A new photon branch in the standard Panasonic UD-802 Dose Algorithm at the CIEMAT
External Dosimetry Service

A. M. Romero, R. Rodríguez and A. Delgado

CIEMAT, Ionizing Radiation Dosimetry, Avda. Complutense, 22-Ed.36, 28040-MADRID, Spain
e-mail: ana.romero@ciemat.es

Abstract. The standard dose algorithm provided by Panasonic to be used with the four element UD-802 TLD
badge is widely employed in Personnel Dosimetry Services all around the world. The algorithm was developed
to satisfy the obsolete standard ANSI 13.11-1983 that was reviewed in 1993 (HPS N13.11-1993) and revised
again in 2001 (HPS N13.11-2001) including differences in the NIST x-ray techniques used as test spectra and
updated values of the air kerma to dose equivalent conversion factors. In addition, the x-ray reference radiations
employed in Spain and in most of the european countries for calibrating dosemeters are the specified in the ISO
4037-1 (1996) and the conversion coefficients from air kerma to dose equivalent are those given in the ISO
4037-3 (1999). All these conditions made necessary a deep revision of the photon correction factors and
categories included in the photon branch of the standard UD-802 dose algorithm. With this aim, dosemeters from
the CIEMAT External Dosimetry Service (EDS) were irradiated at the CIEMAT Reference Laboratory for X-ray
at Protection Level employing the X-ray from the narrow-spectrum series given by the ISO 4037-1 (1996) and
the ISO water slab phantom. The results allowed testing the energy response of the four element of the
dosemeter, to define its real discrimination capability and to determine the correction factors that best
accommodate the results to the reference doses. This process concluded with the proposal of a completely new
photon branch in the standard UD-802 dose algorithm that has recently undergone a blind test to guarantee its
performance. This work presents the proposal of the new photon branch and the comparison between the results
of the blind test from both the modified and the standard UD-802 dose algorithm.
1. Introduction

Thermoluminescent dosimetry (TLD) is a technique widely employed with the purpose of individual monitoring of radiation exposed workers. The TL dosemeters usually combine different materials and use dose algorithms to estimate the dose in the wide range of possible radiation fields present in the work environment [1].

The CIEMAT External Dosimetry Service (EDS) provides TL dosimetry to the Spanish customers since the year 1993 using a four-element TLD badge model UD-802 from Panasonic. The standard dose algorithm that the manufacturer provided to be used with the UD-802 dosemeter was developed to satisfy the standard ANSI 13.11-1983 [2]. This standard was reviewed in 1993 (HPS N13.11-1993) [3] and revised again in 2001 (HPS N13.11-2001) [4] including differences in the NIST x-ray techniques used as test spectra and updated values of the air kerma to dose equivalent conversion factors. In addition, the x-ray reference radiations employed in Spain and in most of the European countries for calibrating dosemeters are specified in the ISO 4037-1 (1996) [5] and the conversion coefficients from air kerma to dose equivalent are those given in the ISO 4037-3 (1999) [6]. All these conditions made necessary a deep revision of the photon correction factors and categories included in the photon branch of the standard UD-802 dose algorithm.

2. Materials

The whole body dosemeter employed by the EDS consists of the badge model UD-802 [7] inserted in the hanger model UD-874, both from Panasonic. The TLD has two \( \text{Li}_2\text{B}_4\text{O}_7 : \text{Cu} \) elements under plastic filtration of 14 mg·cm\(^{-2}\) and 300 mg·cm\(^{-2}\) and two \( \text{CaSO}_4 : \text{Tm} \) elements under 300 mg·cm\(^{-2}\) of plastic and 1000 mg·cm\(^{-2}\) of plastic and lead energy correction filters. Table I illustrates this configuration.

<table>
<thead>
<tr>
<th>Element</th>
<th>Phosphor</th>
<th>Filtration (Material)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>( \text{Li}_2\text{B}_4\text{O}_7 : \text{Cu} )</td>
<td>14 mg·cm(^{-2}) (Plastic)</td>
</tr>
<tr>
<td>E2</td>
<td>( \text{Li}_2\text{B}_4\text{O}_7 : \text{Cu} )</td>
<td>300 mg·cm(^{-2}) (Plastic)</td>
</tr>
<tr>
<td>E3</td>
<td>( \text{CaSO}_4 : \text{Tm} )</td>
<td>300 mg·cm(^{-2}) (Plastic)</td>
</tr>
<tr>
<td>E4</td>
<td>( \text{CaSO}_4 : \text{Tm} )</td>
<td>1000 mg·cm(^{-2}) (Plastic + Lead)</td>
</tr>
</tbody>
</table>

The dosemeter was designed to discriminate the effective energy of both beta and photon radiation in any mixed radiation fields \( \beta-\gamma \). It also detects the presence of neutron radiation but its unable to quantify the neutron component in terms of dose without additional information about the neutron spectra. The energy dependent response characteristics of the \( \text{CaSO}_4 : \text{Tm} \) phosphor relative to the near-tissue equivalent \( \text{Li}_2\text{B}_4\text{O}_7 : \text{Cu} \) were used for photon discrimination. For radiation measurement the \( \text{Li}_2\text{B}_4\text{O}_7 : \text{Cu} \) element under minimal filtration is employed. This configuration allows assessing the operational dose quantities \( H_p(10) \) and \( H_p(0.07) \) using an algorithm based on the ratio of the four elements readouts.

There are three main branches in the algorithm: photons, beta plus gamma and neutron plus gamma. The photon branch uses the ratio of element E3 to element E4 (E3/E4) as an indicator of the effective photon energy and estimates the photon dose by applying a calibration factor specific of the photon energy to the element E2 readout. The standard UD-802 algorithm [7] divides the photon branch in six categories of X-ray, namely LG, LI, LK, MFG, MFI and MID, ranging energies from 20 keV to 70 keV. These categories were established to accomplish with the requirements of the standard ANSI-N13.11 (1983). The updating of this branch was the main interest of this work.
Two automatic Panasonic TLD readers, models UD-710 and UD-716, operate in the EDS. The heating system is a non-contact method based in the infrared emission of a tungsten lamp specially designed as heat source. The badge contains a hole code including the dosemeter identification and additional information that is automatically decoded by the reader during the readout process. The lamp flashes each detector three times (pre-readout, readout and anneal) in a very short time. The output signals from the Photo Multiplier Tube are integrated digitally using a hybrid integrator that contains a photon counter (low signals) and a frequency converter (high signals). The readers are internally microprocessor controlled and communicated with the computer through RS-232 port.

3. New algorithm design

With the aim of updating the UD-802 algorithm, dosemeters from the CIEMAT External Dosimetry Service (EDS) were irradiated at the CIEMAT Reference Laboratory for X-ray at Protection Level employing the X-ray from the narrow-spectrum series given by the ISO 4037-1 (1996) and the ISO water slab phantom. An additional irradiation with high-energy photons from a $^{137}$Cs source was performed at the CIEMAT Reference Laboratory for Gamma Radiation at Protection Level in order to normalize the elements response to perfectly calibrated system conditions. For all the irradiations the dosemeters were exposed in hanger UD-874 and the imparted dose equivalents were around 2 mSv.

The first step in the design of the new algorithm was to characterize the energy response of the four elements of the dosemeter in order to know the real capability of the dosemeter to determine the effective photon energy. With this purpose, groups of twelve dosemeters were irradiated at 0º degrees using the next radiation fields established in ISO 4037-3: N-40, N-60, N-80, N-100, N-120, N-150, N-200, N-250 and N-300. The mean photon energy averaged over the fluence spectrum ranged from 33 keV to 250 keV. The dosemeters were processed following the routine procedure: responses were corrected with individual element correction factors, quality-control dosemeters were included to monitor the reader stability and control dosemeters were employed to evaluate the background signal.

The Figure 1 presents the average net response and standard deviation for each of the four elements for each energy. As expected, the element E3 ($\text{CaSO}_4$:Tm under 300 mg·cm$^{-2}$ plastic filtration) overresponds to low energy photons and the element E4 also presents an overresponse but in less extension due to the additional lead filter. In consequence, the mean ratio E3/E4 was calculated and represented as a function of photon quality to verify its capability for photon energy discrimination (see Figure 2). The error bars represent the maximum and minimum values of the twelve dosemeters irradiated for each radiation field.
FIG. 1. Energy response and standard deviation for each of the four dosemeter elements

FIG. 2. Ratio of the response of element E3 to the response of element E4 as a function of photon energy
From the results plotted in Figure 2 can be inferred that the ratio E3/E4 is valid to discriminate photons of N-40, N-60 and N-80 qualities but its unable to distinguish nor among photons of N-100, N-120 and N-150 qualities neither among N-200, N-250 and N-300 radiation fields. In consequence, the photon branch in the proposed new algorithm was designed to have only five categories of X-ray qualities, namely N-40, N-60, N-80, N-MID (including N-100, N-120 and N-150) and N-HIGH (including N-200, N-250 and N-300). Theoretically, this means the use of an approximated step function to the conversion coefficients \( h_{pk}(10;N) \) and \( h_{pk}(0.07;N) \) from air kerma to the dose equivalents \( Hp(10) \) and \( Hp(0.07) \) established in the ISO 4037-3 for the narrow series. This is illustrated in Figure 3 where the solid line represents the mentioned conversion coefficient curve and the dotted line indicates the approximation.

Once the radiation quality was determined, the calibration factor necessary to convert the element response to the dose equivalents \( Hp(10) \) and \( Hp(0.07) \) was calculated. As can be appreciated in Figure 1, the elements of \( \text{Li}_2\text{B}_4\text{O}_7: \text{Cu} \) are fairly tissue equivalents so the calibration factors will be very close to unity for all radiation qualities. Therefore, the element selected to calibrate the system was the element E2 (\( \text{Li}_2\text{B}_4\text{O}_7: \text{Cu} \) under 300 mg·cm\(^{-2}\)) due to its tissue equivalence and charged particle equilibrium conditions. For the categories N-40, N-60 and N-80 the calibration factors implemented in the new algorithm were directly obtained dividing the imparted dose by the mean response of element E2. The calibration factor for the X-MID and X-HIGH categories were derived as the mean values of calibration factors for N-100, N-120 and N-150 radiation qualities and N-200, N-250 and N-300 radiation fields, respectively. The dose evaluation was then performed multiplying the corresponding calibration factor by the element E2 readout. The calculated total uncertainty of the reported doses was less than 15% at the 95% confidence level.

The procedure described above concluded with the definition of a new photon branch in the standard UD-802 algorithm. This branch consists of five X-ray categories selected as a function of the ratio E3/E4 and including specific calibration factors for each category to evaluate the operational quantities \( Hp(10) \) and \( Hp(0.07) \).
4. Validation

With the intention of testing the performance of the new photon branch to estimate the dose equivalent without prior knowledge of the radiation field in which the dosemeter was used, the new algorithm underwent a simulated blind test in the CIEMAT Reference Laboratory for X-ray at Protection Level.

A group of 120 dosemeters were sent to the irradiation facility with the only indication to be irradiated using different radiation qualities and imparting different reference doses. Both the radiation quality and the imparted dose were completely unknown for the EDS.

The dosemeters were processed as in routine procedure with the standard UD-802 algorithm and, afterwards, the new photon branch was applied to the element readouts in order to have the dose evaluations from both the standard and the modified UD-802 dose algorithms. After the dose evaluation, the reference doses and radiation qualities were supplied by the metrological service and the results were analysed.

The dosemeters for the blind test were irradiated following the next protocol: 9 photon fields at three different reference doses each and with 4 replicates for each irradiation. The photon fields were the same as the employed for the algorithm design, i.e. from N-40 to N-300. The imparted doses for each photon quality varied around 0.2 mSv, 1 mSv and over 2 mSv. At the moment of dosemeter processing this information was unknown for the dosimetric service and it was only revealed after the dose report.

The results analysis was performed by two methods: applying the criteria of the so-called trumpet curves \[8, 9\] and considering the criteria based on bias and standard deviation related to those used in the USA \[3, 10\].

4.1 Criteria based on trumpet curves

The requirements given by the recommendations in ICRP-60 \[11\] and ICRP-75 \[12\] with respect to the acceptable uncertainty for monthly monitoring can be met by the trumpet curves. The upper limit of the trumpet curve is given by

\[
\left( \frac{H_m}{H_t} \right)_{UpperLimit} = 1.5 \left( 1 + \frac{H_0}{2 \cdot H_0 + H_t} \right)
\]

and the lower limit by

\[
\left( \frac{H_m}{H_t} \right)_{LowerLimit} = \frac{1}{1.5} \left( 1 - \frac{2 \cdot H_0}{H_0 + H_t} \right)
\]

where

- \(H_m\) measured dose value
- \(H_t\) conventionally true dose value
- \(H_0\) recording level

According to the ICRP Publications 60 and 75, the equivalent to the recording level for photon based on monthly monitoring \((H_0)\) was considered equal to 0.085 mSv for the analysis.
FIG. 4. Trumpet curve for blind test results evaluated with standard UD-802 algorithm

FIG. 4. Trumpet curve for blind test results evaluated with modified UD-802 algorithm
The Figure 4 presents the results of the blind test using the standard UD-802 dose algorithm and the Figure 5 the analysis of the modified algorithm estimates. As can be easily appreciated the introduction of the new algorithm implies an important improvement in the accuracy of dose evaluation. With the use of the modified algorithm all the evaluated doses fell within the limits of the trumpet curve and, except for the lower dose irradiations, the results were in the range of ± 20%.

4.2 Criteria based on bias (B) and standard deviation (S)

In Spain the performance of dosemeters is assessed using a tolerance criterion of $|B| + S < 0.30$ based on the bias (B) and standard deviation (S) and applied for the whole dose range up to 100 mSv. The equations employed to calculate B and S can be found elsewhere [3].

![Figure 6](image1.png)

**FIG. 6. Criteria based on bias (B) and standard deviation (S) applied to the results evaluated with the standard algorithm**

![Figure 7](image2.png)

**FIG. 7. Criteria based on bias (B) and standard deviation (S) applied to the results evaluated with the modified algorithm**
The analysis of the validation experiment results can be graphically seen in Figures 6 and 7 where the evaluation with both the standard and the proposed algorithm are presented, respectively. The figures include the evaluation of $Hp(10)$ and $Hp(0.07)$ and the tolerance limits are shown for clarity. Each point in the graphs represent one of the radiation fields used in the blind test.

As can be deduced from comparison of Figure 6 and Figure 7, the use of the modified algorithm is a significant advance in the reliability of the doses from X-ray radiations reported by the CIEMAT External Dosimetry Service.

5. Conclusions

The CIEMAT External Dosimetry Service has undertaken a deep revision of the standard UD-802 algorithm employed for dose evaluation. In the EDS experience, most of the dosemeters showing doses different from background doses were irradiated in photon fields; consequently, the first step of this revision was to update the photon branch in the algorithm. The updating includes the definition of new categories of X-ray according to those established in the ISO-4073 series and the implementation of new energy-dependent calibration factors to convert the element readouts to the dose equivalents $Hp(10)$ and $Hp(0.07)$. The algorithm was calibrated for a range of photon energies from 33 to 250 keV under $^{137}$Cs calibrated reader conditions.

The proposed algorithm was tested to validate its reliability in photon dose evaluation. The test consisted of a serial of irradiations with different photon fields covering doses in a range from 0.2 to 4.5 mSv. The doses imparted were evaluated employing the two algorithms, the standard and the proposed, and the results were compared. The analysis of the results was performed applying two different criteria: the trumpet curves and that based on the bias and standard deviation.

Both analyses showed a remarkable improvement in the accuracy and reliability of the dose evaluation when the proposed algorithm is applied. The precision of the doses evaluated with the new algorithm was within the 15% for all radiation qualities.

This work will continue in the future with the revision of the rest of the algorithm branches, with the validation of its performance in mixed field and including a study of the angular dependence.

6. References


