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EXTENSION OF THE RADTRIAGE COLORIMETRIC DOSIMETER TO LOW DOSE GAMMA-RAY EXPOSURE USING SCANNING DENSITOMETRY

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Abstract

There is a need for an instantly indicating, easy-to-read, and inexpensive ionizing radiation dosimeter for first responders and members of the general public. One commercially available option is the RADTriage50™ colorimetric dosimeter. However, existing literature has not adequately addressed the accuracy of RADTriage50 dosimeters at low doses of ionizing radiation (<50 mSv) or the need for methods to quantitatively read the RADTriage50 dosimeters after they are exposed. In this paper, we use digital scanning methods to read the RADTriage50 dosimeters. The performance of the dosimeters was evaluated by irradiation with a gamma irradiator traceable to national standards. Experiments covered a range of deep dose equivalents (50 mSv to 2,000 mSv) within the manufacturer's specified range (50 mSv to 4,000 mSv) and also below 50 mSv to determine if the digital scanning densitometry method allowed for a quantitative readout with a greater dynamic range. We also conducted tests using different gamma energies, ^{137}Cs (662 keV) and ^{60}Co (1.17 and 1.33 MeV), and different dose rates, to evaluate the dependency of the RADTriage50 dosimeters on these parameters. Modeling of our measurements suggests that the dose-response of the RADTriage50 dosimeter is linear at low doses with strong non-linearity beginning at ~750 mSv and the dosimeter response appearing to plateau at ~2000 mSv, although additional measurements at doses beyond 2000 mSv are needed to confirm this finding. We also found that the RadTriage50 dosimeter response varied with gamma energy, but not with dose rate.

Keywords

personnel dosimetry; emergency planning; external dosimetry; dose assessment

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INTRODUCTION

Currently, it is not common for first responders to carry radiation dosimetry devices. Training requirements, hardware space, and cost are all obstacles to wider deployment of dosimetry devices (Klemic et al. 2007; Brodsky 2010). When dosimeters are used, thermoluminescent dosimeter (TLD) badges are the most frequently chosen device, as they are small, lightweight, and do not require user interaction. However, TLD badges do not allow for any real-time dose estimation because specialized laboratory instruments are needed for dosimeter readout. Furthermore, the operational expertise required to operate a TLD program with appropriate calibrations can be quite burdensome. For this reason, emergency management stakeholders have interest in finding alternative dosimeters to address the unique needs of first responders. Colorimetric ionizing radiation dosimeters are a potential solution because they can provide first responders with an immediate visual indication of their radiation dose while working in the field.

One such commercially available dosimeter is the RadTriage Model 50 colorimetric dosimeter card (RADTriage50™) manufactured by JP Laboratories Inc. (Middlesex, NJ) which is marketed as an acute dose monitor in the operability dose range of 50 to 4000 mSv and is currently available through online marketplaces for approximately US$21. The dosimeter contains a sensor strip which darkens upon exposure to ionizing radiation. As the lowest color scale indicator on the card is for 50 mSv, readings below 50 mSv are not possible by eye. However, in many radiation emergency scenarios it is likely the first responder will receive an exposure less than 50 mSv and it is unclear whether scanning densitometry could be used to perform quantitative readings within, or perhaps even below, the manufacturer specified dose range after returning from the field (Stewart 2005; Riel et al. 2006).

In this paper, we demonstrate a methodology for making quantitative readings of the RADTriage50 dosimeters. The RADTriage50 dosimeters were exposed to a known gamma-ray dose and readings of the colorimetric sensor were subsequently performed using a standard flatbed scanner. The sensitivity of the RADTriage50 dosimeters to gamma-ray energy and dose-rate were also explored. Similar experiments were conducted for TLD chips, the de facto gold standard, for comparison purposes. The results provide valuable information on the potential advantages and disadvantages of deploying the RADTriage50 dosimeters in an emergency response setting.

MATERIALS AND METHODS

RadTriage Model 50 dosimeters

The RADTriage50 dosimeter comes in the form of a flat card (8.5 cm long, 5.5 cm wide, 0.5 mm thick, weight 2 g) designed to fit in a wallet, pocket or badge holder (Fig. 1). The dosimeter relies on the radiochromic polymerization of diacetylenes, colorless monomers which link to form blue polymers upon exposure to ionizing radiation. The color development is cumulative and irreversible. Diacetylenes are also sensitive to ultraviolet light (UV), so the card is covered in a yellow protective plastic designed to filter much of the UV exposure. The combination of the blue polymer formation with the yellow plastic results

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in the sensor having a gray/green color after being exposed to ionizing radiation (Patel et al. 2007).

The RADTriage50 cards are intended to be read at cumulative x-ray or gamma-ray doses between 50 mSv and 4000 mSv. Visual readout is performed by comparing the gray-level of the sensor strip (running horizonal to the card) to adjacent color scale indicators (50, 100, 250, 500, 1000, 2000, and 4000 mSv). The RADTriage50 cards are generally stable in ambient environments. However, exposure to extreme temperatures can impact the cards; low temperatures do not drastically affect the sensor strip, but high temperatures (exceeding 50°C) can cause premature polymerization and may indicate a false positive. A fit indicator on the card provides a visual indication when the card is likely to be compromised or has expired due to shelf-life.

Dosimeter irradiation

The RADTriage50 dosimeters were irradiated using a Hopewell Designs Model GC 60-100 Gamma Beam Irradiator (GC-60) equipped with both a ^{137}Cs and a ^{60}Co source. The responses of the RADTriage50 dosimeters were compared to those of the Harshaw TLD-700H series TLD chips (LiF:Mg,Cu,P or LiF:MCP) manufactured by Thermo Fisher Scientific (Waltham, MA) which were irradiated simultaneously to allow for consistent comparison. A summary of the exposure conditions used for each irradiation is shown in Table 1. New RADTriage50 dosimeters and calibrated TLD chips were used for each set of measurements. For each irradiation, a total of seven RADTriage50 dosimeters and 10 TLD chips were fastened to an acrylic slab as shown in Fig. 2. The exposure rate for each experimental setup was calibrated using a spherical ionization chamber traceable to the National Institute of Standards and Technology (NIST). As the ionization chamber was calibrated in units of mR s^{-1}, a conversion factor of 1.21 was applied to get the deep dose equivalent in units of mSv shown on the card. The conversion factor was taken from the American National Standards Institute (ANSI) N13.11 criteria for testing personnel dosimetry performance (ANSI 2015) and accounts for backscatter from a whole-body phantom behind the dosimeters.

Dose-response analysis was conducted at 10 deep dose equivalent values between 0 and 2000 mSv using the ^{137}Cs source at a fixed distance of 100 cm, with the delivered dose being varied by controlling the exposure time. To test the limits of the RADTriage50 dosimeter, we included exposures at deep dose equivalents of 10, 20, 30, and 40 mSv which are below the lowest reference color indicator on the card. Additional irradiations were performed to examine sensitivity in the dosimeter response to dose rate by changing the source-to-dosimeter distance to 150 cm and 250 cm while keeping the total deep dose equivalent constant at 100 mSv. Energy sensitivity was evaluated by comparing the responses of the dosimeters to the ^{137}Cs source to that of the ^{60}Co source for deep dose equivalents of 50, 100, and 250 mSv at a fixed source-to-dosimeter distance of 100 cm.

RADTriage50 measurements by scanning densitometry

The RADTriage50 dosimeters were read using a flatbed color scanner (HP Officejet 6500) with a 2400 dpi optical resolution. Scans were conducted 20–24 hours after each exposure to

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allow for the complete chemical reaction to occur in the card sensor strips, consistent with other practices described in the relevant literature (Abdel-Fattah and Miller 1996; Deene et al. 2002; Chen et al. 2016). Each card was scanned five times, and an average densitometry value was taken for the last three scans as recommended by Chen et al. 2016. The resulting color images were analyzed using the software ImageJ (version 1.52a, National Institutes of Health, Bethesda, MD) for the average pixel density value, P, within a rectangular region of interest (ROI) centered on the RADTriage50 sensor strip. The pixel density value was calculated by averaging the 8-bit red, green, and blue color channels of each pixel within the ROI. The size of the ROI was kept consistent (75 pixels wide by 528 pixels length for a total of 39,600 pixels) and was selected to maximize the area of the sensor strip used for analysis while avoiding edges (Fig. 3). The average and standard deviation of the pixel density for each group of seven RADTriage50 dosimeters was calculated for each exposure setting. The change in pixel density, ΔP, was calculated by subtracting the average pixel density for a group of unexposed cards from the measured P value.

TLD measurements

The TLD chips were annealed on the day of each experiment to below 3 nC to reduce the effects of accumulated background radiation and then cooled for at least 30 minutes prior to irradiation. The chips were read using a QS Bicron Model 3500 thermoluminescence manual chip reader starting approximately 1 hour after exposure. A pre-measured element correction factor was used to correct the measurement made by each chip. The average and standard deviation of 10 chips were recorded for each exposure setting.

RESULTS

Dose-response analysis

The mean and standard deviation of the response for each group of dosimeters can be found in Table 2. The change in measured pixel density of the RADTriage50 sensor strip, ΔP, with dose, d, was modeled as:

$$\Delta P(\mathrm{d}) = \alpha\left(1 - e^{\frac{-\ln(2)d}{\beta}}\right) \quad \text{(Eq. 1)}$$

, where α and β are parameters which can be determined by fitting the data. The functional form of Equation 1 can be derived assuming the rate of depletion of the diacetylene monomers in the sensor strip with dose is proportional to the amount of colorimetric chemical remaining. The parameter α corresponds to the maximum change in the pixel density which occurs when the colorimetric chemical is fully depleted at large doses. The parameter β corresponds to the dose required for the diacetylene monomers to deplete by half. The minimum chi-square method of fitting the measurements to Equation 1 yielded a best a fit curve (r^2=0.998) with parameter values α=89.85 ± 2.05 mSv and β=385.18 ± 35.70 mSv.

The RADTriage50 dosimeters exhibited a strong non-linear response which the modeling suggests begins around 750mSv (Fig. 4) and the response appears to plateau around 2000 mSv, although additional measurements beyond 2000 mSv are needed to confirm this

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finding. The manufacturer specifies the maximum dose range of the dosimeters as being 4000 mSv. In contrast, the TLD chips exhibited a strong linear response between the 0 and 2000 mSv (r^2=0.996). The response of the RADTriage50 dosimeters was quite linear below 50 mSv (Fig. 5). However, the standard deviation in the RADTriage50 dosimeter response from repeated measurements was large compared to that of the TLD chips. The coefficient of variation for the RADTriage50 dosimeter measurements performed at doses between 10 and 50 mSv ranged from 50% to 279% versus 11% to 18% for the TLD chips.

Dose rate sensitivity

Sensitivity of the dosimeter response to dose rate was evaluated by calculating the ratio of the dosimeter response at a deep dose equivalent rate of 106.7 mSv hr^{-1} and 297.7 mSv hr^{-1} to that measured at 667.43 mSv hr^{-1} (Fig. 6). The calculated 95% confidence intervals for the response ratios did not suggest any significant difference in the response with dose rate for either dosimeter type.

Gamma energy sensitivity

Sensitivity to gamma ray energy was evaluated by calculating the ratio of the dosimeter response for the ^{60}Co to that of the ^{137}Cs for deep dose equivalents of 50, 100, and 250 mSv (Fig. 7). The response of the RADTriage50 dosimeters were consistently lower for the ^{60}Co source than for the ^{137}Cs source, with the 95% confidence intervals for the response ratios suggesting significant differences for the measurements performed at deep dose equivalents of 50 mSv and 250 mSv, but not at 100 mSv. In contrast, no statistically significant difference in TLD response was observed at any of the dose levels considered.

DISCUSSION

A key advantage of the RADTriage50 dosimeters is that, unlike the TLD badges, they can provide an immediate visual indication of the dose while in the moment of an emergency. A disadvantage is that the immediate visual readout depends on the visual acuity of the reader. However, our study has shown that a more reliable and observer-independent dose reading of the RADTriage50 dosimeter is also possible if the card is instead read by scanning densitometry. We tested the dosimeters up to a dose of 2000 mSv and our modeling suggests significant non-linearity begins around 750 mSv. While the response of the RADTriage50 dosimeters was quite linear below 50 mSv, the results of this study suggest that it will be difficult to reliably distinguish a deep dose equivalent of 10 mSv from that of 50 mSv when using a single RADTriage50 dosimeter. However, by measuring several cards, quantification of doses below 50 mSv could be feasible. This could happen if a first responder carried multiple cards. Conversely, if only one RADTriage50 dosimeter is assigned to each first responder, then a practical alternative might be to average the response of cards carried by different individuals performing similar activities (and presumably receiving similar deep dose equivalents). While we tested the dosimeters only up to 2000 mSv, quantification of doses between 2000 and 4000 mSv (the maximum of the manufacturer's specified range) is also expected to be challenging because the exponential fit of our measurements suggests that the change in pixel density in this dose range is likely to be small compared to

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variability in the response of a single dosimeter. This can be confirmed in the future by performing additional measurements at deep dose equivalents higher than 2000 mSv.

The heterogeneity of the radiation field in terms of energy and radiation type must also be carefully considered when interpretating the RADTriage50 dosimeter response. Our sensitivity analysis did not reveal any large, statistically significant change in either the RADTriage50 or TLD response when the dose rate was varied. The energy sensitivity analysis found small statistically significant differences in the response for the RADTriage50 dosimeter but not for the TLD chips. Lastly, deployment of the RADTriage50 dosimeter in a dirty bomb scenario would require consideration of the possibility of beta contamination on the card. While betas could deliver a substantial skin dose, they would not contribute to the deep dose equivalent. To eliminate any contribution of beta dose, one could encase the RADTriage50 dosimeters in a thick translucent plastic (~10 mm). Future research should also consider the angular response of the dosimeters. We can expect a first responder to be moving through a radiation environment, while the experiments in this study only considered head-on irradiation.

CONCLUSION

The results of this research indicate that the RADTriage50 dosimeter could be a useful tool for emergency first responders. RADTriage50 dosimeters provide an immediate indication of radiation dose, which would benefit first responders with little knowledge of dosimetry in the moment of exposure. For more quantitative results, RADTriage50 dosimeters could also be analyzed after an event using scanning densitometry. Key limitations of the RADTriage50 dosimeters are the large uncertainties in the response (especially below 50 mSv) and energy sensitivity. Therefore, a prudent choice would seem to be to use the RADTriage50 dosimeters in conjunction with TLD badges, rather than as a replacement. This would provide the first responder with the benefits of the immediate dose readings of the RADTriage50 dosimeters as well as the superior dose quantification offered by the TLDs. As with any dosimetry device, it will be important to train first responders on the proper use of RADTriage50 dosimeters as well as their limitations before deploying them in an emergency-response setting.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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The contents are solely the responsibility of the authors and do not necessarily represent the official views of their institutions. Certain commercial equipment are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the authors or their institutes, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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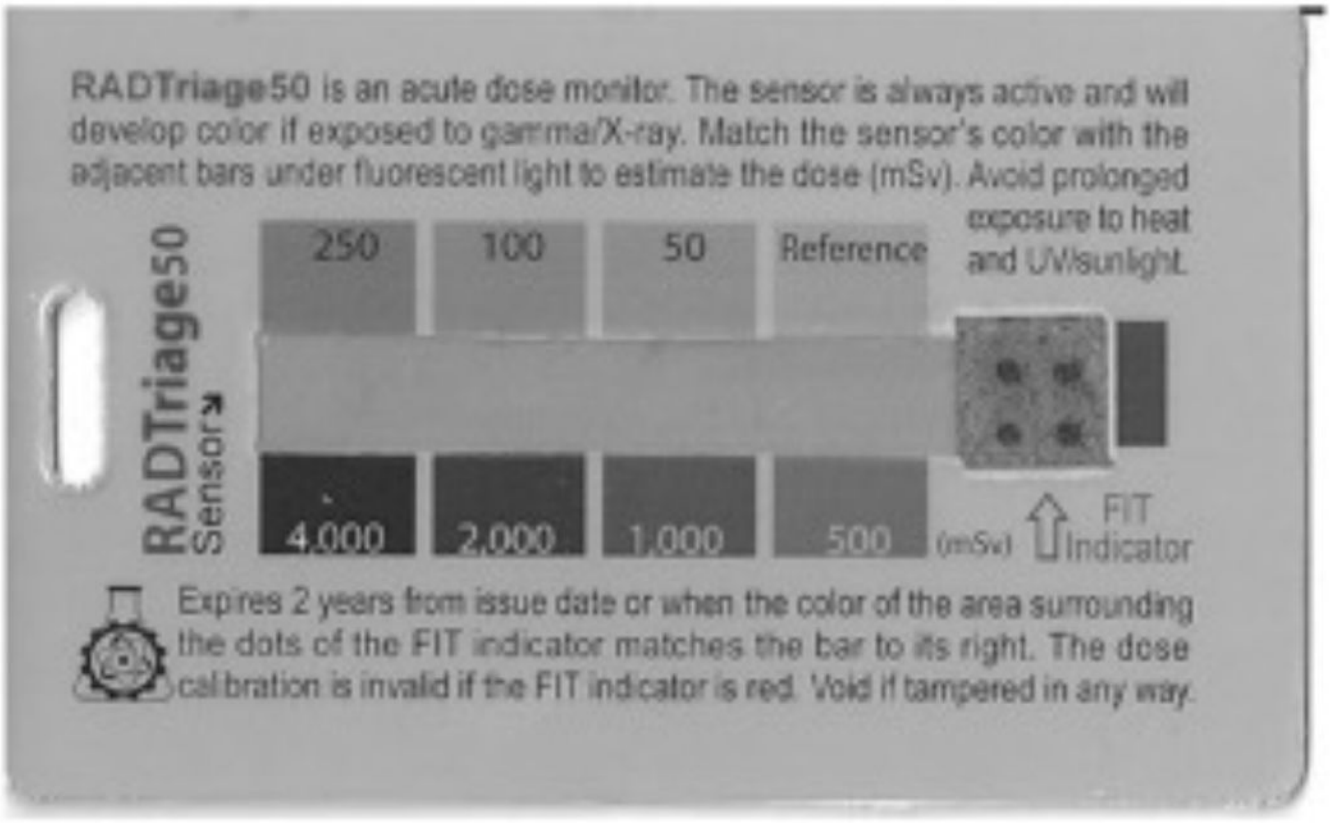


Fig. 1.
Photograph of the RADTriage50 colorimetric dosimeter.

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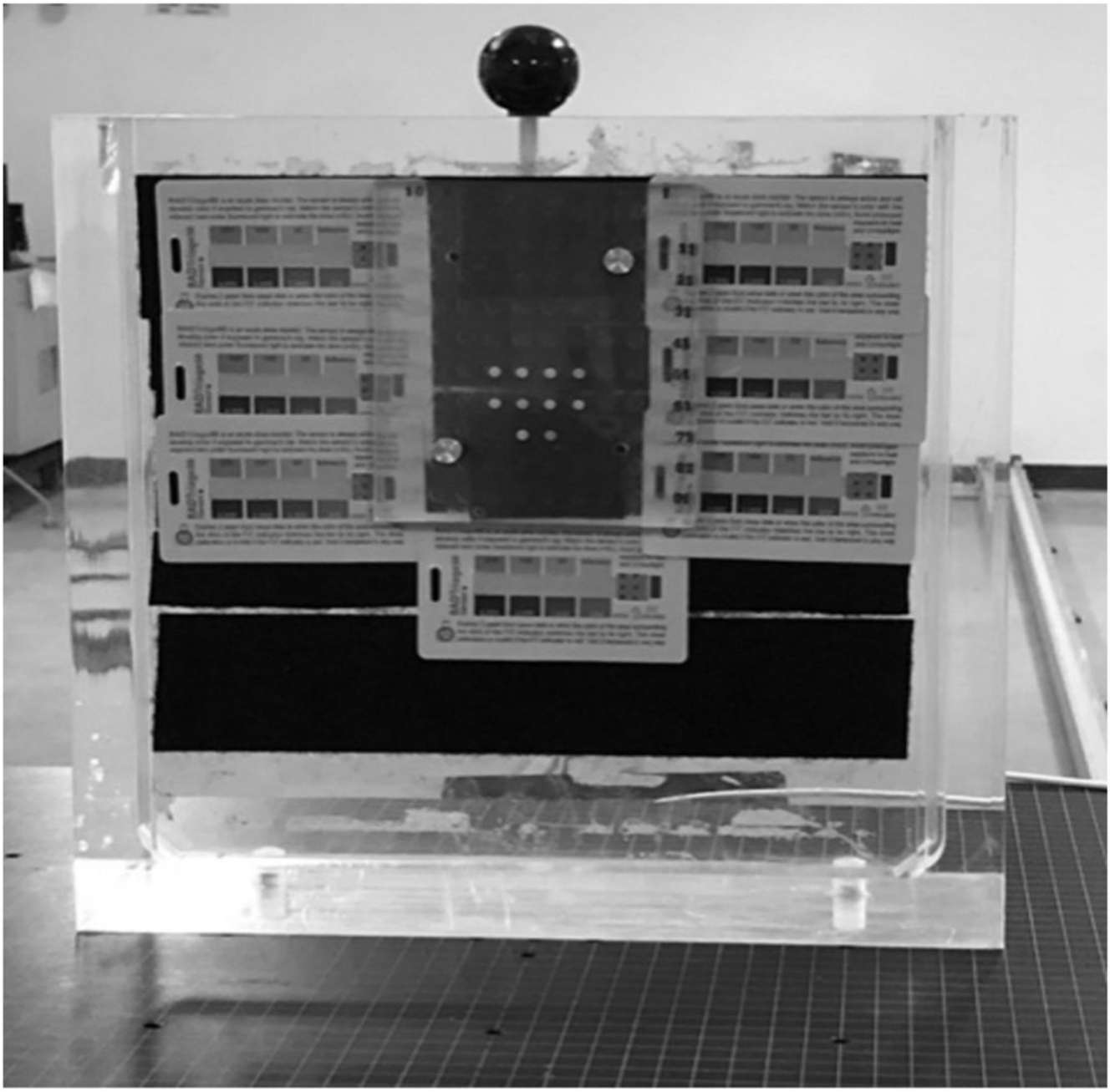


Fig. 2.
Photograph of the dosimeter setup used for each experimental irradiation. For each irradiation, seven RADTriage50 dosimeters and 10 TLD chips were fastened to an acrylic phantom.

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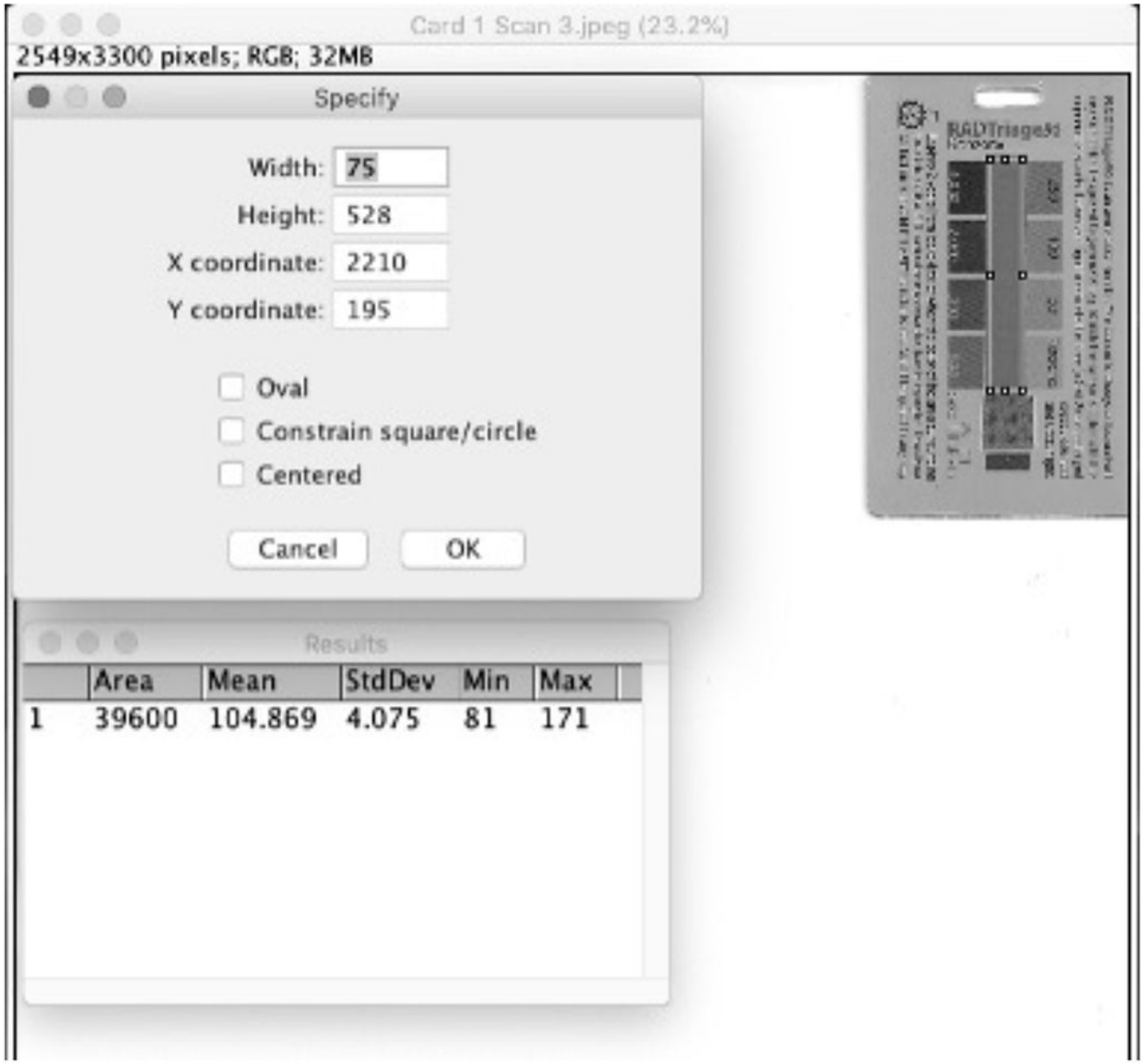


Fig. 3.

The RADTriage50 dosimeters were scanned, and the resulting images were analyzed using the ImageJ software. Gray-level analysis was performed on a rectangular region of interest placed on the sensor strip (shown as the green box above).

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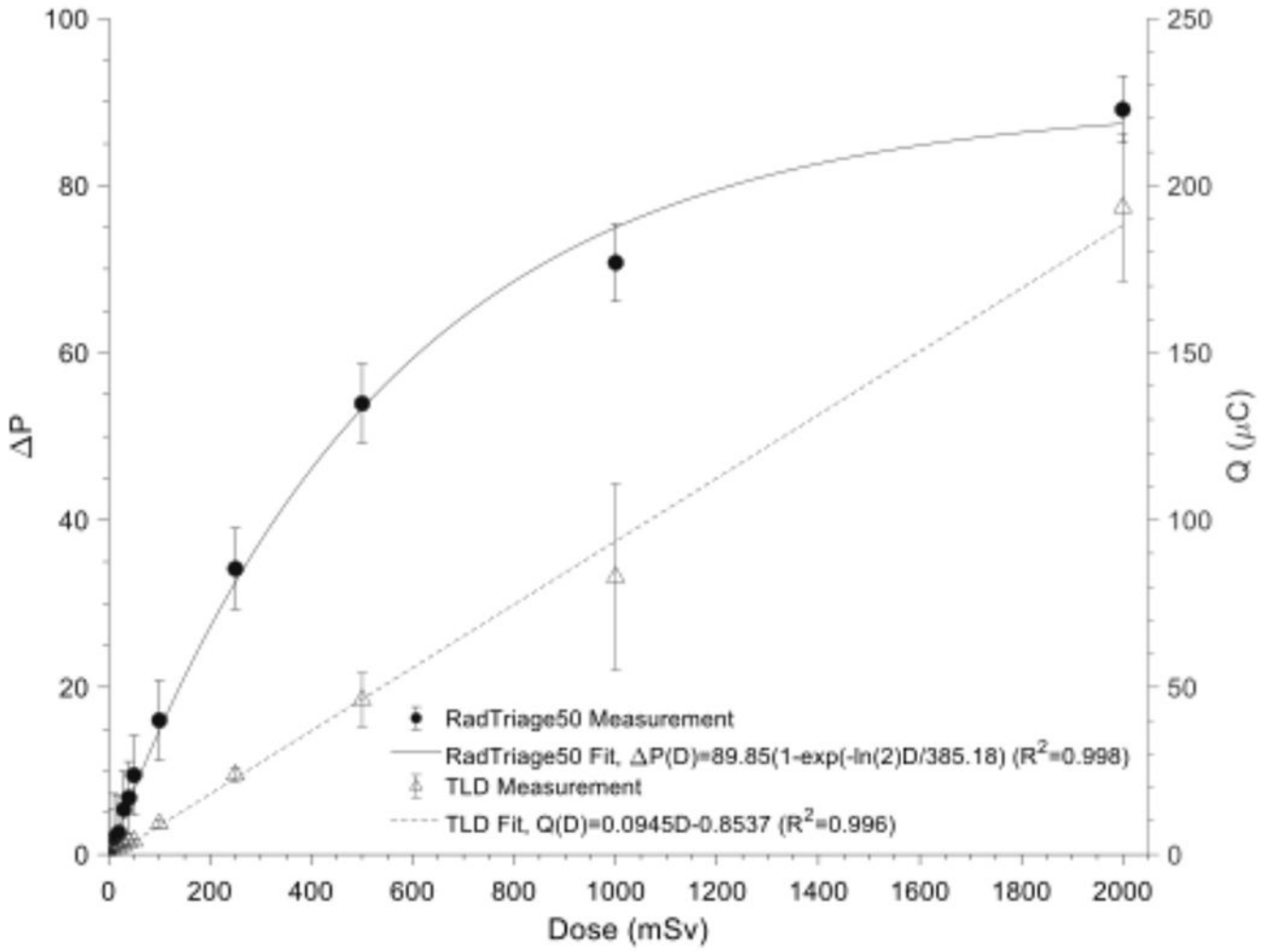


Fig. 4.

Average response of the RADTriage50 and TLD dosimeters to a ^{137}Cs source for deep dose equivalents between 0 and 2000 mSv. The error bars represent the standard deviation of seven RADTriage50 dosimeters or 10 TLD chips.

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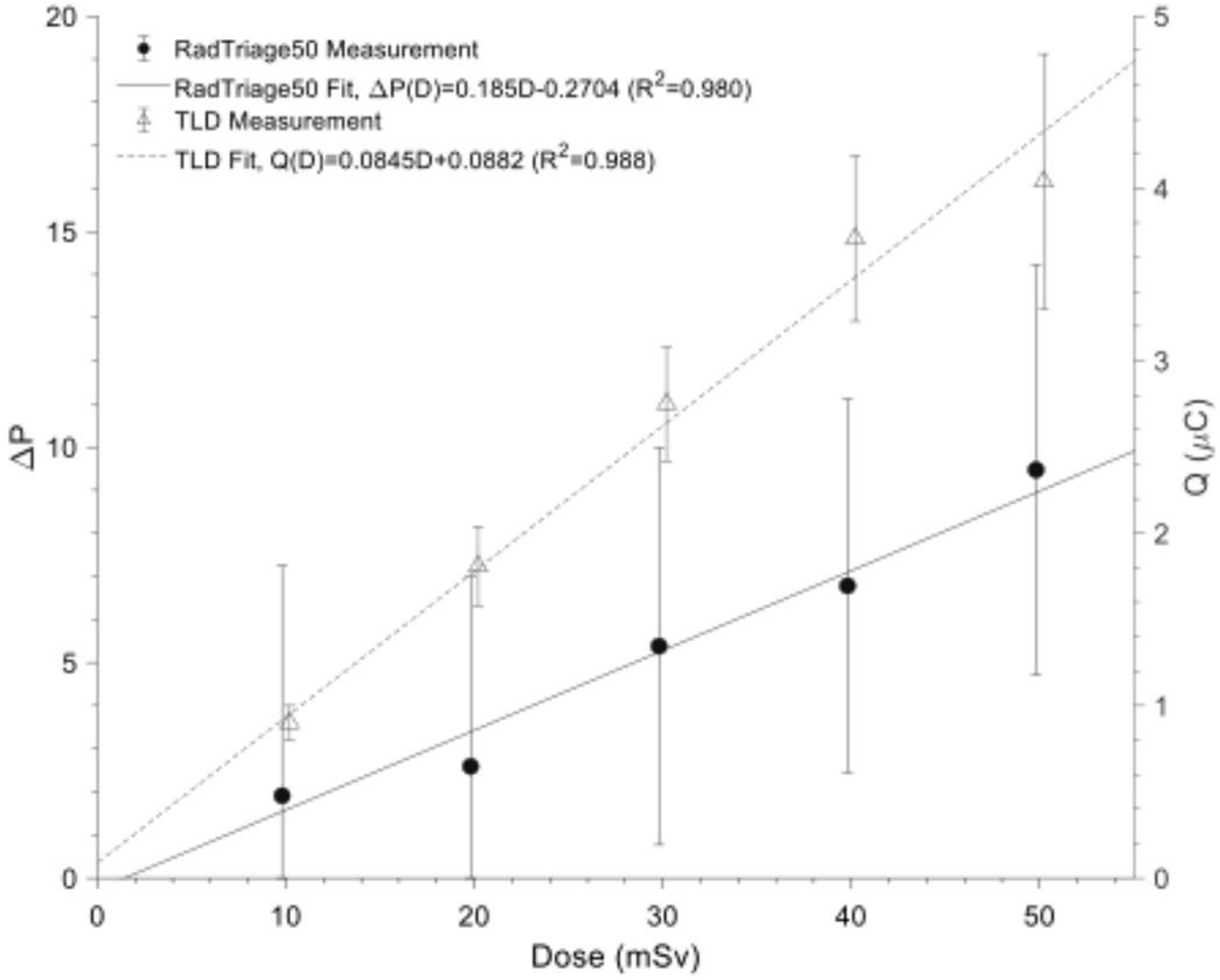


Fig. 5.

Average response of the RADTriage50 and TLD dosimeters to a ^{137}Cs source for deep dose equivalents between 0 and 50 mSv. The error bars represent the standard deviation of seven RADTriage50 dosimeters or 10 TLD chips. Data points have been shifted slightly in dose for clarity.

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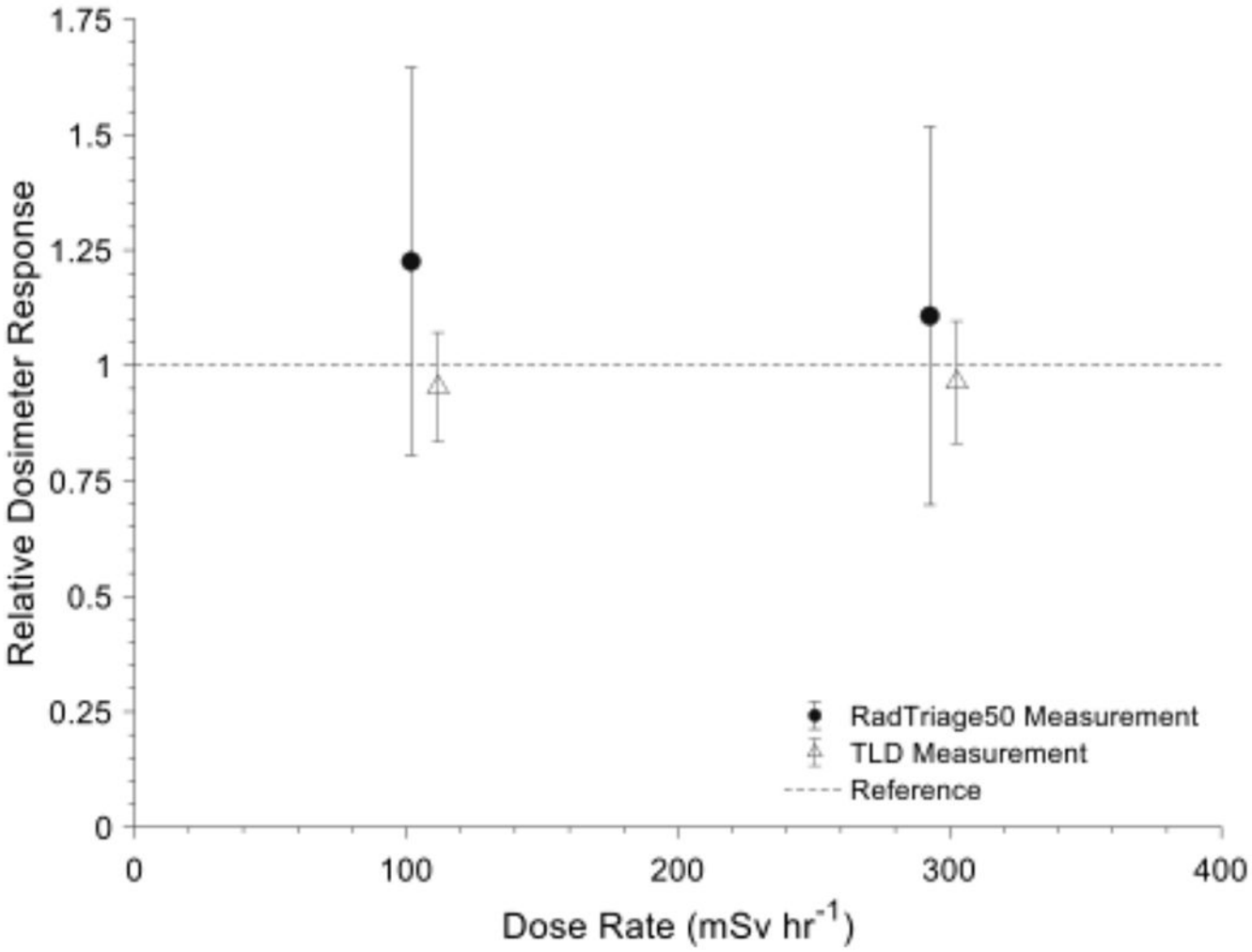


Fig. 6.

Response of the dosimeters to a ^{137}Cs source as a function of dose rate relative to that measured at 667.43 mSv hr^{-1}. The error bars represent 95% confidence intervals in the relative response for an average of seven RADTriage50 measurements or 10 TLD measurements. Data points have been shifted slightly in dose rate for clarity.

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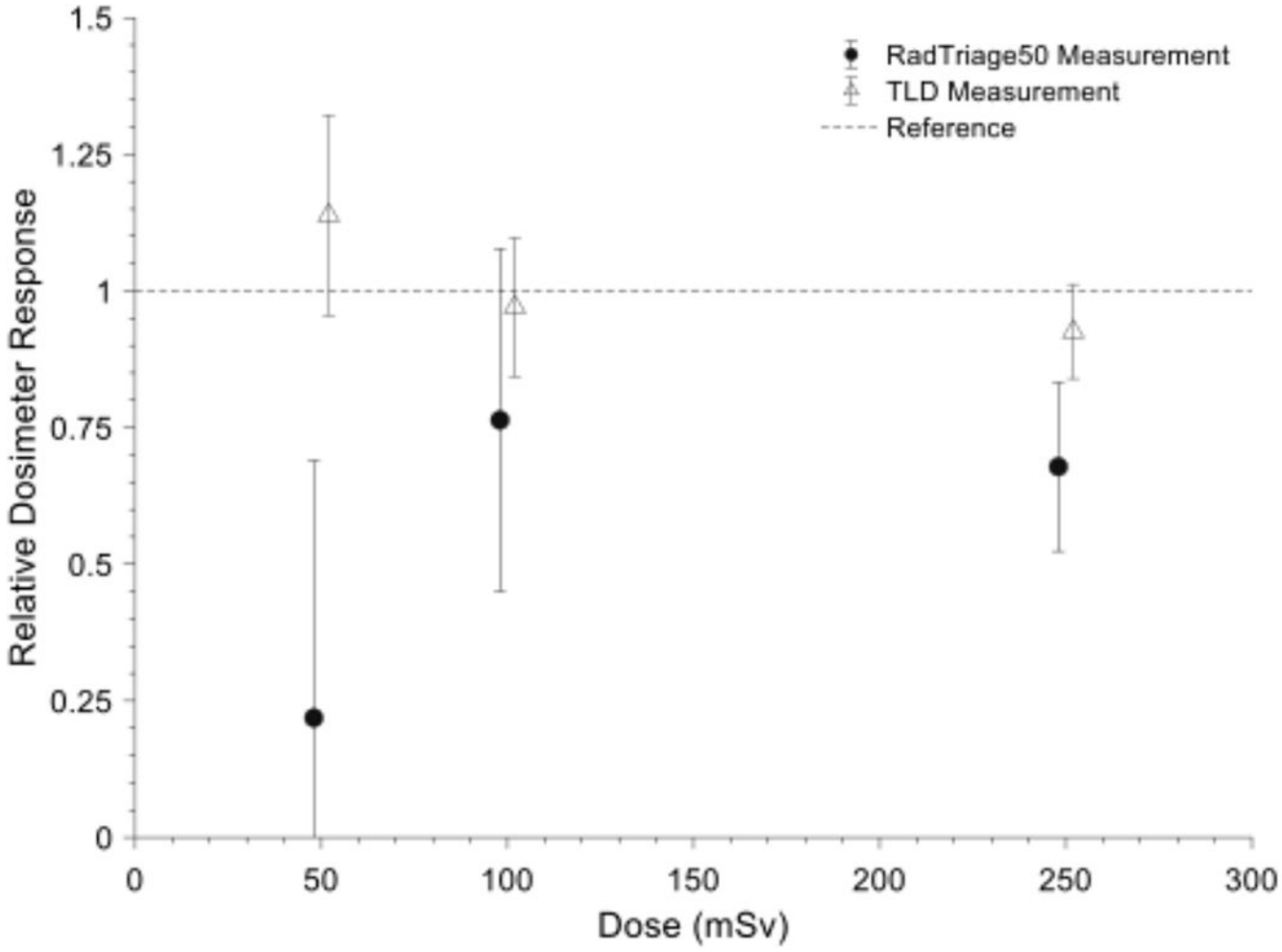


Fig. 7.

Response of the dosimeters to a ^{60}Co source relative to that for a ^{137}Cs source. The error bars represent 95% confidence intervals in the relative response for an average of seven RADTriage50 measurements or 10 TLD measurements. Data points have been shifted slightly in dose for clarity.

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Table 1.

Summary of the irradiation conditions considered in this study.

Irradiation Experiment	Dose (mSv)	Source	Distance (cm)	Calibrated Deep Dose Equivalent (mSv hr^{-1})	Exposure Time (s)
Dose-response within manufacturer specified range	2000	^{137}Cs	100	667.68	10784
	1000			671.79	5358.8
	500			667.43	2696.9
	250			673.24	1336.4
	100			667.43	539.4
	50			667.43	269.7
Dose-response below manufacturer specified range	40	^{137}Cs	100	671.79	214.4
	30				160.8
	20				107.2
	10				53.6
Dose rate sensitivity	100	^{137}Cs	150	297.66	1209.4
	100		250	106.70	3373.9
Energy sensitivity	250	^{60}Co	100	485.69	1853.0
	100				741.2
	50				370.6

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Table 2.

Average and standard deviation of the response of the RADTriage50 (n=7) and TLD dosimeters (n=10) to a ^{137}Cs source for exposures between 0 and 2000 mSv.

Dose (mSv)	σ (Dose) (mSv)	RadTriage				TLD	
		P	σ(P)	ΔP	σ(ΔP)	Q (μC)	σ(Q) (μC)
0[a]	-	139.15	3.86	0	5.46	-	-
10	0.58	137.25	3.68	1.91	5.33	0.9	0.1
20	0.58	136.56	2.12	2.59	4.41	1.81	0.23
30	0.58	133.77	2.51	5.38	4.61	2.75	0.33
40	0.58	132.37	1.96	6.78	4.33	3.71	0.48
50	2.52	129.69	2.77	9.47	4.75	4.04	0.74
100	2.52	123.11	2.74	16.04	4.74	9.17	1.29
250	3.51	104.98	2.86	34.17	4.81	23.79	2.12
500	2.52	85.22	2.64	53.93	4.68	46.2	8.04
1000	0.58	68.38	2.59	70.78	4.65	82.96	27.82
2000	1.53	50.05	1.13	89.10	4.03	193.45	22.03

[a]The RADTriage50 dosimeters were read before irradiation and this reading was used as a baseline for comparison for the color change after irradiation. The TLD chips were not read before irradiation because their reading was not based on a comparison, but rather was a value adjusted with an element correction factor that was determined in the initial calibration.