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PERSONAL DOSIMETRY STATISTICS AND SPECIFICS OF LOW DOSE EVALUATION

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RESUMEN

The dose statistics of a personal dosimetry service, considering 35,000+ readings, display a sharp peak at low dose (below 0.5 mSv) with skewness to higher values. A measure of the dispersion is that approximately 65% of the doses fall below the average plus 2 standard deviations, an observation which may prove helpful to radiation protection agencies. Categorizing the doses by the concomitant use of a finger ring dosimeter, that skewness is larger in the whole body, and ring dosimeters.

The use of Harshaw 5500 readers at high gain leads to frequent values of the glow curve that are judged to be spurious, i.e. values not belonging to the roughly normal noise over the curve. A statistical criterion is shown for identifying those anomalous values, and replacing them with the local behavior, as fit by a cubic polynomial. As a result, the doses above 0.05 mSv which are affected by more than 2% comprise over 10% of the data base.

The low dose peak of the statistics, above, has focused our attention on the evaluation of LiF(Mg,Ti) dosimeters exposed at low dose, and read with Harshaw 5500 readers. The standard linear procedure, via an overall reader calibration factor, is observed to fail at low dose, in detailed calibrations from 0.02 mSv to 1 Sv. A significant improvement is achieved by a piecewise polynomials calibration curve. A cubic, at low dose is matched, at ~10 mSv, in value and first derivative, to a linear dependence at higher doses. This improvement is particularly noticeable below 2 mSv, where over 60% of the evaluated dosimeters are found.

Keywords: external personal dosimetry, TLD dosimetry, Harshaw 5500, low dose calibration.

1. INTRODUCTION

Personal dosimetry is practiced at this laboratory, using thermoluminescent LiF(Mg,Ti) elements (TLD-100, from Thermofisher, and MTS-100, from Radpro Intl.). This material is reputed to be usable over the exposition range of 10 pGy to 10 Gy, with accuracy of ±15 %, at 2 standard deviations (Thermofisher), or sensitivity spread of ±5 %, at one standard deviation (Radpro).

The analysis of the dose distribution of large numbers of readings, from workers in highly diverse environments, results in peak (mode) at a low value, followed by a long tail to higher doses. Thus, an effort has been launched into improving the reliability of the dose calculation at low values, without degrading the performance over the higher range. Two aspects of this process have been addressed: i) removal of spurious signals reported by the Harshaw 5500 readers, and ii) detailed fitting of the calibration curve.

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2. THE METHODS

2.1. Statistics of Personal Dosimetry Service

The statistics of personal dosimetry data of nearly 8.000 workers, over the past 3 years has been analyzed, focusing on the dose spread of whole body and extremity dosimeters. In terms of the level of exposure, a higher level is expected of workers who do wear a finger ring dosimeter, in addition to their whole body dosimeter. In this direction, the distinctions shown in Fig. 1, support that expectation.

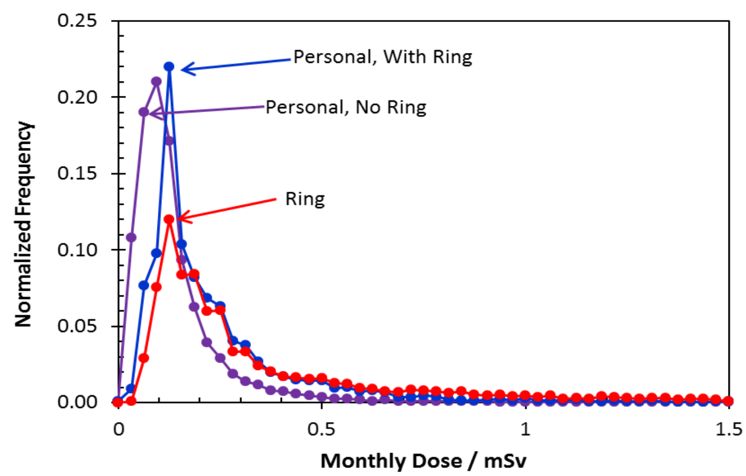


Fig. 1. Histograms of the dose of workers, by their use, or not, of a finger ring.

Table 1. Statistical parameters of the personal and hand dose distributions.

	Equivalent Dose		
	No Ring	With Ring	Rings
Median	0.093	0.150	0.241
Average	0.136	0.243	1.245
Std. Dev.	0.336	0.339	4.186
Pearson Bias	0.384	0.822	0.719
Avrg. + 2 * Std. Dev.	0.809	0.922	9.618
Significant Dose Rate / 1000	2.05	6.51	0.96

For the purpose of comparing their overall shapes, the frequency curves in the histogram have been normalized to unit sum, which include values at higher doses than the displayed dose axis. All three curves present a maximum a low values, followed by long tails into higher doses. As a result, the curves are right skewed, their average falling above the median. A frequent measure of the skewness is the Pearson bias, evaluated as 3 * (Average – Median) / Standard deviation. Over the three distributions, a value under which 97.5% to 99% of the doses are found is given by the Average + 2 * Standard Deviation. These measures of the distributions are given in Table 1. Finally, a figure which may prove helpful for the national radiation protection agencies is the rate of doses above a "significant" level. In Chile, these levels, for quarterly doses, are 5 mSv over the whole body, and 125 mSv for the extremities. The resulting rates, per thousand doses, are included in the table.

2.2. Removal of spurious signals

The values of a collection of measurements, which differ significantly from the major trend are known as outliers. Criteria for the identification and treatment of these values have been developed and applied over mostly all disciplines dealing with data acquisition, in both large and modest numbers. A recent, extensive treatment of the subject is offered by Aggarwal, 2013.

An early landmark criterion for the identification and removal of spurious signals was put forward by Peirce, in 1982. Shortly after, the use of the original formulation was greatly facilitated by the publication of elaborate tables, by Gould, 1855. More recently a simpler method was introduced by Chauvenet, 1960, although acknowledging that its theoretical foundation was weaker than that of Peirce's.

These approaches have been revisited by Ross, 2003, favoring the use of Peirce's criterion, particularly as, with current computing power, its mathematical complexity should be no deterrent. However, as Ross states, perhaps due to its simplicity, Chauvenet's criterion has been in regular use, without much critique, at places like the Environmental Protection Agency, U.S. Army Corps of Engineers, and other institutions.

For some time, the visual inspection of the glow curves from Harshaw 3500, and 5500 readers, has caught our attention to sharp, isolated values, far from the local trend. A study of these apparent anomalies, among the many glow curves observed, shows that they do not appear at fixed, or close-by locations (channels). Further, over a single curve, the anomalies are not correlated to the noise, and the internal correlation function of the noise itself is essentially null. With these observations in mind, the removal of those anomalies appears as a safe and desirable process.

Within that perspective, Peirce's criterion has been implemented (in Fortran), verifying that the results match the tables provided by Gould, 1855. Then, the Peirce procedure has been applied, to the analysis of the glow curves from the Harshaw 5500 readers.

Testing over the reading of many dosimeters, it has been observed that Peirce's criterion labels, as spurious, some 20 to 70 out of the 200 channels of the glow curves. Those numbers of spurious signals result from the direct application of the criterion, leaving no room for adjustments by the experimenter. The ensuing data removal has been judged excessive, risking the loss of relevant data, so, a more adaptable criterion has been sought.

Thus, in an approach that bears some similarity to that of Chauvenet's, a point under test (PUT) will be labeled as spurious if the probability of its belonging to the local signal distribution is below some adjustable value. In summary, the method proceeds by:

1. Choose an even number (StatIntrv) of points to consider in the local reference interval. One half of that number will be taken on either side of the PUT, for evaluation of the local statistics, except for PUTs within StatIntrv /2 of the ends of the glow curve, in which case the first, or last, StatIntrv points are considered as reference.

2. Starting at point 1, and iterating over all points in the glow curve: chose a PUT, and evaluate the lineal local trend, and corresponding standard deviation (StdDev), using only the adjacent points (i.e. excluding the PUT). This exclusion of the PUT from the reference interval sets this approach apart of those of Peirce and Chauvenet.

3. Assuming a normal distribution of the signal noise, the maximum spread of the noise around the local trend that will be accepted as belonging to the glow curve is set by a number, MaxSigmas, of local standard deviations (StdDev). Thus: the difference of the experimental signal value at the PUT to the lineal local trend is evaluated. If that difference is larger than MaxSigmas times the local standard deviation, the PUT is labeled as spurious, and it is excluded from the local statistics for the up coming points.

4. The large deviation of a spurious signal from the local trend resulted in large values of the local StdDev, when it was included within the StatIntrv of the previous (up to StatIntrv/2) points. This effect may have prevented the identification as spurious of an additional largely deviated value within that half interval. To avoid that possibility, once a spurious value is detected, the algorithm backs up, and tests the values over the previous StatIntrv/2 points, while the just found spurious value is removed from the statistics.

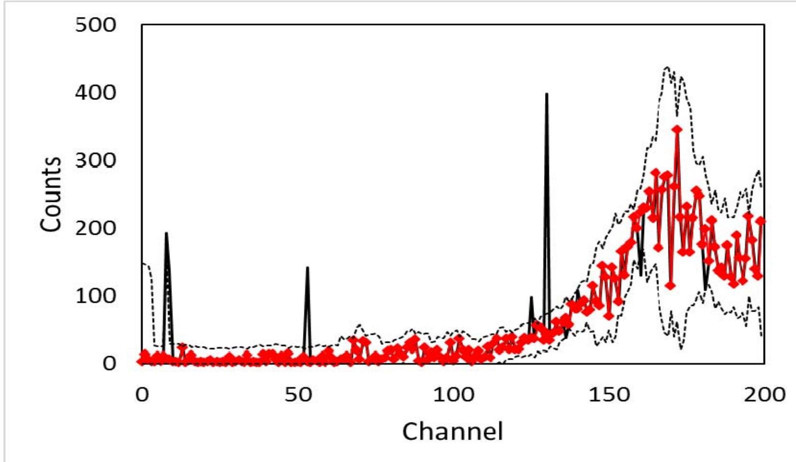
5. To facilitate further analysis (integration) of the glow curve, once all spurious signals have been labeled, the values at such positions are replaced by the local trend, evaluated, now, with a cubic polynomial, fit to the nearby StatIntrv non-spurious points.

The method has been developed in Fortran, and incorporated, via a dynamic link library, into the dose evaluation program developed in-house.

A default value of StatIntrv = 9, has been set for the local reference interval, considering that the peaks of interest in the glow curves span some 4 times that number of points. A default value of MaxSigmas = 3, for the acceptable band, has been set by considering that the implied acceptable noise spread includes up to 99.7% of the values belonging to the trend within the reference interval.

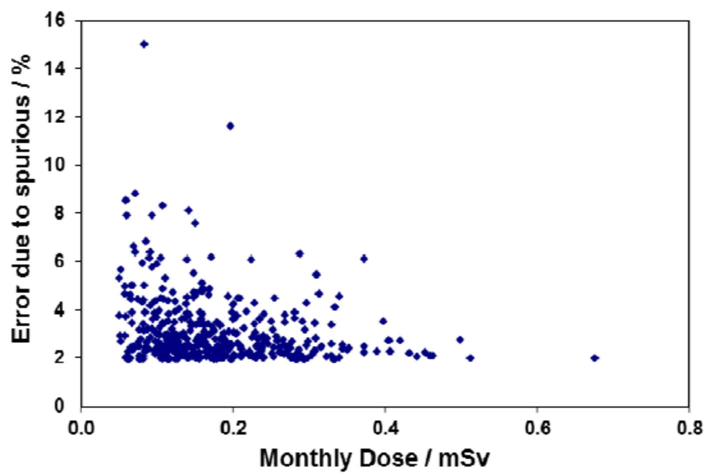
With those parameters, the procedure has been applied to calibration dosimeters, of which an example is shown in Fig. 2. In this case, the dosimeter was exposed to 0.05 mSv, and the error of the integral, due to the spurious values, which were removed, was 5.2%. Other cases have been observed, in one particular set of calibration dosimeters, with significant cases like 11% variation, of a dosimeter exposed to 0.85 mSv, or 2.3% variation at 5.3 mSv.

Fig. 2. Removing spurious signals from the glow curve. The black line shows the measured signal, and the red squares is the filtered data. The dotted lines indicate the lower and upper noise acceptance range of the filter.



The procedure described above has been applied to a set of 3600 dosimeters, and a comparison is made of the resulting dose, against that obtained without the removal of spurious signals. Prior to each evaluation, a calibration is correspondingly performed with or without the removal of spurious values. For an estimate of the relevance of the procedure, attention is restricted to dosimeters with dose above 0.5 mSv, where the removal of spurious signals changes the evaluated dose by more than 2%. This criterion, as shown in Fig. 3, results in approximately 10% of the data set, for the 2-TLD elements dosimeters under study.

Fig. 3. Comparing dosimeters with, vs. without removal of spurious signals. In 388 out of 3600 dosimeters, where the dose is above 0.5 mSv, the removal of spurious signals changes the evaluated dose by more than 2%

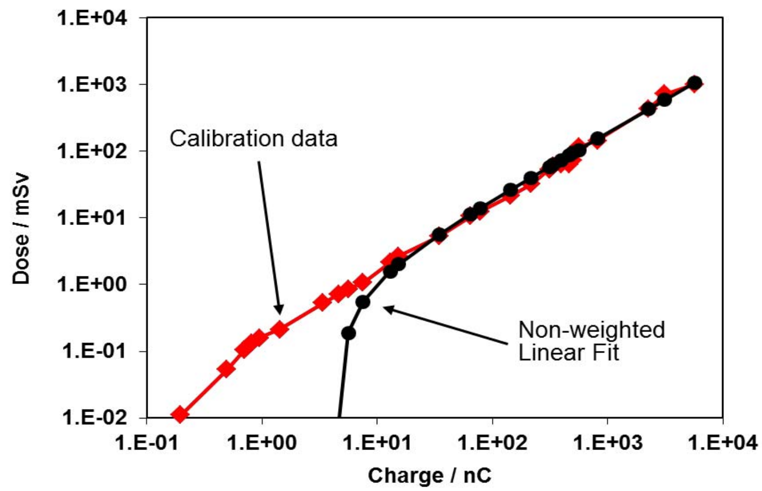


The variations observed, both in the analysis of single TLD elements (Fig. 2), and on two-element dosimeters (Fig. 3) are rather modest. As a result, the present practice of this laboratory, where the TLD elements are not calibrated individually, the variation of the response of one to another element overshadows the variations introduced by spurious signals. It is expected that in the future, with individual calibration of TLD elements held in cards, this spurious signal elimination procedure will significantly benefit the overall accuracy of the dosimetry.

2.3. Adaptive calibration of TLD readers

The signal, charge vs. dose from solid state thermoluminescent dosimeters (TLD) is known to be essentially linear at exposition below 1 Gy. However, during calibration of two TLD readers, a slight deviation has been observed of the expected linear behavior, at dose below some 10 mSv, as shown in **¡Error! No se encuentra el origen de la referencia.**. The observed deviation, by nearly 1 mSv, is significant, considering that 65% of the doses of workers who do not use a finger ring, and 60% of those who do use it, are found below that value. Thus, the simple use of an overall reader calibration factor, to convert the reported charge values to dose, does not seem to be quite accurate over the dose range of the figure.

Fig. 4. Calibration data (red squares), fit by a linear, un-weighted polynonial (black dots).



The deviation of the linear fit to the experimental data can be significantly improved, in the low dose region, albeit at a cost in the high dose region, by weighing the errors, with the inverse of the charge. That result being not fully satisfactory, the next possible attempt could be a fit with a higher degree polynomial, which, again do improve the low-dose fit. However, even as the overall fit may improve, the behavior quickly degrades at the ends of the calibration range, as the polynomial order increases.

To overcome those inconveniences, the fit to the low and high dose regions has been approached with different functional forms. Thus, keeping to the inverse charge weight in the minimum squares fit procedure, quadratic, and cubic polynomials have been fit at low dose, and matched to linear fits above a certain charge value. The results, as measured by the weighted root mean squared error, are only slightly better with the use of the cubic, rather than the quadratic polynomial at low dose. However, a visible improvement is noticed at the high dose end of the range with the cubic choice.

For the following example, a low-dose cubic polynomial

$$D_l = a + q\,(b + q\,(c + q \cdot d\,)) \qquad (1)$$

will fit the charge region up to q = q_{m} = 50 nC, and a linear fit

$$D_h = r + q \cdot s \qquad (2)$$

goes up from that match point; a weight of $1/(q^p)$ being applied on the errors, throughout, with $0.5 \leq p \leq 1$. For smoothness of the fit at q_{m}, the continuity of the value and of the first derivative of the piece wise polynomial fit has been imposed, leading to the equations:

$$s = b + q_m\,(2\,c + 3\,d\,q_{\mathrm{m}}) \qquad (3)$$

$$r = a - q_m^{\,2}\,(c + 2\,q_{\mathrm{m}} \cdot d) \qquad (4)$$

With the expressions in (3) and (4) into equation (2), the coefficients of the cubic polynomial have been fit by minimizing the squared deviations of eq. (1) below q_m, and those of eq. (2) above that match point, simultaneously.

Considering that data fitting is both and art and a science, visual inspection has guided this process all along. For the case shown in **¡Error! No se encuentra el origen de la referencia.**, a value of p = 0.75 is seen to achieve an excellent fit over both the low and high charge regions, with the match charge value, q_m, set at 50 nC. Whereas the non-weighted linear dose fit deviates to negative values below ~ 5 nC, the piece-wise cubic-linear fit follows the calibration data closely all over the range.

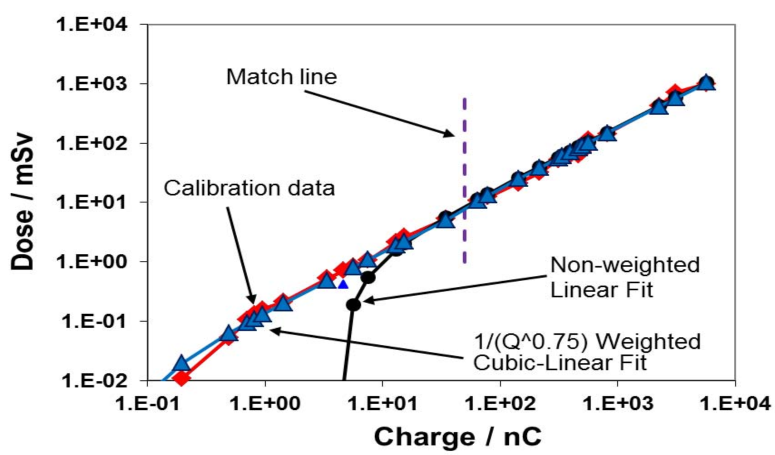


Fig. 5. Calibration curve (red dots), fit with non-weighted linear model (black dots), and with weighted piece-wise polynomials (blue triangles).

At the low-dose end of the range, the example shown has not included the readings from the blank (non-irradiated) dosimeters; the lowest dose values being 0.002 mSv. This has been avoided due to lack of a definite criterion for setting the weight of the corresponding charge values in the fitting procedure.

At the high dose end, our calibration data goes up to a little over 1 Sv. It must be considered that, if a calibration up to several Sieverts will be made, an additional polynomial should be allowed, probably, above 1 or 2 Sv.

3. CONCLUSIONS

The statistics of the personal dosimetry service point to the high relevance of a detailed evaluation of doses below some 2 mSv, where over 60% of the personal doses are found. Two efforts are described to this end: the removal of spurious signals, and a piecewise polynomial calibration which allows for an excellent fit to the slight nonlinearity of the calibration data below some 10 mSv.

4. REFERENCES

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