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Original research article

High accuracy dosimetry with small pieces of Gafchromic films

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ABSTRACT

Aim: To investigate the influence of several factors on the accuracy of dose measurements and feasibility of application of small Gafchromic detectors for postal audit.

Background: Our experience showed that precision of dose measurements with small pieces of Gafchromic films may be significantly improved.

Materials and methods: Gafchromic films with dimensions of 1×1 , 2×2 and 3×3 cm² were exposed to 6 MV X-rays at dose levels of 50 cGy–210 cGy. The single- and multichannel methods (MM) were used for dose measurements. Detectors were scanned with an Epson V750PRO flatbed colour scanner. For 1×1 and larger detector sizes, separate calibration curves were established. The influence of the following factors was investigated: the heterogeneity of Gafchromic detectors group for single- and MM, ambient thermal detector conditions, the dose delivered on the measurement accuracy, application of two separate calibration curves for the smallest and larger pieces of films.

Results: The MM improves significantly the precision of dose measurement. The uncertainty attributed to detector active layer differences and scanner instabilities was about 1 cGy (1 StDev) regardless of dose and detector size. The ambient temperature of the environment in which films were stored after irradiation influenced the dose reading. Significant difference of transmission for detectors sized 1×1 and 2×2 cm² was observed. The maximal difference between applied dose and dose reading performed was 1.1%.

Conclusions: The MM with a scaling protocol leads to a very high precision of dose measurements. The ambient thermal detector environment causes significant changes of measured signal. The detector size has relevant impact on dose reading.

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1. Background

Film dosimetry using Gafchromic films is a method of dose distributions measurement used in quality control of treatment planning systems (TPS) or linear accelerators as well as for

verification of dose distributions, especially for IMRT or VMAT techniques. Gafchromic films are very good dosimeters due to: high spatial resolution, weak energy dependence in kV–MV range, near tissue equivalence, slight UV/light sensitivity, no need of post-exposure processing.

Gafchromic films develop a colored image upon exposure to radiation. RGB flatbed colour scanners are recommended to analyze the signals obtained with a Gafchromic film. There are several different protocols used to convert scanner signals into the absorbed dose.^{1–4}

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Recently, a novel approach to film dosimetry called multichannel film dosimetry^{5–9} has been introduced. This method allows a separation of the measured signal into two parts: the dose-dependent, and the other one which is dose-independent. The latter, which makes this method more accurate, enables the correction of variety of disturbances, i.e. the non-uniformities of the active coating layer.

There are several methods used for in vivo dosimetry. Also Gafchromic films in the form of small detectors with dimensions of $1 \times 1 \text{ cm}^2$ or $2 \times 2 \text{ cm}^2$ are used for in vivo dosimetry.¹⁰ They are quite often used in Total Body Irradiation^{11–13} as well as to measure the dose inside the oral cavity in IMRT treatments.¹⁴

Medical Physics Department provides postal TLD audits for Polish radiotherapy centers. While the method is well established and has been used for many years, we are looking for another method, which allows measurements with a better accuracy.

2. Aim

The aim of this work was to estimate the uncertainty of measurements performed with small pieces of Gafchromic films using a multichannel method and to investigate feasibility of the method for dosimetric postal audit. The influence of several factors on the measurement uncertainty was investigated.

3. Materials and methods

3.1. The notion of multichannel film dosimetry

In this paper, multichannel signal correction was applied. The dependence of the pixel value $PV(D)$ on the dose is different in each of the three color channels. The slope of the $PV(D)$ curve is the most marked in the red channel. In the blue channel the signal is less sensitive to the dose and more sensitive to the disturbance factors, while in the red channel, the signal is much more sensitive to the dose and less sensitive to the disturbance factors. It can be demonstrated that nonuniformities in the thickness of the film active layer cause changes in the scanned optical density which are proportional to the factor describing thickness disturbance. The multichannel correction method, thanks to measurements carried out in three channels separately, allows a limitation of the influence of nonuniformities of the active layer on the result of the measurement.

3.2. Film dosimetry using small Gafchromic detectors

In our department, film dosimetry using small Gafchromic detectors has been applied to in vivo dosimetry to measure doses to eye lenses or the skin, especially in the TBI technique. For a few years, we have been using the single channel method for this purpose, and the main aim of this work was to verify how we could improve the precision of dose measurements using the multichannel correction method and calibration curves scaling procedure. The answer to this question was

obtained by carrying out a series of measurements, which are described below.

3.3. The calibration curves scaling protocol

For the purpose of this work, we used the calibration curves scaling protocol proposed by Lewis.⁸ For all the films with the same batch number, only one set of reference calibration curves $PV_{x,cal}(D)$ was measured (x – means one of the R,G,B channels). The actual calibration curves $PV_x(D)$ for each dosimetry session were determined by scaling the reference calibration curves according to the following formula:

$$PV_x(D) = a_x + b_x * PV_{x,cal}(D) \quad (1)$$

In order to derive coefficients a_x and b_x in Eq. (1), two points of actual dose response curves are needed; therefore, for each measuring session, we used two groups of calibration films together with application films. Calibration films from one group were exposed, after exposing of the application films, to a dose close to the maximum dose D_{max} , while films from the second group remained unexposed.

The a , b parameters are obtained by solving the following two linear equations:

$$PV_x(D_{max}) = a_x + b_x * PV_{x,cal}(D_{max}) \quad (2)$$

$$PV_x(D = 0) = a_x + b_x * PV_{x,cal}(D = 0) \quad (3)$$

The above Eq. (1) is fulfilled regardless of: the scanner model, the temperature and the time between the exposure and the scanning and also of the film orientation during the scanning process.⁸ Both the calibration and the application films were scanned together, which eliminates the influence of the scanner variability on the results.

3.4. Radiochromic films

In this study, we used Ashland Gafchromic EBT3 films with sheet dimensions of $8'' \times 10''$. These films contain a special microscopic silica particles surface in the polyester layer which provides a gap between the film surface and the glass window in the scanner. This layer prevents the formation of Newton's rings patterns. The films were kept in black envelopes to minimize exposure to light. After irradiation, all film dosimeters from the same measurement series were kept in the same conditions.

In accordance with the purpose of this work, the measurements were carried out with small pieces of Gafchromic films with dimensions of 1×1 , 2×2 , $3 \times 3 \text{ cm}^2$. All detectors were cut from Gafchromic sheets with the same batch number (#03311402).

3.5. Irradiation procedure

The irradiation of the films was carried out with 6 MV photons on an Elekta Synergy linac. The dosimeters were placed in a solid water phantom composed of 30×30 sheets of solid water at the depth of 10 cm, perpendicularly to the central axis. The source-to-dosimeter distance was 100 cm. The exposure was

performed with 10×10 cm fields. Before all measurements, the reference calibration curve was established. The eight groups of film dosimeters were exposed to doses in a range from 0 to 300 cGy.

The reference calibration curves $PV_{x,cal}(D)$ were obtained by fitting the rational function to dose-response data using the least squares method:

$$PV_{x,cal}(D) = \frac{\alpha_x + \beta_x D}{\gamma_x + D} \quad (4)$$

where: $PV_{x,cal}$ – pixel value, D – dose, $\alpha_x, \beta_x, \gamma_x$ – equation parameters to be fitted.

The calibration procedures for film detectors with dimensions of 1×1 , 2×2 cm² and 3×3 cm² were performed separately. Depending on the dosimeter size, we exposed simultaneously: 8 dosimeters with dimensions of 1×1 cm², 4 dosimeters with 2×2 cm² dimensions and 1 dosimeter with dimensions of 3×3 cm². The dosimeters were placed in the phantom symmetrically to the axis of the beam.

3.6. Scanning

The dosimeters were scanned with an Epson V750 PRO flatbed colour scanner which generates a response in three channels: red, green and blue at the depth of 16 bit per color channel and a spatial resolution of 72 dpi. The scanning was conducted in a transmission mode and software settings were chosen to disable all color correction options. The films were always scanned in the same orientation in relation to the scan direction. To minimize the influence of the lateral differences of scanner response, all the film samples were placed in the center of the scanner. To account for post exposure changes, we used an appropriate period of time between the exposure and the scanning. This period was at least four times longer than the interval between the exposure of the application films and the calibration films. Consequently, the measurement errors were limited to less than 0.5%.⁸

3.7. Image analysis

Scanned images were analyzed with our own dedicated computer program written in Delphi 5. The program calculates doses using multichannel correction according to the method described by Micke.⁵ For each single experiment, the actual calibration curve was established. Readings were always carried out in the selected region of interest dependent on the dosimeter size. The region of interest was set to 0.6×0.6 cm² (~290 points) for 1×1 cm², 1.5×1.5 cm² (~1800 points) for 2×2 cm² dosimeters and 2.5×2.5 cm² (~5040 points) for 3×3 cm² dosimeters.

3.7.1. The influence of the heterogeneity of the Gafchromic dosimeters group on the dose after implementation of multichannel correction

The Gafchromic film active layer, containing a monomer polymerized upon irradiation, is not perfectly homogenous, even for Gafchromic pieces obtained from one sheet of the film, which has an impact on the measured doses. The uncertainty resulted from this heterogeneity was calculated as the

standard deviation of signals registered by a group of 40 dosimeters exposed to the same dose value. The analysis was performed for dosimeters with 1×1 and 2×2 cm² dimensions separately for two dose values of 50 and 200 cGy. The stability of the linac was controlled by an ionization chamber placed outside the field. We compared results obtained before and after implementation of multichannel correction.

3.7.2. The influence of the dosimeter size on dose measurements

The dosimeter size implies the size of the region of interest selected for dose reading, and the pixel range over which the reading was averaged. We analyzed the influence of the dosimeter size on measured doses. All dosimeters were exposed to 200 cGy. We analyzed signals of 40 dosimeters 1×1 cm², 12 dosimeters 2×2 cm² and 8 dosimeters 3×3 cm². All dose readings were carried out with the application of calibration curves obtained for 1×1 cm² film dosimeters and scaling calibration procedure performed for eight 1×1 cm² dosimeters. We compared the average dose values obtained for all dosimeter sizes separately.

3.7.3. The influence of ambient thermal dosimeter conditions on dose measurements

We analyzed the impact of thermal conditions in which dosimeters were kept after irradiation. Sixteen 2×2 cm² dosimeters were irradiated with a dose value of 200 cGy. After exposure, half of the dosimeters were kept in the fridge at the temperature of about 10 ± 1 °C. The rest of the dosimeters were kept in the room temperature of about 22 ± 1 °C. The dosimeters were kept in these two temperatures separately for 7 days and after that the registered doses were read out.

3.7.4. Analysis of measured dose uncertainties after the implementation of multichannel correction and the calibration curves scaling protocol

To analyze dose measurement precision after the implementation of new procedures, we performed 10 series of exposures. The 2×2 cm² dosimeters were exposed to dose values of 50, 100, 150, 200 cGy (DV) in each of the series. For each experiment, the actual calibration curve was established and the multichannel correction method was applied. Scanning was carried out on the next day after irradiation. The uncertainties for this method were estimated by calculating average value (Σ) and standard deviation (σ) of differences between measured and delivered doses. The dose in each measurement point was calculated as an average reading from 4 dosimeters.

$$D_j^{DV} = \frac{\sum_{k=1}^4 d_{j,k}^{DV}}{4}, j = 1, 2, \dots, 10 \quad (5)$$

where $d_{j,k}^{DV}$ is the dose measured for a single dosimeter, for j -th series of measurement and for delivered dose of DV.

$$\Sigma = \frac{\sum_{DV} \sum_{j=1}^{10} (D_j^{DV} - DV)}{40} \quad (6)$$

$$\sigma = \sqrt{\frac{\sum_{DV} \sum_{j=1}^{10} (D_j^{DV} - DV - \sum)^2}{39}} \quad (7)$$

We also calculated the value of confidence limit¹⁵ which is a valuable parameter describing uncertainties of dose measurements. The parameter was used first to report deviations between measurements and calculations for a large number of points in QA tests of treatment planning systems. Confidence limit is defined by the equation:

$$CL = | \sum | + 1.5 \cdot \sigma \quad (8)$$

Numerically, CL is equal to the range of dose difference which usually is not exceeded by more than 10% of measuring points ($p=0.1$).

Moreover, for the same set of measurements, we assessed the uncertainties for procedure which uses the single dosimeter reading. The uncertainty was calculated with the formulae (160 reading were obtained):

$$\sigma_s = \sqrt{\frac{\sum_{DV} \sum_{j=1}^{10} \sum_{i=1}^4 (d_{j,i}^{DV} - DV - \Sigma)^2}{159}} \quad (9)$$

The uncertainties obtained for the single red channel and multichannel methods were compared. In the single channel method, the reading was done in the red channel only and the calibration curve was obtained in an independent experiment. Scaling calibration curves protocol was not used.

3.7.5. Simulation of postal dosimetric audit

The aim was to measure five dose levels (close to 200 cGy) with 2×2 cm² Gafchromic dosimeters using the multichannel and scaling protocols and with irradiation time schedule required by the postal audit procedure. The main difference in comparison with daily dosimetry procedure (e.g. in vivo dosimetry) is that calibration dosimeters and audit participant dosimeters are irradiated with one week time difference. The actual calibration curves were established by the exposure of 4 dosimeters to a dose of 200 cGy, and by leaving 4 other dosimeters unexposed. After one week, we irradiated the application samples with dose values of: 190, 195, 200, 205 and 210 cGy. For each dose level three samples of dosimeters were irradiated. There were 4 groups (A–D) of application and reference samples. During the period of time between the exposure and reading, all the dosimeters were kept in the same environmental conditions (temperature $\sim 22^\circ\text{C}$, room darkening). The scanning was performed after one month, so the period of time between film exposure and scanning exceeded four times the interval between the exposure of the calibration and application samples.⁸ In the scanning process, the rule was to scan two reference samples with 0 and 200 cGy before and after scanning the application films from one series (that is 190–210 cGy). This was done in order to take into account instabilities of the scanner.

Table 1 – The uncertainties of doses measured with single and triple-channel methods given in terms of standard deviation.

Dosimeter size [cm ²]	Dose [cGy]	σ [cGy]	
		Red channel	Multichannel correction
2×2	50	2.1	1.0
	200	3.4	0.9
1×1	50	1.5	0.6
	200	2.8	1.0

Table 2 – Doses measured with dosimeters of different sizes exposed to 200 cGy. The uncertainty is given in terms of standard deviation and a coverage factor of $k=2$.

Dosimeter size [cm ²]	D_{av} [cGy]
1×1	200.3 ± 0.3
2×2	196.4 ± 0.6
3×3	197.2 ± 0.7

4. Results

4.1. The influence of the heterogeneity of the Gafchromic dosimeters group on the dose after implementation of multichannel correction

Table 1 presents the values of dose standard deviation [cGy] estimated for the group of 40 Gafchromic dosimeters with dimensions of 1×1 and 2×2 cm² using two methods of analysis: in the red color channel and that with the use of multichannel correction.

The results in Table 1 demonstrate that the multichannel correction method improved the precision of dose measurement significantly.

4.2. The influence of the dosimeter size on dose measurements

Table 2 shows the average dose values evaluated for three sizes of dosimeters: 1×1 , 2×2 , 3×3 cm², using the calibration curve obtained for the 1×1 cm² dosimeter.

The uncertainties of average dose values were assessed with 95% confidence level and they represent only type B uncertainties. They do not take into account type A uncertainties which are influenced mainly by the calibration procedure. Table 2 depicts a significant decrease of dose value where the size of the dosimeter increases from 1×1 to 2×2 cm².

4.3. The influence of ambient thermal dosimeter conditions on dose measurements

Table 3 presents the dose values of films kept in different ambient temperatures.

The ambient temperature in which the films were stored after irradiation had a significant influence on dose readings.

Table 3 – The average doses in the set of eight dosimeters which were read out after a week of storage in different surrounding temperatures.

Conditions	D_{av} [cGy]
Room [22 °C]	207.2 ± 0.7
Fridge [10 °C]	201.8 ± 0.7

Table 4 – The standard deviations and the average, maximum and minimum differences between measured and expected doses for three methods of measurements.

Method	σ_s [cGy]	Σ [cGy]	Δ_{max} [cGy]	Δ_{min} [cGy]
Triple-channel correction, 4 dosimeters	0.9	0.4	2.1	–2.1
Triple-channel correction, 1 dosimeter	1.2	0.4	3.6	–2.6
Red channel, 4 dosimeters	3.2	6.9	13.6	–1.6

Table 5 – The results of audit simulation.

Series, D[cGy]	$\Delta\%$			
	A	B	C	D
190	0.7	0.8	–0.3	0.1
195	0.9	0.8	0.0	0.2
200	0.6	1.1	0.0	0.4
205	0.1	1.0	0.5	0.3
210	–0.5	1.0	–0.1	–0.1

where: $\Delta\%$ – percentage error between exposed dose value and average response dose value; A, B, C, D – measurement series; D [cGy] – exposed dose value.

4.4. Analysis of measured doses uncertainties after the implementation of multichannel correction and the calibration curves scaling protocol

The parameters describing uncertainties of doses measured after applying the multichannel correction and calibration curves scaling protocol are presented in Table 4. Determining the dose value as an average value of 4 dosimeters readings gives an average error (the average difference between the dose delivered and measured) of the evaluated dose value of 0.4 cGy and a standard deviation value of 0.9 cGy. The value of confidence limit for analyzed group of dosimeters is equal to 1.8 cGy.

In Table 4 we collect the results obtained for triple-channel correction protocol and 4 dosimeters measurements, for triple-channel correction protocol and 1 dosimeter measurement, and for single channel protocol with 4 dosimeters measurements.

4.5. Simulation of the dosimetric postal audit

The results of audit simulation, presented in Table 5, are expressed as percentage errors between exposed dose values and average response dose values for 5 dose levels. The readings were done in 4 series (A,B,C,D).

The maximal percentage difference between the applied dose value and the dose reading performed one month after irradiation was 1.1%. Gafchromic dosimeters used in the procedure adopting multichannel signal correction and calibration curves scaling seems to be a promising dosimetric tool which can be implemented in the dosimetry postal audit.

5. Discussion

The multichannel correction method improved the precision of dose measurement significantly. For a dose value of 200 cGy, the decrease is about three-fold. The uncertainties attributed to dosimeter active layer thickness perturbations and scanner instabilities are estimated to be ~1 cGy (one standard deviation), regardless of dose and dosimeter size.

There is a significant influence of the size of dosimeter on the measured dose. For different sizes of film pieces, significantly different dose values were measured. We observed a decrease of dose value where the size of the dosimeter increased from 1×1 to 2×2 cm². A dose decrease means that the scanner signal (PV) is increasing. This effect may be explained by the increasing of the light scattering from a bigger dosimeter area. For larger dosimeters the difference between the average reading obtained from the smaller region, used for smaller dosimeters, differs from the one used for larger dosimeters negligibly. The calibration curve for very small dosimeters (1×1 cm²) has to be measured separately. From the practical point of view, for 2×2 and 3×3 cm² dosimeters the same calibration curve may be used.

The ambient temperature in which the films were stored after irradiation had a significant influence on dose readings. The value of the percentage difference between average dose determined for dosimeters kept in room conditions and those kept in a refrigerator was of 2.7%. This observation has significant practical consequences. To diminish the uncertainty of dose measurement, all dosimeters from the same series should be kept in the same temperature (the history of the environment temperature should be the same).

Whenever we measure the dose with small samples of Gafchromic films, we use 4 samples placed on each other. The measured dose is determined as an average value of 4 dosimeters readings. This procedure ensures that an average dose error (the average difference between the dose delivered and measured) is less than 0.4 cGy and a standard deviation value is 0.9 cGy. The value of the confidence limit for the analyzed group of dosimeters described by the formulae (8) is equal to 1.8 cGy. From probabilistic point of view, we may expect that more than 90% of measurements would be in the range of ± 1.8 cGy. The largest difference between the dose delivered and measured in all measured groups was 2.1 cGy. The uncertainty of the dose delivered to the Gafchromic dosimeter, checked with the ion chamber, was negligible, smaller than 0.1 cGy. In the dose range of 50–200 cGy, no relevant dependence of the dose error on the dose was observed. Thus, the percentage errors decrease with an increase of the dose.

The uncertainty given in terms of one standard deviation and maximum error calculated for one dosimeter reading (in the group of 160 dosimeters) were higher: 1.2 cGy and 3.6 cGy, respectively. However, the one-channel method is considerably less precise. The largest difference between measured and the expected doses was 13.6 cGy, the standard deviation value was 3.2 cGy. High value of average dose difference for this method (6.9 cGy) confirms the importance of the calibration curves scaling procedure. Lack of this procedure can lead to large systematic errors.

There are at least two methods used for postal dose audits at national or international levels. The most common one is a postal audit performed with thermoluminescent dosimeters.^{16,17} The other one is a postal audit performed with radiophotoluminescent glass rod dosimeter.¹⁸ Measurements with TLDs are very well established. The main limitation of this method is its uncertainty. The uncertainty is 2.4% for high energy X-rays (1 standard deviation). For dose of 200 cGy, the confidence limit calculated according to the formulae number (9) is 4.9 cGy. These data comes from the accredited laboratory established in the Medical Physics Department at the Cancer Center-Institute of Oncology in Warsaw. Our measurements revealed that Gafchromic films assure much better precision. We simulated postal audit. For 20 measurements made for 4 different delivered doses, the largest difference was 1.1% (close to 2 cGy). However, the disadvantage of Gafchromic films is that the time which has to elapse from the film irradiation to the dose reading must be at least four times longer than the times between calibration and irradiation of films.

6. Conclusions

We showed that small Gafchromic dosimeters could be introduced and used as a precise dosimetric tool for dosimetry. We showed that the multichannel method with a scaling protocol achieves a much higher precision than the single channel method. Confidence limit of measured doses is equal to 1.8 cGy. That means that about 90% of measured doses differ from irradiated doses by not more than 1.8 cGy.

Attention was drawn to other relevant factors which have an influence on dose reading accuracy. One of them is the ambient thermal dosimeter environment, which can cause significant changes in measured signals. It is very important to ensure that during the Gafchromic dose measurement procedure, the thermal environment for all the dosimeters from the same series, including the calibration samples, are very similar. We also showed that a dosimeter size has a relevant impact on dose readings. Whichever size of dosimeters is used, the calibration curve should be measured using dosimeters of that particular size.

Conflict of interest

None declared.

Financial disclosure

None declared.

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