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D_μ—A new concept in industrial low-energy electron dosimetry

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ABSTRACT

Irradiation with low-energy electrons (100–300 keV) results in dose gradients across the thickness of the dosimeters that are typically used for dose measurement at these energies. This leads to different doses being measured with different thickness dosimeters irradiated at the same electron beam, resulting in difficulties in providing traceable dose measurements using reference dosimeters. In order to overcome these problems a new concept is introduced of correcting all measured doses to the average dose in the first micrometer—D_μ. We have applied this concept to dose measurements with dosimeters of different thickness at two electron accelerators operating over a range of energies. The uncertainties of the dose measurements were evaluated, and it was shown that the dose in terms of D_μ was the same at each energy for all dosimeters within the measurement uncertainty. Using the concept of D_μ it is therefore possible to calibrate and measure doses from low-energy electron irradiations with measurement traceability to national standards.

1. Introduction

In the context of radiation processing, "low-energy electrons" are generally thought of as electrons with energy less than 300 keV (ISO/ASTM 51818, 2009). Irradiation with low-energy electrons has traditionally been used in the polymer and printing industry for crosslinking of plastics, radiation grafting and polymerization of monomers for curing purposes. However, recently low-energy electrons have been used for surface sterilization of medical devices or containers for pharmaceutical products, and the dosimetry requirements for these applications are more clearly defined compared to the dosimetry requirements for polymer irradiation. The international standard for radiation sterilization EN ISO 11137 (2006) specifies requirements for measurement traceability to national standards for dose measurements used in all stages of the process. The first step in obtaining measurement traceability is to calibrate the dosimeters correctly. The traceability requirement is normally fulfilled by one of two routes (ISO/ASTM 51261, 2002; Sharpe and Miller, 2009): Either through irradiation of dosimeters at the irradiation facility where the dosimeters are to be used together with reference dosimeters (in-plant irradiation), or by irradiation of the dosimeters at a calibration facility followed by verification irradiation in-plant. For the in-plant irradiation it is necessary that the reference dosimeter and the routine dosimeter to be calibrated receive the same dose. This requirement can be fulfilled without difficulty at high energy electron or gamma irradiation. However, even the thinnest available reference dosimeter – alanine film coated on a substrate – has a thickness (130 μm) that is similar to or larger than the range of low-energy electrons. As a consequence significant dose gradients will occur over the thickness of the dosimeter. The routine dosimeter is often a radiochromic thin film dosimeter with thickness in the range beween 10 and 50 μm. The routine and the reference dosimeter will therefore not receive the same dose when irradiated with low-energy electrons. In-plant irradiation for calibration can therefore not be carried out at low-energy electron accelerators without introducing a measurement error.

It might be assumed that a calibration for these dosimeters that was obtained at 10-MeV electron irradiation can be applied for dose measurement at low-energy electron irradiation if dose measurement was carried out in terms of average dose in the dosimeter. However, this is not true even for the well-characterized alanine dosimeter, the response of which is affected only by temperature, because of effects arising from the non-linear response function. Radiochromic thin film dosimeters are even more problematic because of complex dependence on irradiation conditions such as temperature and relative humidity (Abdel-Fattah and Miller, 1996).

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The considerations above mean that the simplified calibration approach, where routine dosimeters are irradiated at gamma or high-energy electron calibration facilities and used at the low-energy electron facility is not valid. When used it has resulted in inconsistent calibrations giving different dose measurements from different dosimetry systems irradiated at the same low-energy accelerator. It was therefore questioned if the response of the dosimeters that were calibrated at gamma or high-energy electron irradiation was valid, when the dosimeters were irradiated at a low-energy electron facility. This question can be rephrased into two specific questions:

(1) Is the radiation chemical yield of the radiation-induced species that are measured as the response of the dosimeter constant with the energy of the radiation?
(2) Is the thickness of the dosimeter giving rise to measurement errors?

The questions are not easy to answer, because there are no national (or international) standard for low-energy electron dosimetry that can be used as a reference for verification at low energy. However, the questions have been addressed in two papers. In the first paper the development of a calorimeter is described (Helt-Hansen et al, 2005a) that could effectively serve as a primary standard for dose measurement for irradiation with low-energy electrons. The performance of this calorimeter was tested at the Risø 100 keV electron accelerator. The project highlighted the difficulties of low-energy calorimetry, where thermal insulation is insufficient – or non-existent – leading to rapid heat loss of the heated calorimetric body. In addition, major fractions of the beam energy are absorbed in the electron accelerator window and in the air gap between the window and the calorimetric body leading to external heating of the calorimetric body. However, the validity of the calorimeter dose measurement was verified by testing three calorimeters with significantly different construction designs that all gave the same results.

The second paper investigated the dose response of Risø B3 radiochromic film dosimeter (thickness 20 μm) and of alanine film dosimeters (thickness 130 μm) when irradiated with 10 MeV and with 80–120 keV electrons using the low-energy calorimeter as a reference (Helt-Hansen et al, 2005b). The traceability to the national standards at NPL, UK, of the 10 MeV irradiations was ensured through the accreditation of Risø High Dose Reference Laboratory. The conclusion of the investigation was that the response of these two significantly different dosimeters was the same within the measurement uncertainties for the two energies (10 MeV and 100 keV), and it might therefore be assumed that they would exhibit no energy dependence over that energy range. The uncertainties were in the order of 10% ($k=1$) and were caused mainly by the relatively large uncertainty of dose measurement of the low-energy calorimeter.

The conclusion of energy independence of response could only be reached when effects caused by the dosimeter thickness were taken into account. Fig. 1 illustrates the problem. It shows a typical depth dose distribution for an electron accelerator operating at 125 keV. Three commonly used dosimeters (18 μm Risø B3, 50 μm FWT-60 and 130 μm alanine film) are shown, each with thickness and measured average dose for irradiation at this accelerator. The dosimeters measure 3 different doses for irradiation at the same electron accelerator. This is caused by the dose gradients over the thickness of the dosimeter generated at this electron energy, most pronounced at the lowest energy and the thickest dosimeter, where the electrons are completely stopped in the dosimeter material.

When the dosimeter response is measured and converted to dose using a calibration function based on a 10 MeV irradiation, we refer to the obtained dose as the apparent dose (D_{app}). The apparent dose will be a function of the dose distribution within the dosimeter and the shape of the dosimeter response function. Generally the apparent dose D_{app} will not be the same as the average dose (D_{ave}) in the dosimeter (see Section 1.1). The dose through the thickness of the dosimeter will vary, and for a given set of irradiation conditions, the apparent dose will depend on the thickness of the dosimeter, i.e. different thickness dosimeters will measure different apparent doses. In order to overcome this problem we have suggested (Helt-Hansen et al, 2005b) that all dose measurements are specified as average dose to water in the first micrometer of water equivalent absorbing material. This is given the symbol D_{μ} and is independent of dosimeter thickness. A thickness of 1 μm was chosen as a finite thickness that will receive almost the same dose as an infinitely thin layer. It may be considered as a rational choice for radiation sterilization applications where it is comparable to the size of a micro-organism.

The D_{μ}-approach therefore makes it possible to calibrate routine dosimeters by the preferred method (Sharpe and Miller, 2009) of in-plant irradiation at low-energy electron accelerators

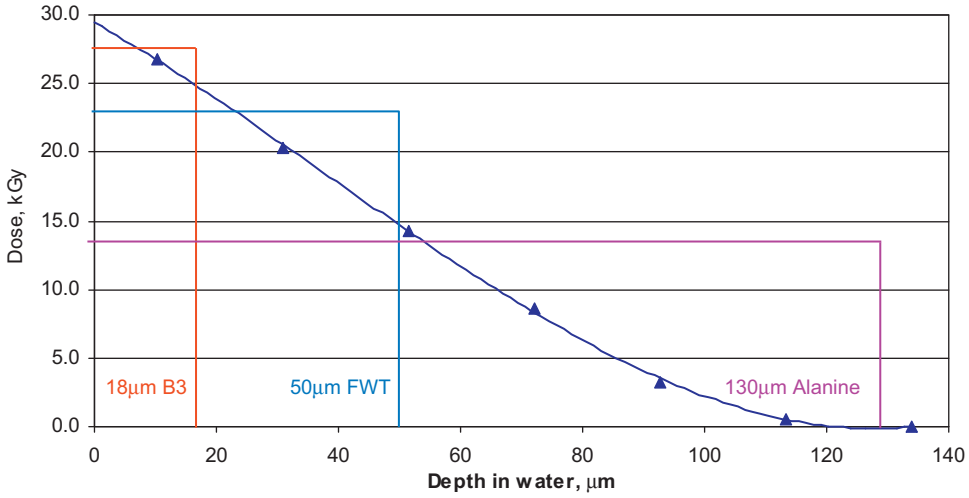

Fig. 1. Typical depth dose distribution for a 125 electron accelerator. Three commonly used dosimeters (18 μm Risø B3, 50 μm FWT-60 and 130 μm alanine film) are shown, each with thickness and measured average dose for irradiation at this accelerator.

with traceability to national standards using the alanine film dosimeter as the reference dosimeter.

1.1. Correction factors for obtaining D_μ

The relationship between D_μ and D_{app} depends strongly on dosimeter response function, dosimeter thickness, dose, radiation energy, accelerator window material and thickness, distance window to dosimeter, and temperature of the air between electron beam window and dosimeter. This relationship must be determined for each set of irradiation conditions.

Three correction factors are considered in order to obtain D_μ from the measured D_{app}. The relationship is described by Eq. (1):

$$D_\mu = \frac{k_{water/dosimeter}}{k_\mu \eta} D_{app} \quad (1)$$

The backscatter correction factor $k_{water/dosimeter}$ is found by Monte Carlo calculations. It corrects for differences in back-scattered electrons from the different materials upon which the dosimeter might be placed. By applying $k_{water/dosimeter}$ it is assured that the dose measured by the dosimeter is expressed as dose to water as if the dosimeter was placed on water. The value of $k_{water/dosimeter}$ is close to 1 when low atomic number materials are used as backing materials, and in most practical situations it can be ignored (Helt-Hansen et al, 2005b).

The dose gradient correction factor k_μ corrects for the geometrical difference in dose caused by the dose gradient through the thickness of the dosimeter. Calculation of the value of k_μ is based on a measured depth dose curve. k_μ is almost always less than 1 in low-energy applications.

The sensitivity correction factor η corrects for the fact the response functions of the dosimeters are not linear. The dose gradient over the thickness of the dosimeter leads to different parts of the dosimeter being irradiated with different doses. The relative response of the dosimeter decreases as the dose increases because of the non-linear response function, and the measured average response does therefore not correspond to the average dose. The calculation of the value of η is based on the measured depth dose function and the response function of the dosimeter. A response function obtained by irradiation at high energy electrons or at gamma can be used for this purpose. η is always equal to or less than 1 for the dosimeters used in low-energy dosimetry.

1.2. General approach for calculation of D_μ from the measured D_{app}

It is not possible to generate a generic Eq. (1) for dose measurement at specified energies, because, as described above, the corrections factors depend on several parameters that will vary from accelerator to accelerator. However, for a given type of dosimeter and a given set of irradiation conditions, a generalized relationship between D_μ and D_{app} can be determined, and for this purpose two sets of data are needed: The depth dose curve and the response function of the dosimeter. The following example shows how the relationship can be found.

The depth dose curve can be obtained by Monte Carlo calculations using the stated irradiation conditions as input data (radiation energy, accelerator window material and thickness, distance window to dosimeter, and temperature of the air between electron beam window and dosimeter). However, we found that the input data for the Monte Carlo calculation were often not well determined, and we therefore decided to rely on measured depth dose curves.

The depth dose curve is measured using a stack of radiochromic film dosimeters that are thin compared to the range of the electrons or by placing a dosimeter film under increasing layers of thin films like a staircase (Helt-Hansen et al, 2005b). Each depth point is determined as the midpoint of the individual dosimeters in the stack or in the staircase. The depth dose curve in a different dosimeter material is determined by scaling with the ratio of the densities of the two materials (ICRU 35, 1984). The ratio of densities can be used as an approximation to translate depth dose curves between different materials if the continuous slowing down approximation (CSDA) ranges are similar. The differences in CSDA ranges are 2% or less for alanine, PVB (base of Risø B3 dosimeters) and water for energies below 400 keV (NIST ESTAR database).

The depth dose data points are fitted by a function, Dose=$P(x)$ that is normalized such that $P(0)=1$.

This function is constrained to give $P(x)=0$ for values of x greater than the depth at which the dose can be considered negligible. The conditioned function is called $P'(x)$.

The dosimeter response function to be used for determination of D_μ as a function of D_{app} is obtained by irradiation in a 10-MeV electron beam. The function is described by a polynomial, $R(D)$ such as the function shown for the alanine film dosimeter in Fig. 2. The zero dose data point is included in the response function in order to avoid un-irradiated parts of the dosimeter influencing the calculation of the sensitivity correction factor.

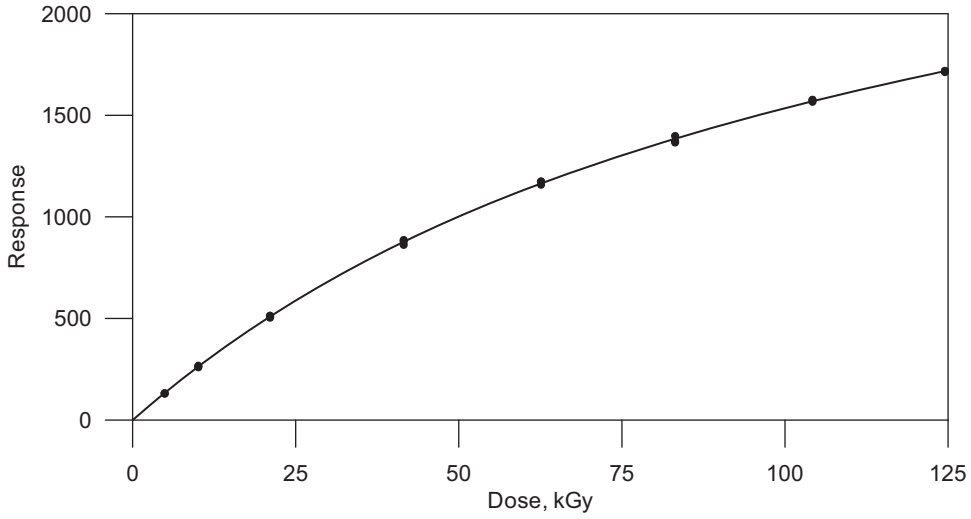

Fig. 2. Response function of alanine film dosimeters used in the example for calculation of relationship between D_μ and D_{app}.

The backscatter correction factor $k_{water/dosimeter}$ is considered insignificant (equal to 1) in this example as only low atomic number materials are involved (Helt-Hansen et al, 2005b).

The dose gradient correction factor k_μ is the ratio between the average dose in the dosimeter.

D_{ave} and the dose at a depth of 0.5 μm water D(0.5 μm water). The latter is taken to be equivalent to the average dose over the first micrometer, D_μ. The correction factor can be determined from the normalized and conditioned depth dose curve, $P'(x)$.

$$k_\mu = \frac{D_{ave}}{D(0.5\,\mu\text{m water})} = \frac{P'_{ave}}{P'(0.5\,\mu\text{m} \times (\rho_{water}/\rho_{dosimeter}))} \quad (2)$$

ρ_{water} is the density of water (1 g/cm^3).

The apparent dose, D_{app}, is the dose corresponding to the measured response of the irradiated dosimeter, R_{meas}. However, if there is a dose gradient through the thickness of the dosimeter, a non-linear response function will lead to an apparent dose that is lower than the average dose of the dosimeter, D_{ave}.

The sensitivity correction factor η is the ratio between the measured apparent dose and the average dose of the dosimeter:

$$\eta = \frac{D_{app}}{D_{ave}} = \frac{D(R_{meas})}{D_{ave}} \quad (3)$$

The value of ratio η depends on the dose level. It is possible to calculate D_{app} if D_{ave} is known, but D_{ave} is not the known value. D_{app} is the measured value, and it is not straightforward to find D_{ave}. An iterative approach can be used, but it is rather complicated, and we recommend using an alternative method: For a given set of irradiation conditions, a number of D_{app} values can be calculated for a number of D_{ave} values. The data sets can be tabulated or plotted against each other, and a function can be generated that can be used for finding D_{ave} for any value of D_{app}. Using this method it is not necessary to determine η, although it can easily be obtained from Eq. (3).

Dividing D_{ave} by k_μ gives D_μ.

Table 1
Measured depth dose distribution in a stack of B3 dosimeters.

Dosimeter layer	Depth (μm)	Corresponding depth in alanine (μm)	Dose (kGy)
1	9.2	7.0	26.8
2	27.6	20.9	20.3
3	46.0	34.8	14.3
4	64.4	48.7	8.6
5	82.8	62.6	3.2
6	101.2	76.5	0.6
7	119.6	90.4	0.0

2. Example of D_μ calculation

This example shows how D_μ is calculated for the alanine film dosimeter irradiated with 125 keV electrons at a specific facility. The example corresponds to the experiment described later (3M facility).

Two dosimetry systems are used in this example:

- Dosimeter 1: Risø B3 radiochromic film, thickness 18.4 μm, density (ρ_1) 1.12 g/cm^3.
- Dosimeter 2: Alanine film, thickness 128 μm, density (ρ_2) 1.482 g/cm^3.

The response function of the alanine dosimeter was obtained by irradiation in a 10-MeV electron beam. The function is described by a 4th order polynomial, $R(D)$ (Fig. 2)

The depth dose curve was measured using a stack of Risø B3 dosimeters. The measured doses of the dosimeters in the stack are shown in Table 1, where the depth is given as the midpoint of each dosimeter. In the third column of the table, the depth is scaled by ρ_1/ρ_2=0.756, as an estimate of the corresponding depth in alanine, see Fig. 3.

The depth dose curve in alanine is fitted by a 3rd order polynomial, $P(x)$ and normalized so $P(0)$=1, and constrained to zero for depths at which the dose is considered negligible. The coefficients of the normalized depth dose curve are given in Table 2.

The relationship between D_{ave} and D_{app} is established by calculating for the specific conditions a number of a D_{app} values for a number of D_{ave} values. The calculations are performed numerically and for that purpose the thickness of the alanine dosimeter is divided into N=128 sub layers, each of 1 μm thickness.

In the following calculations for D_{ave}=9 kGy are carried out in detail as an example.

The average value of the normalized depth dose curve, $P'(x)$, (Fig. 4a) is calculated to be P'_{ave}=0.273.

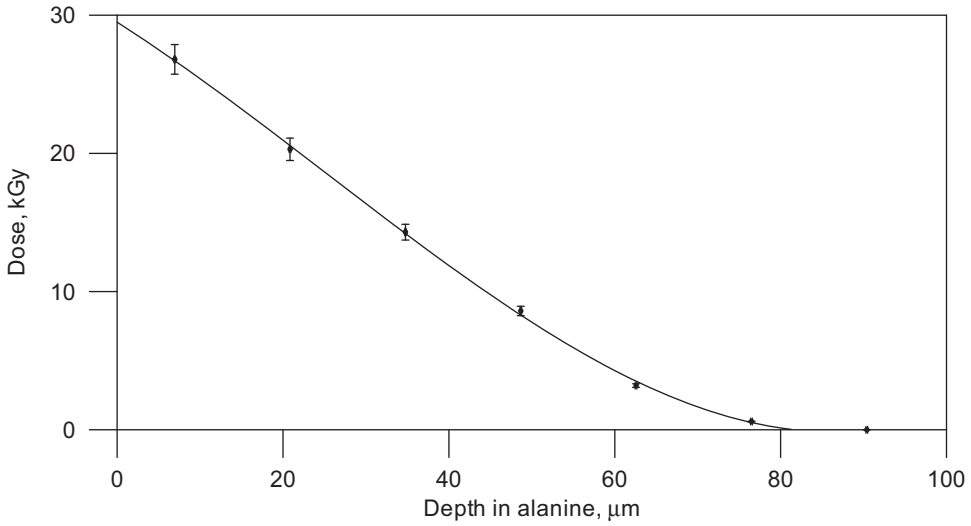

Fig. 3. Depth dose curve in alanine dosimeter irradiated at a 125 keV electron accelerator and used in the example for calculation of relationship between D_μ and D_{app}. Error bars are at 1 standard deviation. The standard deviation for the depth is approximately 0.1 μm.

Table 2
Polynomial coefficients for the normalized depth dose curve in the alanine film dosimeter, $P(x)$.

Order	Coefficient
B_0	1.000E+00
B_1	−1.291E−02
B_2	−1.063E−04
B_3	1.401E−06

$T=B_0+B_1*D+B_2*D^2+B_3*D^3$.

To obtain a depth dose curve that has an average value of 9 kGy, the normalized depth dose curve is multiplied by $(D_{ave}/P'_{ave})=(9/0.273)\,\text{kGy}=33.0\,\text{kGy}$ (Fig. 4a and b).

The response of each sub layer, R', is calculated using the response function of the alanine dosimeter (Fig. 2) for the dose at the midpoint of each sub layer. The response function is divided by the number of sub layers, N, to obtain the response per sub-layer (or per μm) (Fig. 4c).

The response corresponding to an average dose of 9 kGy is found by summing the response of each sub layer: $\sum_{i=1}^{N=128} R'(x_i)=236.1$

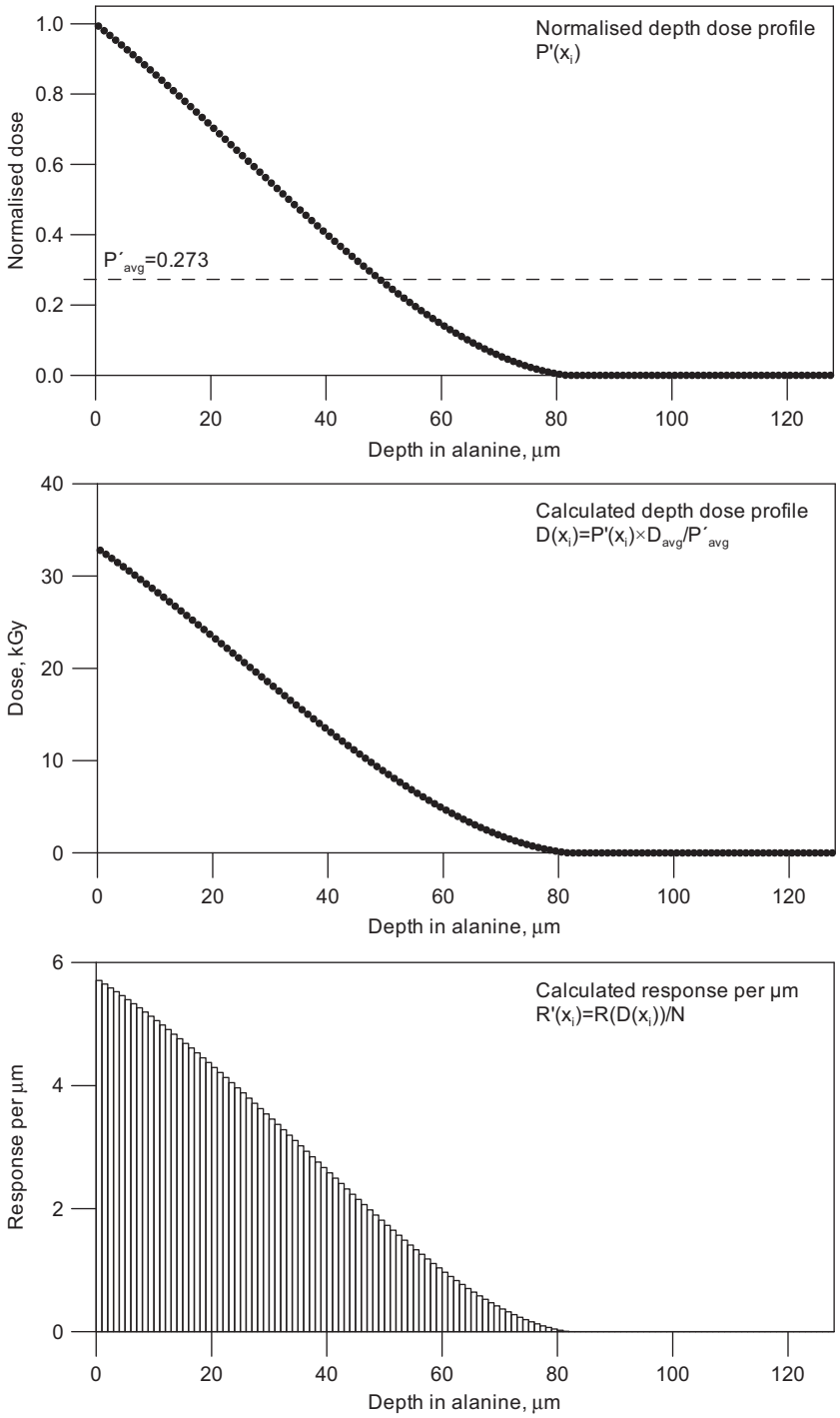

Fig. 4. (a) The depth dose curve in Fig. 3 normalized such that $P(0)=1$. (b) Calculated depth dose curve corresponding to an average dose of 9 kGy. (c) Response per micrometer in the alanine dosimeter.

The apparent dose D_{app} corresponding to D_{ave}=9 kGy is found using the inverse response function: $D_{app}=R^{-1}(236.1)=8.27$ kGy

This calculation is repeated for as many doses as needed in order to be able to establish the relationship $D_{ave}=f(D_{app})$. In Table 3 the calculation has been carried out for 8 values of D_{ave}, and the corresponding value of η is also shown.

The dose gradient correction factor, k_μ, is not dose dependent. It is found as the ratio of the average value of the normalized depth dose curve, $P'(x)$, and the normalized dose in 0.5 μm water Eq. (4). The normalized dose in 0.5 μm water is found by extrapolation of the normalized depth dose curve towards the surface of the dosimeter.

$$k_\mu = \frac{P'_{ave}}{P'(0.5\,\mu\text{m}\times(\rho_{water}/\rho_2))} = \frac{0.273}{P'(0.5/1.482)} = \frac{0.273}{0.996} = 0.274 \tag{4}$$

Table 3
Sensitivity correction factor η for 8 values of D_{ave}.

D_{ave} (kGy)	D_{app} (kGy)	Sensitivity corr. η
1.0	0.99	0.99
3.0	2.92	0.97
5.0	4.77	0.95
7.0	6.56	0.94
9.0	8.27	0.92
11.0	9.91	0.90
13.0	11.49	0.88
15.0	13.00	0.87

Table 4
Values of D_μ for 8 values of D_{ave}.

D_{ave} (kGy)	D_{app} (kGy)	Sensitivity corr. η	Dose gradient corr. k_μ	D_μ (kGy)
1.0	0.99	0.99	0.27	3.6
3.0	2.92	0.97	0.27	10.9
5.0	4.77	0.95	0.27	18.2
7.0	6.56	0.94	0.27	25.5
9.0	8.27	0.92	0.27	32.9
11.0	9.91	0.90	0.27	40.1
13.0	11.49	0.88	0.27	47.4
15.0	13.00	0.87	0.27	54.7

D_μ is the average dose divided by the dose gradient correction factor. For D_{ave}=9 kGy, D_μ is:

$$D_\mu = \frac{D_{ave}}{k_\mu} = \frac{9}{0.274}\,\text{kGy} = 32.9\,\text{kGy} \tag{5}$$

k_μ has been applied in Table 4. This table can be entered for a value the measured D_{app} and the corresponding value of D_μ can be found.

By calculating D_μ for several values of D_{app} a function can be established relating D_μ and D_{app}. This is shown graphically in Fig. 5, where the dashed line represents a polynomial fitted function. The function can be used to determine D_μ for any value of a measured D_{app}.

3. Verification measurements

A series of measurements were carried out to verify the D_μ-approach when applied to dosimetry at industrial low-energy facilities. The aim was to show that using high-energy calibrations for different types of dosimeters would lead to the same value for D_μ when these dosimeters were used for dose measurements at 100–300 keV electron irradiations.

The dosimeters that were used are given in Table 5.

The dosimeters were placed on 1-mm polystyrene plates for the irradiation at the two accelerators. All dosimeters were placed close to the centre of the irradiation zone in order to ensure that the dosimeters on each plate were irradiated with the same beam at the same condition. After irradiation, the radiochromic films were heated in accordance with the instructions for each dosimeter type in order to stabilize the radiation-induced colour.

Each dosimeter type had previously been calibrated by irradiation at a 10 MeV electron accelerator (Rhodotron type, Sterigenics, DK). The doses were measured with alanine reference dosimeters from Risø High Dose Reference Laboratory with traceability to NPL, UK. The environmental conditions experienced by the dosimeters during calibration and irradiation at the low-energy electron beams will be different, but the magnitude of any resultant effects will be small in comparison to the size of the correction factors that the experiment was designed to verify.

Irradiations were carried out at two electron accelerators: Electron Crosslinking AB, Halmstad, Sweden and 3M Corporate Research, St. Paul, MN, USA. The general data for the two accelerators are given in Table 6.

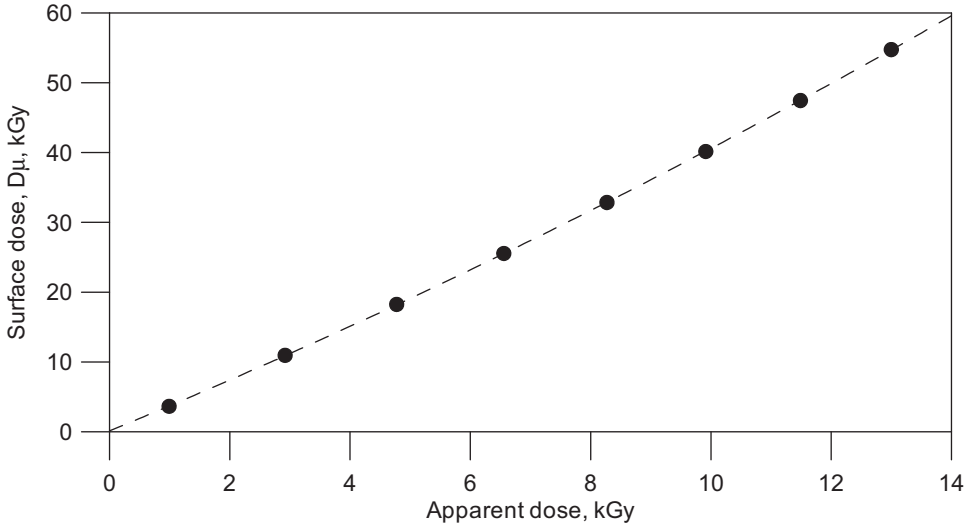

Fig. 5. D_μ, as a function of D_{app}. This function is only valid for the specific conditions of this experiment: 128 μm alanine dosimeters irradiated at the 3M facility with 125 keV electrons.

Table 5
Dosimeters used in this work.

	Crosslinking EC-LAB 400	*3M*	Thickness (μm)	*Measurement*
Alanine film, Kodak	Batch 307	Batch 308	130	Bruker EMS-104 Risø
Risø B3 (not packaged)	Batch B3-02, 8.200.1		17	Scanner+RisøScan
Crosslinking G1A10 (grey films)	Batch, 6 710 023		12	DR 020 Crosslinking
GEX DoseStix without package		Batch BB	18	Genesys 20 Risø
GEX DoseStix without package		Batch BA	17	Genesys 20 GEX
FWT-60		1081	47	Genesys 20 GEX

Table 6
General characteristics of the electron accelerators used in this work.

	Crosslinking EC-LAB 400	*3M*
Energy range	100–300 keV	100–300 keV
Beam current range	1–50 mA	2–20 mA
Product speed through beam zone	30 m/min	10 m/min
Extended beam	Scanned	Long cathode
Beam window	12 μm titanium	13 μm titanium
Distance window–dosimeter	33 mm	47 mm

The Electron Crosslinking EC-LAB 400 accelerator is a laboratory model with a vertical, scanned beam. Samples or dosimeters are placed on a tray that is passed under the beam at the selected speed. The tray height can be adjusted to different window-to-dosimeter distances.

The 3M accelerator is a pilot scale machine for experiments where long webs of materials are passing at constant speed under the beam. In this experiment plates with dosimeters were affixed to the web and moved under the beam. A constant distance window-to-dosimeter was ensured as the web moved under the beam in close contact with a metal backing.

Depth dose curves were measured with stacks of Risø B3 dosimeter films for both accelerators at each energy used in this experiment. The dosimeter films were measured with a scanner and RisøScan software (Helt-Hansen and Miller, 2004). The depth dose curves in Fig. 6 (Crosslinking) and Fig. 7 (3M) show significant differences for the same energies at the two accelerators. These differences are caused by differences in window material and thickness, by differences in window-to-dosimeter distance and by differences in temperature of the air between window and dosimeter.

After irradiation each dosimeter was measured and a value for the apparent dose D_{app} was obtained based on the 10 MeV response function for each dosimeter system.

The correction factor k_{μ} (dose gradient) was calculated and the relationship $D_{ave}=f(D_{app})$ was established for each set of irradiation conditions, and D_{μ} was calculated from the value of D_{app}. The backscatter correction factor $k_{water/dosimeter}$ was assumed to be unity, because only low atomic number materials were used in these experiments.

An example of the results is given in Table 7 for irradiation at the Crosslinking electron accelerator at 100 keV. The correction by k_{μ} (dose gradient) is large at this low energy, in particular for the thickest dosimeter (the alanine film) where also the difference between D_{app} and D_{ave} is also large. For the thinner radiochromic film dosimeters D_{ave} and D_{app} are practically equal not leading to any correction, and k_{μ} gives rise to 11–12% correction.

The alanine film dosimeter was considered as the reference dosimeter, and the doses measured by the other dosimeters were compared with the dose found by the alanine dosimeter with all doses expressed as D_{μ}.

Table 8 shows an example for irradiation at the 3M electron accelerator which leads to the same conclusions as for the irradiations at the Crosslinking accelerator, only in this case the corrections from D_{app} to D_{μ} are larger due the lower effective energy of the 3M accelerator.

All results from the two electron accelerators are averaged in Table 9. The closeness of the overall ratio to unity is a good indication of the validity of the approach. There is also no significant difference in the average doses of the different film dosimeter types. The scatter associated with results from the 3M accelerator was significantly higher than that associated with the Crosslinking accelerator, which probably reflects the intrinsic differences in the machines and the method of product transport. The overall standard deviation of ~10% can be taken as a realistic value of the standard uncertainty of a single dose measurement using this approach. A complete uncertainty analysis would also include the uncertainty of the 10 MeV alanine calibration, typically around 2% ($k=1$), and the uncertainty associated with the use of this calibration at low electron energies. The latter uncertainty has been quoted to be the order of 10% (Helt-Hansen et al, 2005b), but the results in this paper, particularly the close agreement between independent film and alanine doses given in Table 9, indicate that 10% is probably an overestimate.

The average correction factors for each energy are given in Table 10 (Crosslinking) and Table 11 (3M). The corrections to be applied to D_{app} to obtain D_{μ} are relatively small for the thinnest dosimeters (DoseStix and G1A10) and become more significant for increasing thickness of the dosimeter.

At energies close to 200 keV the correction from D_{app} to D_{μ} becomes close to 1 (no correction) for all dosimeters, because at this energy there is almost no dose gradient through the thickness of the dosimeter. At 250 and 300 keV, on the other hand, the correction becomes less than 1, which means the D_{μ} becomes smaller than D_{app}, because at energies higher than approximately 200 keV the dosimeters are at the ascending part of the depth dose curve. The corrections at 200 keV and higher are small and are most significant for the relatively thick alanine film dosimeter.

The calibration method utilizing the D_{μ} principle strictly applies only to the irradiation conditions under which the calibration was obtained. In routine use, the electron energy at the location of the dosimeter may be different from the energy at the position used for calibration because of, for example, differences in air gap distance. In principle a new calibration would be required under these conditions, but in practice the effect is a function of dosimeter thickness and is not likely to be significant for a dosimeter with thickness less than 20 μm. For thicker dosimeters, the effects of energy changes need to be considered on a case-by-case basis.

4. Conclusion

We have introduced a new dosimetric term D_{μ}, the average dose to water in the first micrometer of a water equivalent absorber that eliminates the effects of dose gradients through the thickness of the dosimeter when irradiated with low-energy electrons.

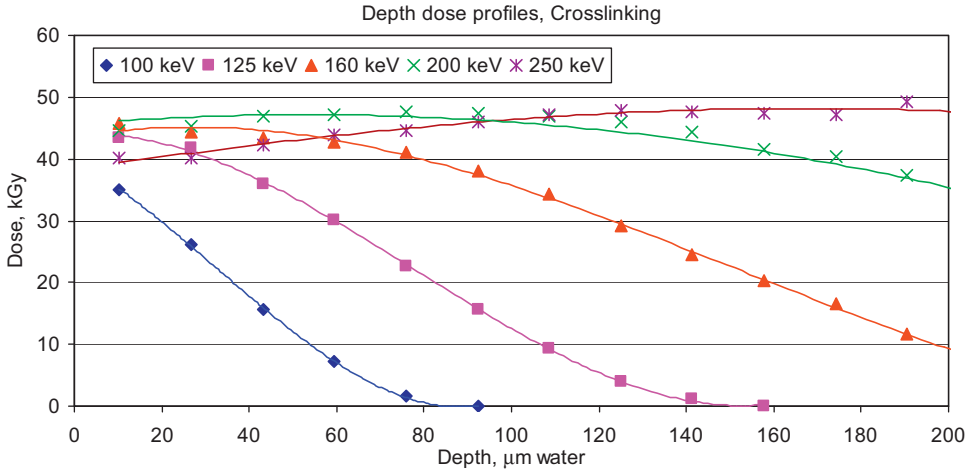

Fig. 6. Measured depth dose curves at the Electron Crosslinking accelerator.

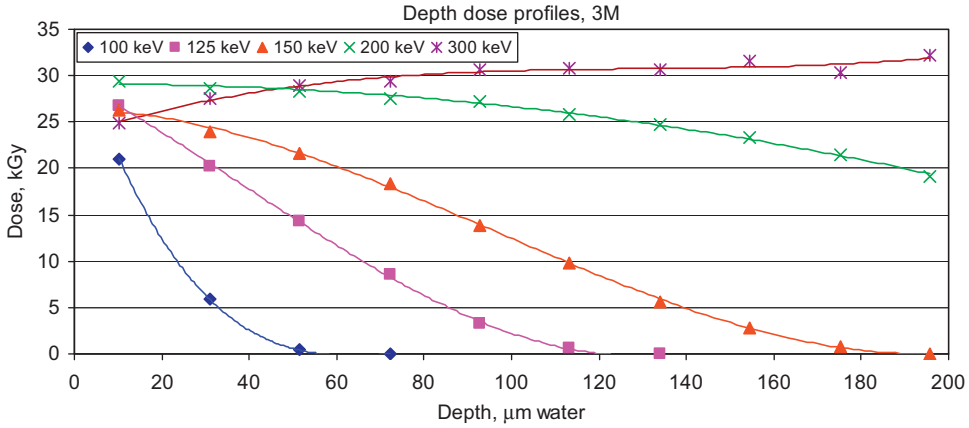

Fig. 7. Measured depth dose curves at the 3M accelerator.

Table 7
Calculation of D_μ for irradiation at the Crosslinking accelerator at 100 keV.

Crosslinking, 100 keV	D_{app}	D_{avg}	k_μ		D_μ(water)	Ratio to alanine		
Dosimeter	kGy	kGy	Dose gradient correction factor	Combined correction factor $1/(k_\mu * \eta)$	kGy		Average	St. dev.
Alanine 132 µm	2.82	2.95	0.19	5.51	15.5			
	3.68	3.91	0.19	5.59	20.6			
	5.12	5.59	0.19	5.75	29.4			
	6.89	7.80	0.19	5.96	41.1			
Risø B3 18 µm	12.8	12.8	0.89	1.12	14.4	0.93		
	17.0	17.0	0.89	1.12	19.1	0.93		
	25.8	25.8	0.89	1.12	28.9	0.98		
	35.1	35.1	0.89	1.12	39.4	0.96	0.95	0.03
Crosslinking G1A10 12 µm	14.5	14.5	0.88	1.14	16.6	1.07		
	18.7	18.7	0.88	1.14	21.4	1.04		
	27.4	27.4	0.88	1.14	31.3	1.06		
	35.6	35.6	0.88	1.14	40.7	0.99	1.04	0.04

We have shown that calibration of routine dosimeters can be carried out by in-plant irradiation at low-energy electron accelerators by irradiating the routine dosimeters and the reference dosimeters together so that they receive the same dose. The response function for the routine dosimeter can be generated in terms of its measured response versus D_μ as measured with the reference dosimeter. In subsequent dose measurements, the dose measured with the routine dosimeter will be in terms of D_μ.

Verification that a calibration of a routine dosimeter obtained by gamma or by 10-MeV electron irradiation is valid at low-energy irradiation can be carried out in the same way as an in-plant calibration. In this case it is necessary to calculate D_μ for both the reference dosimeter and for the routine dosimeter, but as described above, for dosimeters that are thinner than approximately 20 µm the difference between D_{app} and D_μ is small and at energies above 125 keV it may be acceptable not to apply corrections to D_{app}.

Table 8
Correction factors and calculation of D_μ for irradiation at the 3M accelerator at 100 keV.

3M, 100 keV	D_{app}	D_{avg}	k_μ		D_μ(water)			
Dosimeter	kGy	kGy	Dose gradient correction factor	Combined correction factor $1/(k_\mu * \eta)$	kGy			
Alanine 128 μm	2.06	2.21	0.10	11.33	23.3			
	2.85	3.17	0.10	11.70	33.4			
	3.26	3.69	0.10	11.91	38.9	Ratio to alanine		
	4.53	5.43	0.10	12.61	57.2		Average	St. dev.
FarWest 43.5 μm	5.63	5.72	0.36	2.82	15.9	0.68		
	9.32	9.57	0.36	2.85	26.6	0.80		
	10.8	11.2	0.36	2.86	31.0	0.80		
	21.7	23.1	0.36	2.96	64.3	1.12	0.85	0.19
B3 BB DoseStix (Risø) 17.6 μm	15.8	15.9	0.67	1.51	23.9	1.02		
	24.5	24.7	0.67	1.51	37.1	1.11		
	30.5	30.8	0.67	1.51	46.2	1.19		
	43.3	43.8	0.67	1.52	65.7	1.15	1.12	0.07
B3 BA DoseStix(GEX) 17.0 μm	13.1	13.2	0.68	1.48	19.4	0.83		
	18.1	18.2	0.68	1.49	26.9	0.81		
	21.9	22.1	0.68	1.49	32.6	0.84		
	29.9	30.2	0.68	1.49	44.6	0.78	0.81	0.03

Table 9
Average ratios from $D_{dosimeter}$ to $D_{alanine}$ in terms of D_μ for all dosimeters irradiated at the two electron accelerators.

Overall average		
	Ratio	St. dev.
All	1.00	0.08
Crosslinking	0.97	0.04
3M	1.02	0.10

Table 10
Crosslinking accelerator.

Energy→	**100**	**125**	**160**	**200**	**250**
Alanine	5.70	2.75	1.39	0.98	0.89
DoseStix	1.12	1.02	1.01	0.97	0.99
G1A10	1.14	1.02	1.01	0.95	0.99

Average correction factors $1/(k_\mu * \eta)$.

Table 11
3M accelerator.

Energy→	**100**	**125**	**150**	**200**	**300**
Alanine	11.89	3.92	2.08	1.13	0.84
Far West	2.87	1.35	1.10	1.02	0.88
DoseStix	1.50	1.11	1.03	1.01	0.94

Average correction factors $1/(k_\mu * \eta)$.

In most practical situations the user does therefore not have to carry out corrections to the routine dosimetry system in order to report dose as D_μ. The calibration laboratory must be able to provide dose measurements in terms of D_μ, and the user can then calibrate in terms of dosimeter response versus D_μ.

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