuclide because the biological half-life of this radionuclide is zero under these conditions. Table 1 presents the actual Ga-67 radionuclide data used to calculate the absorbed dose.

Table 1 clearly shows that the outcome based on the MCNP estimate, 3.10E-8 Gy/s, exceeds that based on the simplified equation, 2.41E-8 Gy/s, since the equation does not consider auger electrons, delta rays or Compton electron scattering mechanisms. However, the simplified equation still provides useful data for determining the lowest absorbed dose.

### Data collection

The water phantom was divided into equal sections separated by three horizontal planes (coronal cross sections). On all planes, acrylic hooks installed on both sides of the inner wall of the phantom at 10-cm intervals across each plane were tied together with plastic string to form a web system for holding the TLDs (Fig. 1). Figure 3 presents the precise positions of the TLDs in each coronal cross section. Three to five TLDs were separately sealed inside two layers of waterproof polyethylene (PE) bags before being placed inside the phantom to monitor radioactivity in internal organs or tissues.

After loading the TLDs, the phantom was filled with 44.0 kg fresh water. A Ga-67 citrate solution with a radioactivity of 74 MBq was then added through the tube at the

| \(E\) (MeV) | \(I_i\) (%) | \((\mu/\rho)_i\) (cm\(^2\)/g) | \(\mu_i\) (cm\(^{-1}\)) | Center dose (Gy/s) |
|------------|-------------|------------------------|----------------|------------------|
| 0.091      | 3.07        | 0.0259                 | 0.1895         | 4.00E-10         |
| 0.093      | 37.80       | 0.0258                 | 0.1878         | 5.02E-09         |
| 0.185      | 20.90       | 0.0291                 | 0.1416         | 6.01E-09         |
| 0.209      | 2.37        | 0.0299                 | 0.1347         | 7.87E-10         |
| 0.300      | 16.80       | 0.0319                 | 0.1161         | 8.41E-09         |
| 0.394      | 4.66        | 0.0327                 | 0.1039         | 3.11E-09         |
| 0.484      | 0.07        | 0.0330                 | 0.0954         | 5.66E-11         |
| 0.703      | 0.01        | 0.0325                 | 0.0819         | 1.32E-11         |
| 0.794      | 0.05        | 0.0321                 | 0.0779         | 6.92E-11         |
| 0.888      | 0.15        | 0.0316                 | 0.0744         | 2.16E-10         |
| **Sum**    |             |                        |                | **2.41E-08**     |
| **MCNP simulation** |  |                        |                | **3.10E-08**     |

Fig. 3. The precise positions of the TLDs in each coronal cross section (A) upper, (B) medium and (C) bottom. Three to five TLDs were separately sealed inside PE bags, which were placed in another water-proof PE bag inside yet another water-proof bag before being placed inside the phantom to monitor the radioactivity of the internal organ or tissue.
center of the top of the phantom (Fig. 1). After letting the Ga-67 citrate sit for 1 h to ensure a uniform distribution, fresh water was fed through the tube to replace the water mixed with the Ga-67 radionuclide in the preceding stage. Precise control of the amount of feed water injected by the automatic infusion device, which enabled adjustment of the half replacement time of the radioactive water inside the phantom to 1.5, 3.0, 4.5 and 6.0 days. The half replacement time of the radioactive water was effectively the biological half-life of the Ga-67 radionuclide in a standard -g male body. Increasing the half replacement time of the radioactive water increased the concentration of Ga-67 radioactive solution maintained inside the phantom and increased the resulting internal dose.

TLD readout
The exposed TLDs were measured and analyzed with a TLD reader (RA94, MIKROLAB) before annealing in a Barnstead International model 19200 at 400°C for 1 h followed by further annealing in a Barnstead International model 47900 at 100°C for 2 h. The reading of each exposed TLD was not recorded until 28 h later to ensure a stable TLD glow curve. The TLD counts were recorded by a read out system with a 2-s holding time and heated at a rate of 5°C/s to enable data acquisition over a temperature range of 50–180°C. The TLD readout system was optimized using the Taguchi method [23].

DATA ANALYSIS AND RESULTS

Error compiling
Table 2 shows the error for each derived effective dose, \( E \), for various biological half-lives, which was calculated as the square root of the sum of the squares of the individual errors, \( \Delta \). The uncertainty in \( \omega_T \) was defined as 5% because the weighting factor was normalized. The internal normalization errors for TLDs were obtained from the preliminary survey of all TLDs. Since the phantom consisted of only pure water, the uncertainty associated with non-tissue equivalence effects of the water phantom was defined to a maximal 10%. The specific value of uncertainty was estimated from the weighted average of the various organ volumes [24, 25].

Because the non-tissue equivalence effects are related to variation in Compton scattering electrons used to determine doses for the soft tissue, rib or spine in the phantom, they may result in inaccurate estimates of the scattering effect. This effect can be estimated by a Monte-Carlo simulation of a digital homogeneous or heterogeneous phantom exposed to a similar gamma ray field. The total error was dominated by the statistical error in counting, which could be suppressed by repeated measurements. Averaging the data from three independent trials obtained a maximum counting statistical error and total error of 11.6% and 19.4%, respectively.

Effective dose
Table 3 presents the effective dose, \( E \), which was determined according to the various set biological half-lives of the 74-MBq Ga-67 citrate solution used in the nuclear examination. The tissue weighting factors, \( \omega_T \), for the various internal organs or tissues are also presented. The effective dose, \( E \), was determined by multiplying \( \omega_T \) by the corresponding equivalent dose, \( H_T \), which was itself obtained by multiplying each TLD count by the relevant calibration factor. The use of similar exposure conditions based on preliminary measurements simplified the conversion of TLD counts into specific equivalent doses for each organ of interest.

DISCUSSION

Comparisons with \( E \) values obtained elsewhere
Table 3 shows that the effective dose, \( E \), was derived using a 6-day counting period and then extended to infinite time by multiplying it by the correction factor (CF) obtained by Eq. 4.

\[
CF = \frac{1 - e^{-\lambda t_c}}{\lambda} / \frac{1 - e^{-\lambda t_c}}{\lambda} = \frac{1}{1 - e^{-\lambda t_c}}
\]

Where \( t_c \) is the counting period, which was 6 days, in this investigation, and \( \lambda \) is the decay constant for each of the effective half lives, \( T_E \). CFs were 1.02, 1.07, 1.12 and 1.16 for \( T_E \) values of Ga-67 of 1.03, 1.56, 1.89 and 2.11 days, respectively. The corresponding \( T_B \) of the water phantom was adjusted to 1.5, 3, 4.5 and 6 days based on the decay constant \( \lambda \) obtained by Eq. 4. Apparently, the short \( T_B \) of the
phantom results from the small correction factor since activity inside the phantom is minimal after 6 days. Therefore, the CF values used to obtain the internal doses are negligible.

Table 4 shows how the effective doses calculated using various biological half lives are revised by applying the CFs. The table includes effective doses obtained in other studies for comparison. Both Dr Saha [12] and Dr Stabins [13] used the MIRDDOSE code [26] to perform simulations, whereas Shanehsazzadeh et al. [14, 27] used the MIRDOSE code and verified the results in rat studies before extrapolating the effective dose to humans. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [15] estimated the effective dose by reviewing medical case reports throughout the United States and determined the effective dose as a function of the weight of the patient. Patients weighing 70, 55, 33, 18 and 10 kg had effective doses of around 18.5, 23.3, 28.1, 28.5 and 34.4 mSv, respectively, in Ga-67 citrate nuclear examination. The derived effective doses herein are consistent with the results reported by both Saha [12] and Shanehsazzadeh [14] but are lower than those reported by Stabin and those recommended by UNSCEAR. A study by Shanehsazzadeh also reported a low effective dose of 5.26 mSv in a recent study performed using a similar approach [27].

**Simplified one group model of human body for evaluating effective dose**

Theoretical simulations yield highly controversial estimates of the radioactive effective dose; $E$, even though they all are based on the same MIRDOSE code. In contrast, the practical method applied using the water phantom and TLDs herein yields effective doses with the required confidence. The phantom is designed to model the human body as a homogenous volume of water, despite the presence of Ga-67 citrate solution in various organs. However, this simplified dose evaluation method enables the use of the TLD method to determine the radioactive internal dose required for a patient undergoing nuclear examination.

The simplified model assumes that the residence time of the Ga-67 radionuclides in various organs is directly related to the transient equilibrium phenomenon described by the
chain decay theorem. This assumption is also supported by the finding reported by the Society of Nuclear Medicine [29] based on consecutive evaluations of patients that 10–25% of the injected dose is excreted by the kidneys during the first 24 h after injection. The main excretion route then changes to the gastrointestinal tract. By 48 h after injection, about 75% of the injected dose remains in the body and is equally distributed among the liver, bone and bone marrow, and soft tissues. Accordingly, the whole body and a series of internal organs, which are defined according to the bio-kinetic model, can be interpreted as the parent compartment and the series of daughter compartments along the same decay chain. Unlike the secular equilibrium in the parent compartment, which has an extremely long decay half-life; the transient equilibrium exists in the bio-kinetic model when the effective half-life of the parent compartment is ten-fold that of the daughter compartment; the activity of the daughter compartment is maximal at time $t_{\text{max}}$. The subsequent decay associated with the effective half-life of the parent is given by Eq. 5 [30].

$$A_d = \lambda_d N_d = \frac{\lambda_d}{\lambda_d - \lambda_p} \cdot A_p = \frac{\lambda_d}{\lambda_d - \lambda_p} \cdot \lambda_p N_p;$$

$$t_{\text{max}} = \frac{\ln \lambda_d - \ln \lambda_p}{\lambda_d - \lambda_p}$$

(5)

Where $\lambda_d \cdot [\ln 2/T_E(d)]$ and $\lambda_p \cdot [\ln 2/T_E(p)]$ are the decay constants of the daughter (internal organ) and parent (whole body) compartments, respectively. The effective half-life equals the reciprocal of the sum of the reciprocal of the biological half-life and that of the physical half-life ($T_E^{-1} = [T_B^{-1} + T_R^{-1}]$). Therefore, change in the biological half-life of the whole body (parent) compartment determines overall performance since the physical half-life of Ga-67, $T_R$, is fixed at 78.2 h.

The MIRD-3 code indicates that most daughter compartments have biological half-lives of 1–10 h. For example, the biological half-lives in the stomach, small intestine and upper large intestine are 0.7, 2.7 and 9.2 h., respectively. Therefore, for the internal organ, $t_{\text{max}}$ is 4.4–19.3, 5.4–26.0, 5.6–28.0 and 5.8–29.2 h for Ga-67 biological half-lives of 1.0, 3.0, 4.5 and 6.0 days, respectively [Eq. 5]. Specifically, $t_{\text{max}}$ equals either 4.4 or 19.3 h if (i) the biological half-life of Ga-67 in the internal organ (daughter) is either 1 or 10 h, respectively, and if (ii) the biological half-life of the whole body (parent) is 1.0 day [$T_E(p)/T_E(d) = 18.4$ or 1.8]. In contrast, the $t_{\text{max}}$ increases to 5.8 and 29.2 h if the biological half-life of the whole body (parent) is extended from 1.0 day to 6.0 days, respectively. Restated, stabilization of transient phenomenon in the first 1.5 days (~36 h) is followed by decay of the whole body compartment (parent) even in the worst case of dangling ($t_{\text{max}} = 29.2$ h; the biological half-life in a particular internal organ and the whole body is 10 h and 6 days, respectively [$T_E(p)/T_E(d) = 5.9$]). The 150 TLDs were left inside the water phantom for 6 days, which is longer than the $t_{\text{max}}$ for most

| Team | Type | Method | Object | $E$ (mSv/185 MBq) |
|------|------|--------|--------|------------------|
| Saha [12] | Ga-67 citrate | MIRDOSE 3 | Human | 13.0 |
| Stabin et al. [13] | Ga-67 citrate | MIRDOSE 3 | Human (M/F) | 18.5/22.2 |
| Shanehsazzadeh et al. [14] | Ga-67 DTPA-ACTH | MIRDOSE 3 & animal base | Extrapolating from rat to human (M/F) | 10.1/10.3 |
| Shanehsazzadeh et al. [27] | Ga-67 cDTPA-GnRH | animal base | Extrapolating from rat to human | 5.26 |
| UNSCEAR [15] | Ga-67 citrate | N/A | Human | 18.5–34.4 |
| MIRD [28] | Ga-67 citrate | MIRDOSE 3 | Human | 13.0 |
| SNM [29] | Ga-67 citrate | MIRDOSE 3 | Human | 22.2 |
| **This work** | Ga-67 citrate | TLD | Phantom | 6.0/6.8 |
| | | | $T_E = 1.03$ days (M/F) | |
| | | | $T_E = 1.56$ days (M/F) | 8.7/9.9 |
| | | | $T_E = 1.89$ days (M/F) | 10.7/12.0 |
| | | | $T_E = 2.11$ days (M/F) | 10.7/12.2 |

Ga-67 nuclear examination via TLD technique
of the cases considered herein. Accordingly, the fluctuation of the gross activity of Ga-67 radionuclides in any specific daughter compartment generates an acceptable uncertainty in the real measurement. Although the simplified hypothesis assumes that a single compartment of a body structure may not apply clinically in an actual human body, the obtained data are highly consistent and reproducible.

**Isodose plot inside the water phantom**
The water phantom is filled with water mixed with Ga-67 citrate solution to model a 70-kg human body undergoing an actual nuclear examination. After keeping the phantom stationary for 1 h to ensure uniform distribution of the radioactive solution, water is fed into the system. Since the filling tube extends from the center top of the phantom to the bottom of the phantom (Fig. 1), the fresh feed water diffuses slowly toward the drain tube. Diffusion in the water phantom may cause the original radioactive solution to accumulate gradually near the drain tube before it overflows. In an actual human, however, biological excretion through the kidney and bladder represents a unique internal diffusion mechanism.

Figure 4 presents several isodose curves in both the coronal and the sagittal directions. The dose is highest near the tail of the middle coronal and near the central sagittal images. Most of the high doses are near the center of the bottom of the phantom since the diffusion mechanism determines the distribution of the dose therein.

**TLD glow curve of Ga-67**
A glowing curve was plotted according to the recorded TLD counts and responded uniquely to temperature from the TLD readout device. The TLD is sealed in two waterproof PE bags before being placed in the water phantom. Therefore, the TLD is exposed to the radioactivity of the ambient Ga-67 citrate solution. Since the water solvent either moderates or attenuates the incoming gamma rays under these conditions, the original glow curve of the TLD exposed only to the radioactivity of Ga-67 in the air is deformed. Figure 5 plots three glow curves of a single TLD.
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The Compton-scattered electrons. In contrast, the directly received gamma rays are also converted into several Compton-scattered electrons, and the transfer of their energy to the TLD molecular structure is clearly reduced as indicated by the temperature response curve ([high–high peaks] dotted line in Fig. 5, glow curve of TLD in water). The Compton-scattered electrons dispersed widely inside the molecular structure of a TLD with more straggling energy compared with those attenuated with only an acrylic plate [23, 31].

Because of the unique plot of the TLD glow curve of the Ga-67 citrate solution, optimization of the TLD readout settings is critical in an actual TLD count. An inappropriate setting may cause an error when recording the TLD glow curve, which can generate an erroneous count–dose calibration curve.

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