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SAND2012-3371
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Dose Algorithm for EXTRAD 4100S Extremity Dosimeter for Use at Sandia National Laboratories

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Abstract

An updated algorithm for the EXTRAD 4100S extremity dosimeter has been derived. This algorithm optimizes the binning of dosimeter element ratios and uses a quadratic function to determine the response factors for low response ratios. This results in lower systematic bias across all test categories and eliminates the need for the "red strap" algorithm that was used for high energy beta/gamma emitting radionuclides.

Acknowledgment

The author wishes to acknowledge the staff of the Radiation Protection Dosimetry Project, especially Sarah Goke, for their contributions to this work. In addition, the author thanks Dann Ward for his superior review and suggestions for improvement.

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Nomenclature

Black Strap Algorithm Dose determination algorithm used at SNL for photons and betas of unknown energy consisting of three element ratio bins with corresponding response factors.

Chipstrate TLD element part of extremity dosimeter consisting of LiF chip embedded in a plastic substrate.

DOELAP Department of Energy Laboratory Accreditation Program. In this document, DOELAP refers specifically to that program for personnel (external) dosimetry.

Element see Chipstrate.

EXTRAD 4100S Extremity dosimeter manufactured by Thermo Fisher employed by the Radiation Protection Dosimetry Project at SNL.

Generic unit, gU Readout unit from dosimeter reader corresponding to exposure to internal calibration irradiator over specific time interval.

Cesium response factor, $\mathbf{k}_s$ Factor that converts gU to shallow dose in rem.

Fade, fade factor f Tendency of LiF response to be reduced over time. Fade factor is determined by the time elapsed between dosimeter preparation and readout.

LEPB Low-energy photons and betas.

HEPB High-energy photons and betas.

$\mathbf{H}_s$ Shallow dose.

L2 Background-corrected response from the TLD-700 chipstrate typically read in carrier card position 2.

L3 Background-corrected response from the TLD-100 chipstrate typically read in carrier card position 3.

Red Strap Algorithm Dose determination algorithm used at SNL for high-energy photons and betas consisting of a single dose coefficient.

Response Factor, $\mathbf{R}_s$ Factor used to correct shallow dose calculated using the cesium response factor to that from the appropriate beta or photon field.

Supralinearity, supralinearity factor S Tendency of LiF response to become non-linear when dosimeter is exposed to extremely high doses. Factor accounts for this non-linearity.

TLD Thermoluminescent Dosimeter.

TLD-100 TLD material consisting of natural LiF.

TLD-700 TLD material consisting of LiF enriched in ^{7}Li.

Chapter 1

Introduction

The Radiation Protection Dosimetry Program (RPDP) at Sandia National Laboratories uses the Thermo Fisher EXTRAD 4100S extremity dosimeter[1], shown in Fig 1.1 to determine shallow dose to the extremities of potentially exposed individuals. This dosimeter consists of two LiF TLD elements or "chipstrates", one of TLD-700 (^{7}Li) and one of TLD-100 (natural Li) separated by a tin filter. Following readout and background subtraction, the ratio of the responses of the two elements is determined defining the penetrability of the incident radiation. While this penetrability approximates the incident energy of the radiation, X-rays and beta particles exist in energy distributions that make determination of dose conversion factors less straightforward in their determination.

Original Dose Determination Algorithm

Dose determination using the Thermo Fisher dosimetry system is based on an internal irradiator of ^{90}Sr that provides a precise dose to the unfiltered TLD elements. This dose measured in an arbitrary generic unit or "gU" is compared to a ^{137}Cs standard traceable to the National Institute of Standards and Technology by irradiating a set of dosimeters attached to an appropriate phantom to a known dose, reading the dosimeter, and deriving a "cesium response factor" or k_s in units of gU/rem. Once a cesium response factor is obtained, different response factors (R_s) based on penetrability of the incident radiation can be developed for different radiation fields. These field-specific response factors are simply the ratios of the dose obtained from exposure to the specific field in question to that of ^{137}Cs.

For the EXTRAD 4100S, penetrability of the radiation type and energy is represented by the element ratios of the top D (TLD-700) and bottom A (TLD-100) chipstrates. The response factor from the resultant ratio is applied to the D-chipstrate response value along with the cesium response factor to determine the shallow dose:

$$H_s = \frac{L2}{k_s R_s} \tag{1.1}$$

where:

[1] Thermo Fisher Scientific Inc., Franklin, MA

L2	=	background-corrected response of the D-chipstrate (gU),
k_s	=	^{137}Cs shallow dose response factor = 850 gU/rem, and
R_s	=	field "response factor", i.e., the ratio of the dose obtained from exposure to the specific field in question to that of ^{137}Cs.

In this work, performance evaluation data from RPDP's blind audit program and results of performance testing by the U. S. Department of Energy Laboratory Accreditation Program (DOELAP) for Personnel Dosimetry were used to develop an improved equation to be used in the determination of R_s from element ratios.

The original algorithm was designed and implemented in 1998 [5]. This actually consists of two algorithms, one for high energy beta/gamma fields and one for unknown fields. The high energy beta/gamma or "red strap" algorithm was designed using ^{60}Co, ^{137}Cs, and ^{90}Sr/Y fields and consisted of a single response factor. The unknown field or "black strap" algorithm consisted of three response ratio bins. Each bin used a single constant response factor. This algorithm had been periodically tested through the blind audit program, but had not been rigorously reviewed or updated since its inception and in 2008 unexpectedly failed DOELAP testing. Because of the length of time since the development of the original algorithm, an attempt was made to design an updated algorithm that would meet DOELAP requirements.

The red strap algorithm was intended for and designated as high-energy photon and beta (HEPB) and was intended for use in SNL Technical Areas IV and V. The response factor for this algorithm is 0.96. The black strap algorithm had values as shown in Table 1.1 and was intended for use in all other SNL locations. LEPB refers to low-energy betas and photons.

Table 1.1. "Black strap" algorithm parameters and designators. L2 and L3 are the background-corrected responses of the TLD-700 chipstrate located in position 2 in the carrier card and the TLD-100 chipstrate located in position 3 of the carrier card respectively.

Designator	Ratio	Response Factor (R_s)
^{204}Tl	$\frac{L2}{L3} > 40$ or $\frac{L2}{L3} < 0$	0.657
LEPB	$40 \geq \frac{L2}{L3} > 3$	1.425
Unknown	$\frac{L2}{L3} \leq 3$	1.07

Dosimeter fade and supralinearity corrections are discussed in the next section.

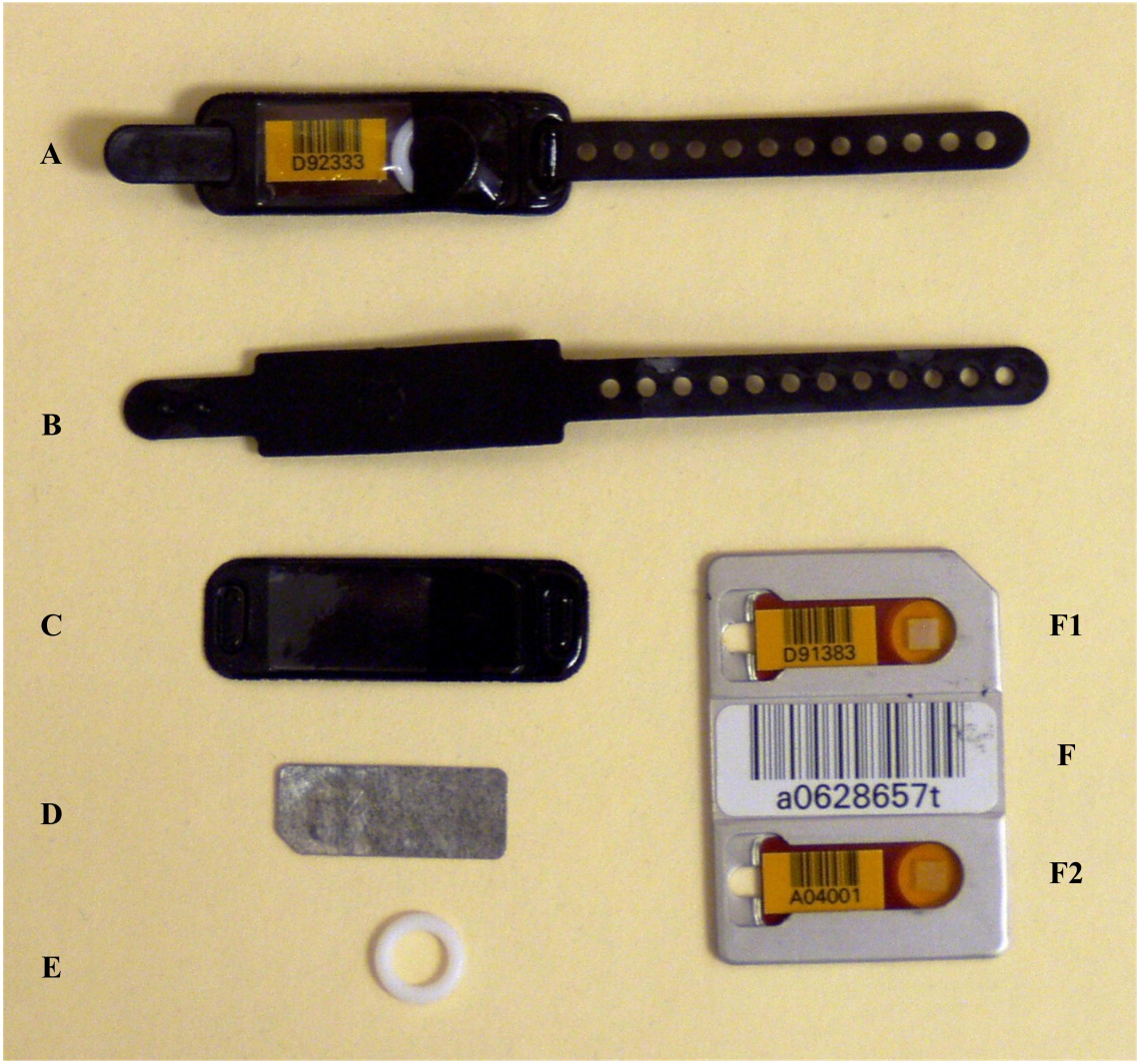

Figure 1.1. EXTRAD 1400S extremity dosimeter. Item A is the dosimeter assembled for use. Item B is the strap. Item C is the pouch in which the chipstrates are inserted. Item D is the tin filter located between the chipstrates. Item E is an O-ring placed above and around the crystal location to prevent damage from bumping. Item F is a carrier card containing the TLD-700 chipstrate in position F1 and the TLD-100 chipstrate in position F2.

Chapter 2

Development Methodology for Updated Algorithm and Results

Prior to developing the algorithm, it was recognized that the shallow dose response factor, k_s had not been verified or updated in several years. Using 2 rem blind audit exposures, the k_s was updated from 791 gU/rem to 850 gU/rem, a 7.3% increase. Following this, data from several quarters of blind audits (1st quarter 2005 - 2nd quarter 2007) were reviewed to observe trends in response ratios.

The following trends were observed (see Fig 2.1):

1. ^{204}Tl results showed little or no response in the TLD-100 resulting in ratios ranging from 40 to infinity. ^{204}Tl response ratios can also be less than unity if the TLD-100 background is less than its response.
2. M30 X-ray ratios are less than those for ^{204}Tl, but are easily distinguishable from other fields.
3. The remaining test fields can be seen visually to follow an approximate quadratic function.

These observations were used to create a more representative dose algorithm. Since M30 and ^{204}Tl fields were easily distinguished, R_s values were derived for them specifically. The remaining fields were fit to a quadratic function. Fig. 2.2 shows that subset of data and the quadratic function that was derived from those data. The function was obtained using Microsoft Excel [1]and is of the form:

$$R_s = -0.1981\left(\frac{L2}{L3}\right)^2 + 1.1995\left(\frac{L2}{L3}\right) + 0.1552 \tag{2.1}$$

where:
L2 = response of element 2 (top element or D-chip), and
L3 = response of element 3 (bottom element or A-chip).

[1]Microsoft Inc., Seattle, WA

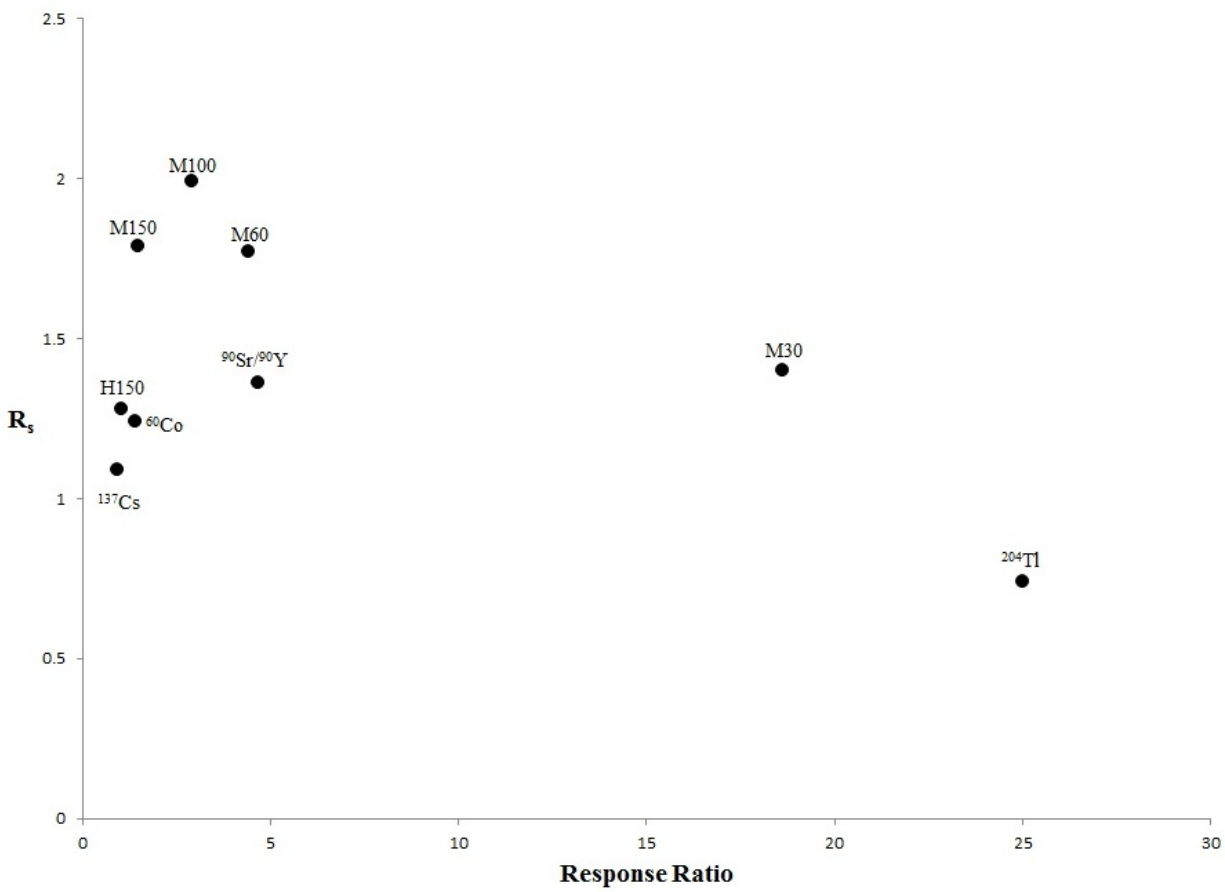

Figure 2.1. Response factor, R_s as a function of response ratio ($\frac{L2}{L3}$)for all tested radiation fields.

Response factors for ^{204}Tl and M30 fields were determined to be 0.74 and 1.35 respectively. The entire algorithm can then be represented:

$$R_s = \begin{cases} 0.74 & \left(\frac{L2}{L3}\right) < 0 \\ -0.1981\left(\frac{L2}{L3}\right)^2 + 1.1995\left(\frac{L2}{L3}\right) + 0.1552 & 0 \leq \left(\frac{L2}{L3}\right) \leq 5 \\ 1.35 & 5 < \left(\frac{L2}{L3}\right) \leq 40 \\ 0.74 & 40 < \left(\frac{L2}{L3}\right) \end{cases} \tag{2.2}$$

Once the R_s value determination is set, the rest of the dose algorithm follows. First the fade factor is determined. The default fade factor provided by Thermo (then Harshaw) and verified by Hill [2] is determined using the equation:

$$f = \exp\left(-0.00331\left(\frac{T}{2} - 8\right)\right) \tag{2.3}$$

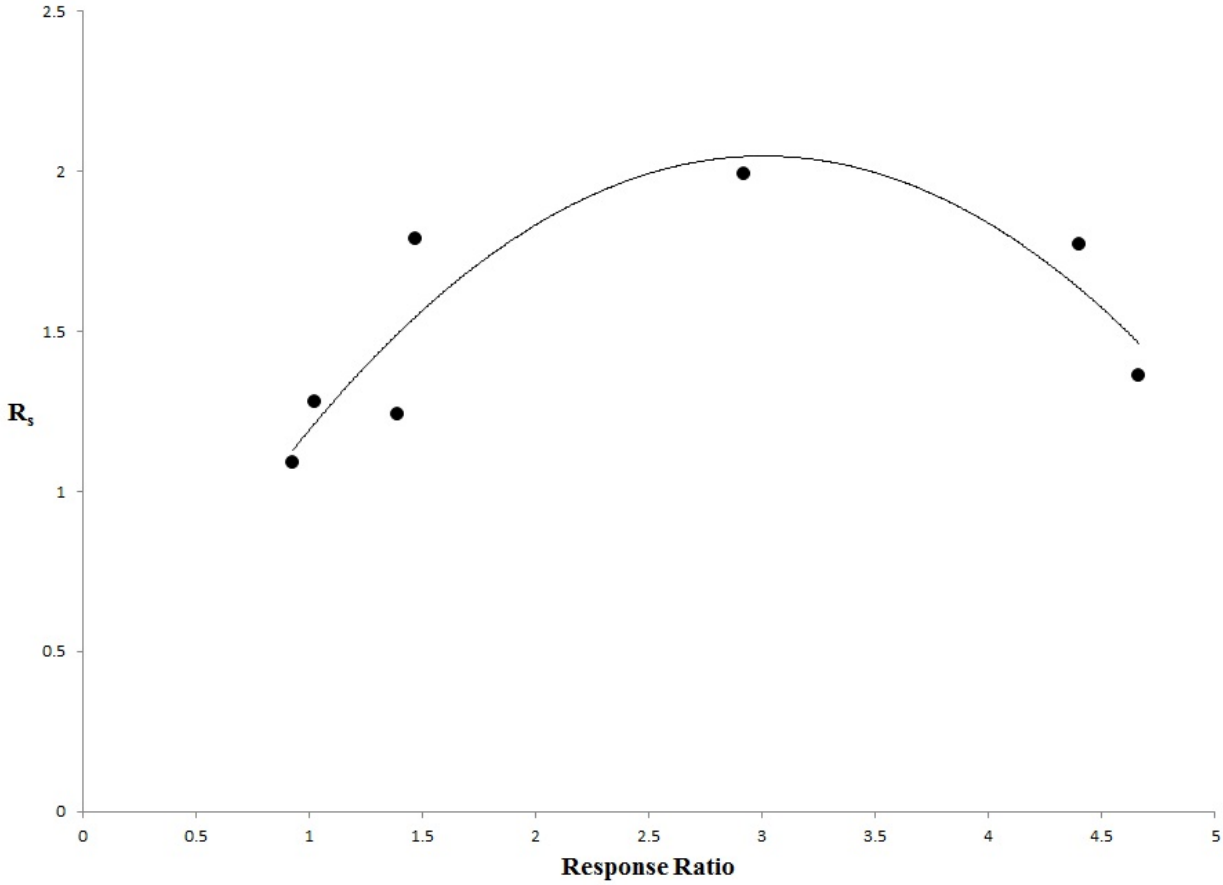

Figure 2.2. Response factor as a function of response ratio for quadratic segment of data.

where T is the time in days from anneal to readout. It is recognized that the study in question was performed for the 8802 dosimeter, which is a combination of TLD-700 and TLD-600, but since the element material in that card are essentially the same as both chipstrates in the EXTRAD, the study adequately describes the fade of the EXTRAD also. The fade factor is a divisor in the algorithm. Thus if the dose is less than that requiring supralinearity correction, the dose is calculated by:

$$H_s = \frac{L}{k_s R_s f} \tag{2.4}$$

At large doses (e.g., 100 rem) the linearity of the dosimeter response begins to break down due to saturation of the traps in the LiF matrix. The supralinearity factor accounts

for this (common to both element-types) and is calculated by[1]:

$$S = 1.18 - 0.23 \log \frac{H_s}{(L2)k_s} 0.0785 \log \left(\frac{H_s}{(L2)k_s} \right) \tag{2.5}$$

This supralinearity factor is again divided into H_s to obtain the corrected dose.

Chapter 3

Performance Testing of Updated Algorithm

The algorithm was evaluated to three separate data sets. These were the blind audits from 2009, the most current DOELAP performance testing exposures, and a set of exposures obtained from the reference laboratory at Pacific Northwest National Laboratory. Bias values were determined using both the DOELAP standard criteria [3] and the ANSI HPS N13.32 [4] criteria. In addition, the 2011 DOELAP performance testing data was evaluated with both algorithms using the updated k_s to evaluate the difference in the response factor calculation methodology. Those latter results are presented here.

Table 3.1. DOELAP performance testing data for the original EXTRAD algorithm evaluated using the ANSI HPS N13.32 criteria.

Category	Field	Bias	σ	Criteria	Limit
IIA	Photons	0.287	0.324	0.433	0.350
IIIA	Betas	-0.053	0.141	0.151	0.350

Table 3.2. DOELAP performance testing data for the updated EXTRAD algorithm evaluated using the ANSI HPS N13.32 criteria.

Category	Field	Bias	σ	Criteria	Limit
IIA	Photons	0.098	0.145	0.175	0.350
IIIA	Betas	-0.128	0.167	0.210	0.350

This evaluation shows that with the updated algorithm, the beta response remains acceptable, the photon response is much improved and the performance criteria is now within acceptable limits using the new algorithm.

Chapter 4

Conclusion

An updated algorithm was derived for the EXTRAD 4100S extremity dosimeter and is repeated below.

$$R_s = \begin{cases} 0.74 & \left(\frac{L2}{L3}\right) < 0 \\ -0.1981\left(\frac{L2}{L3}\right)^2 + 1.1995\left(\frac{L2}{L3}\right) + 0.1552 & 0 \leq \left(\frac{L2}{L3}\right) \leq 5 \\ 1.35 & 5 < \left(\frac{L2}{L3}\right) \leq 40 \\ 0.74 & 40 < \left(\frac{L2}{L3}\right) \end{cases} \tag{4.1}$$

This algorithm replaces both the existing "black" and "red" algorithms with a single algorithm that includes specific response factors for the M30 and ^{204}Tl fields and a quadratic equation for the remaining fields. The algorithm now passes the DOELAP standard and associated ANSI HPS N13.32 standard criteria.

References

[1] Bicron Saint-Gobain/Norton Industrial Ceramics Corporation, Solon, Ohio. *Dose Calculation Algorithm for Extremity Radiation (EXT-RAD) User's Manual*, ALGM-X-U-0393-002 edition, Mar 1993.

[2] Carolyn Hill. An algorithm for pre- and post-irradiation fade in the thermo 8802 lif:mg,ti thermoluminescent dosimeter. *Opertional Radiation Safety*, 88(Supplement 2):S73–S78, May 2005.

[3] U.S. Department of Energy. Department of energy standard for the performance testing of personnel dosimetry systems. DOE Standard DOE/EH-0027, U.S. Department of Energy, 1986.

[4] Health Physics Society. Performance testing of extremity dosimeters. ANSI Standard ANSI HPS N13.32, American National Standards Institute, Inc., 2008.

[5] Scottie W. Walker. Extrad algorithm setup profile determination. memo to file describing EXTRAD algorithm, Jul 1998.

Appendix A

Data Used for Development of Response Factors.

Table A.1. Raw Data Used for the Development of Response Factors.

Field	Element 2 Net Response (gU)	Element 3 Net Response (gU)	Fade Factor	Delivered Dose (rem)	Response Factor
^{60}Co	1988.721997	1458.263401	0.932850805	2.000	1.254555229
^{60}Co	983.6520508	683.7964214	0.932850805	0.9996	1.241540689
^{60}Co	486.1253478	357.1975754	0.932850805	0.500	1.226659328
^{137}Cs	5533.365802	5630.668902	0.934395951	6.072	1.147848483
^{137}Cs	7294.906773	7639.859366	0.931308214	8.051	1.145076178
^{137}Cs	3016.45731	3116.976309	0.931308214	3.334	1.143394367
^{137}Cs	688.679065	715.242938	0.942160158	0.765	1.124575467
^{137}Cs	3806.779529	4173.474383	0.942160158	4.252	1.11840121
^{137}Cs	1050.6348	1084.862296	0.931308214	1.188	1.117634505
^{137}Cs	416.436328	424.219989	0.934395951	0.472	1.111305735
^{137}Cs	249.660083	267.021075	0.934395951	0.283	1.111193317
^{137}Cs	5444.757403	5912.308063	0.934395951	6.220	1.102592655
^{137}Cs	2031.869373	2153.427508	0.942160158	2.304	1.101657177
^{137}Cs	764.6725195	842.924674	0.931308214	0.881	1.096892419
^{137}Cs	1732.767657	1825.805133	0.934395951	2.000	1.091282732
^{137}Cs	278.57259	306.610156	0.942160158	0.325	1.070750239
^{137}Cs	1281.559925	1411.894061	0.942160158	1.498	1.068710962
^{137}Cs	510.5854225	556.794974	0.931308214	0.613	1.05262189
^{137}Cs	833.0283328	918.0524034	0.932850805	0.9996	1.05142725
^{137}Cs	1653.044507	1954.24802	0.932850805	2.000	1.042798155
^{137}Cs	399.1327338	461.0132184	0.932850805	0.500	1.007147422
H150	2114.12251	1866.651463	0.932850805	2.041	1.306871385
H150	514.5804568	523.2530254	0.932850805	0.5027	1.291487199
H150	1225.069981	1206.362296	0.931308214	1.210	1.27949911
H150	1813.927479	1779.914813	0.942160158	1.775	1.276599651
H150	515.75075	508.212909	0.934395951	0.516	1.258975018
H150	1005.360547	1025.050389	0.932850805	1.009	1.257118956
M150	414.880419	275.402636	0.934395951	0.290	1.801987964
M150	1443.639356	969.9986314	0.932850805	1.012	1.799798575
M150	12626.22123	8597.563468	0.931308214	8.885	1.795892855
M150	732.5740478	496.8774454	0.932850805	0.5194	1.779488915
M150	2823.875684	2019.167698	0.932850805	2.022	1.762017127
M150	3874.070789	2627.226824	0.942160158	2.808	1.723469521
M100	1029.661451	256.9803204	0.932850805	0.500	2.598185486
M100	1480.421421	602.961051	0.931308214	0.927	2.018227348
M100	7514.341876	2989.685748	0.934395951	4.76	1.988432913
M100	584.640064	215.715258	0.942160158	0.370	1.973876643

Table A.2. Raw Data Used for the Development of Response Factors (cont.).

Field	Element 2 Net Response (gU)	Element 3 Net Response (gU)	Fade Factor	Delivered Dose (rem)	Response Factor
M30	8599.297442	555.95119	0.934395951	7.579	1.429150645
M30	3752.310337	186.257941	0.931308214	3.346	1.417220003
M30	919.627491	45.447	0.942160158	0.834	1.377460182
M60	2960.567462	641.254596	0.934395951	2.042	1.826190881
M60	892.6019015	211.965842	0.931308214	0.626	1.801971571
M60	5261.980457	1202.422991	0.942160158	3.932	1.671740564
^{90}Sr/^{90}Y	5887.208575	1294.201495	0.934395951	5.181	1.43127398
^{90}Sr/^{90}Y	300.985217	48.923015	0.934395951	0.266	1.425248113
^{90}Sr/^{90}Y	8478.000567	1876.211871	0.934395951	7.781	1.372413469
^{90}Sr/^{90}Y	710.5771825	146.412879	0.931308214	0.657	1.366816927
^{90}Sr/^{90}Y	1245.262486	306.871054	0.931308214	1.180	1.333654572
^{90}Sr/^{90}Y	764.678211	170.978075	0.942160158	0.721	1.3248802
^{90}Sr/^{90}Y	1657.909534	341.548052	0.942160158	1.575	1.314962688
^{90}Sr/^{90}Y	417.327625	108.367297	0.942160158	0.403	1.293615607
^{90}Sr/^{90}Y	728.3038458	0.0751774	0.932850805	1.000	0.918878958
^{204}Tl	362.5323308	0.3255814	0.932850805	0.500	0.914792177
^{204}Tl	1391.267657	0.66014	0.934395951	2.284	0.767258194
^{204}Tl	4978.902867	1.748076	0.931308214	8.245	0.763145687
^{204}Tl	504.7192725	0.0001	0.931308214	0.861	0.740817439
^{204}Tl	1918.40482	0.0001	0.931308214	3.287	0.737573005
^{204}Tl	255.657763	0.731851	0.934395951	0.442	0.728557211
^{204}Tl	2571.322254	1.048382	0.942160158	4.465	0.719396307
^{204}Tl	1604.342151	0.0001	0.942160158	2.876	0.696853156

Table A.3. Average R_s Values by Field and Category. Category IIA is Photons, General and Category IIIA is Betas, General.[4]

Category	Field	$\frac{L2}{L3}$	R_s
IIA	^{137}Cs	0.9299	1.09
IIA	H150	1.024373432	1.28
IIA	^{60}Co	1.387739627	1.24
IIA	M150	1.468466257	1.79
IIA	M100	2.92142137	1.99
IIA	M60	4.401349549	1.77
IIIA	^{90}Sr/^{90}Y	4.663564516	1.36
IIA	M30	18.61621925	1.4
IIIA	^{204}Tl	25	0.74

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