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PAPER

Optimizing the recalibration process in radiochromic film dosimetry

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Abstract

Intra-lot, inter-scan and other variabilities in radiochromic film dosimetry may have a severe impact on absolute dosimetry with this dosimeter. In the literature, several dosimetry protocols may be found characterized by different calibration functions and different film response variables. Also, the re-calibration methods found in the literature correct and minimize the impact of the variabilities in the absolute dose estimates. In this work, several recalibration methods and dosimetry protocols are evaluated. In order to find optimal configurations, their accuracy is compared, and the accuracy level that can be reached in each case is discussed. The efficient protocol and the parameter escalation are used to recalibrate EBT3 films from two different film batches. The mean absolute deviations between known doses and estimated doses for eight dose levels are obtained and compared with the self calibration of each reading, named intrinsic film calibration. Eight film sheets from two different lots and two digitizers are used. The parameter escalation method with a four-level recalibration using net optical density (NOD) and a power law as dosimetry protocol obtains the highest accuracy. Regarding the number of control strips, increasing the number from two to three makes the parameter escalation protocol to come close to intrinsic film calibration in all cases, but has a less important effect on the efficient protocol. Regardless the choice of the sensitometric variables, using the appropriate recalibration method results in accuracy levels typical of self calibration of the film. In addition, the parameter escalation method provides better results than the efficient protocol with three calibration strips.

1. Introduction

Radiochromic films (RCFs) are used to perform dosimetry measurements in the radiotherapy field. In particular, RCFs are widely employed when challenging irradiation conditions far from reference conditions are found. Due to their well-known characteristics, such as high spatial resolution, small response dependence on the energy spectrum or dose rate of the beams and equivalence to water or soft tissue (Arjomandy *et al* 2010, Karsch *et al* 2010, Martišíková and Jäkel 2010, Devic *et al* 2016), RCFs are a common dosimeter used to verify treatments and beams in IMRT (Healy *et al* 2013, Azorín *et al* 2014, Marrazzo *et al* 2015, Palmer *et al* 2017), SRS dose distributions (García-Garduño *et al* 2014, Morales *et al* 2016, Calvo-Ortega *et al* 2017) and brachytherapy procedures (Zwierzchowski *et al* 2017, Smith *et al* 2017, Aldelaijan *et al* 2017).

The usual workflow with RCFs in a hospital department involves three steps: a film is irradiated with an unknown dose distribution, the film is read with a flatbed scanner and, finally, the reading is converted to a dose map. In this final step, calibration functions that relate film responses in the different color channels with absorbed doses are employed. These calibration functions are generally obtained by fitting absorbed doses versus readings from a series of film pieces exposed to known doses. This calibration procedure is usually carried out with a single sheet from the same lot when the film box is received in the hospital department. Then the other

sheets from the box are stored in the department until they are employed for dosimetry measurements, typically several days or weeks after the calibration is performed.

Despite RCFs aforementioned favourable features, there are several factors that may give rise to inaccurate dose estimates when RCF dosimetry is accomplished. These well-known factors are due to several causes that may not be prevented or controlled, such as the manufacturing process of the films, the impact of the ambient conditions on the radiochromic media and the variabilities of the reading device, among others. In this way, corrective methods should be employed in order to obtain accurate absolute dosimetry with RCFs.

On the one hand, the active layer of a particular sheet may present thickness fluctuations as well as the digitizer response may not be uniform across the scanning area. These two factors give rise to local inhomogeneities of the film-digitizer dosimetry system (Niroomand-Rad *et al* 1998, van Battum *et al* 2016, Schoenfeld *et al* 2016). The most effective methods to deal with local inhomogeneities are the multichannel methods (Micke *et al* 2011, Mayer *et al* 2012, Méndez 2015), that simultaneously use the three color channels of the digitizer reading to accomplish an optimization process that produces dose estimates by minimizing the effect of these local inhomogeneities. However, multichannel methods do not compensate for other sources of inaccuracy like the inter-scan variations (Vera-Sánchez *et al* 2016).

On the other, sources of inaccuracy such as the ambient storage conditions, inter-lot, intra-lot and inter-scan variabilities are another big challenge in RCF dosimetry. Between different film sheets or even in a series of consecutive readings of the same film, the readings show an important variability that may have a large impact on dosimetry (Vera-Sánchez *et al* 2016, Ruiz-Morales *et al* 2017). In this way, depending on the dose level, the dosimetry protocol and the color channel, deviations up to 10% may be found in the dose estimates for exposure doses higher than 1 Gy. In order to deal with these variations, recalibration protocols have been developed, such as the efficient protocol (EP) (Lewis *et al* 2012) and the parameter escalation (PE) (Ruiz-Morales *et al* 2017). These protocols adapt a generic lot calibration function to every reading of an irradiated film before converting readings into estimated dose. To adapt the lot calibration function, a number of film pieces (control strips) exposed to known doses are read together with the rest of the film. Then, the readings of these control strips are used to obtain new recalibration functions that take into account and mitigate the effect of the variabilities.

As shown in previous works (Lewis *et al* 2012, Vera-Sánchez *et al* 2016, Ruiz-Morales *et al* 2017), the use of the recalibration protocols leads to an improvement in the accuracy of absolute RCF dosimetry. However, regarding the general accuracy of absolute RCF dosimetry process, there are some unresolved issues, like the number of recalibration strips that should be employed and what is the maximum level of accuracy achievable with the use of these recalibration methods.

The aim of the investigation described in this paper is to study what level of accuracy is achievable in RCF dosimetry with usual clinical dosimetry protocols and how to perform the recalibration procedure to maximize the accuracy of the dose estimates. Thus, a simple experiment is conducted by exposing film pieces to known doses to meet the objective. Finally, according to the findings, some recommendations on how to perform the recalibration process are presented.

2. Material and methods

2.1. Films, irradiations and readings

In this work, four EBT3 films (Ashland Inc, Russell, USA) per lot from two different lots (lot numbers #01171702 and #04191602) were employed. These films were irradiated in a Varian iX linac (Varian, Palo Alto, USA) and read in two Epson digitizers (Seiko EPSON Corp., Nagano, Japan) corresponding to different models, a 10000XL and a V800.

Each film sheet was cut in 8 pieces of 2.7×20.4 cm^2 and each piece was labelled and exposed to a different dose. For the first film sheet from each lot, these doses were 0, 125, 275, 400, 600, 750, 900 and 1200 cGy, and for the rest of the films the doses were the same with the sole exception of the highest dose level piece that was exposed to 1100 cGy. In this way, the first film from every lot was considered as the calibration film and the dose estimates in the other films from the same lot could be compared avoiding extrapolations, as recommended in the work of Lewis *et al* (2012)

In order to proceed as in the usual RCF dosimetry practice, four irradiation sessions were considered with a time interval of seven days between consecutive sessions. In each session, the pieces from two film sheets, one per lot, were exposed to the aforementioned known doses. Before the film pieces irradiation, the calibration of the linac was verified with a 30013 type ionization chamber (PTW, Freiburg, Germany) inside an RW3 slabbed phantom. Every RW3 slab had a thickness of 1 cm and twenty slabs were employed. With the aid of an RW3 specific holder for the chamber, its effective point was situated in the linac isocenter at a depth of 10 cm inside the RW3 phantom. In order to assure knowledge of the exposure doses, the centers of the film pieces were also situated at the linac isocenter with the same irradiation set up and the same slabbed phantom, except for the chamber

holder that was replaced by two conventional slabs. The beams employed for the irradiations had a nominal size of 20×20 cm^2 and a nominal energy of 6 MV.

The films were stored in a closet at monitored temperature and pressure during the four weeks that the process lasted. Also, the temperature history of the film lots was checked before the irradiation of every film in the study as recommended by the manufacturer.

The same reading protocol was followed with the two digitizers, they were switched on half an hour before performing a warm-up of five scans of the whole reading field with a resolution of 50 dpi. All the pieces from every film in the study were scanned together five times in portrait orientation, i.e. the long dimension of the film sheet and the scanner bed were parallels. The transmission mode with a spatial resolution of 72 dpi and a signal resolution of 48 bits (16 bits per channel RGB) was employed. A glass with 3 mm of thickness was placed on top of the films during the reading process in order to avoid undesired effects due to the curvature of the film pieces (Palmer *et al* 2015). Also, one minute interval was left between consecutive readings to avoid reading variations due to the temperature increase of the films in the scanner bed (Lewis and Devic 2015).

The data analysis was conducted with the averaged image obtained from the five single scans that were taken for every film in the study. In this way, the film responses to exposure doses in every color channel were obtained by averaging the pixel values in a ROI of 1×1 cm^2 centered in the film piece. Also, the centers of the film pieces were placed in the central axis of the scanner bed defined by the light source moving direction to avoid the lateral scanning artefact (Paelinck *et al* 2007, Poppinga *et al* 2015).

Finally, to obtain net optical density (NOD) values, every film in the study, once divided into pieces, was scanned twenty four hours before and twenty four hours after exposition to ionizing radiation. Thus the NOD values were obtained after performing an image registration of the pre and post exposition averaged images. To do this, special care was taken to digitalize the strips that were previously marked on one corner, and the matching was performed via a rigid transformation carried out strip by strip by considering the unexposed image as the moving one.

2.2. Dosimetry protocols and recalibration methods

Dosimetry protocols employed in RCF dosimetry are characterized by the choice of a magnitude to measure the film responses and the sensitometric curve that relates those film responses to the applied doses. For instance, the sensitometric curves that may be found in the literature propose polynomial, power and rational functions among others, to relate the absorbed doses and the film responses that may be also expressed with different magnitudes such as optical density (OD), NOD and raw pixel values (PV). Finally, from the knowledge of the film responses and the exposure doses (D) in some pieces of film(s), the fit parameters of the lot sensitometric curves for every color channel may be obtained by a simple fit procedure. In this work, four dosimetry protocols are considered:

1. The first protocol considers normalized PV versus D, while the lot calibration function for every color channel is a rational curve, $X(D) = a + \frac{b}{D-c}$, where $X(D) = PV/PV(0)$ is the normalized response at dose D, as described in Lewis *et al* (2012).
2. The second protocol works with PV and D as sensitometric magnitudes, while the lot calibration function for every color channel is again a rational curve, $PV(D) = a + \frac{b}{D-c}$, as described in Ruiz-Morales *et al* (2017).
3. The third protocol works with D and OD as sensitometric magnitudes, while the lot calibration curve for every color channel is a polynomial curve, $D = aOD^3 + bOD^2 + cOD + d$, where $OD = -log\left(\frac{PV}{PV_{max}}\right)$ with $PV_{max} = 2^{16} - 1$, as described in Chung *et al* (2016).
4. The fourth protocol works with D and NOD as sensitometric magnitudes, while the lot calibration function for every color channel is a power curve, $D = aNOD + bNOD^c$, where $NOD = -log\left(\frac{PV_{exp}}{PV_{unexp}}\right)$, as described in Devic *et al* (2016)

The general behaviour and shape of the calibration curves for the four dosimetry protocols is shown in figure 1. As may be seen, these curves relate the film readings in a color channel to the applied doses. The parameters of the curves are obtained by ordinary least squares fitting.

Regarding the parameter escalation recalibration method, a lot calibration function is expressed as a functional relationship $y = f(x;a_i)$, where $a_i, i = 1,2,..,N$ are fit parameters of the analytic expression of f. When another film from the same lot is analyzed, in order to obtain a particular calibration function that accounts for the variabilities, some strips from the film should be exposed to known doses and read together with the rest of the film.

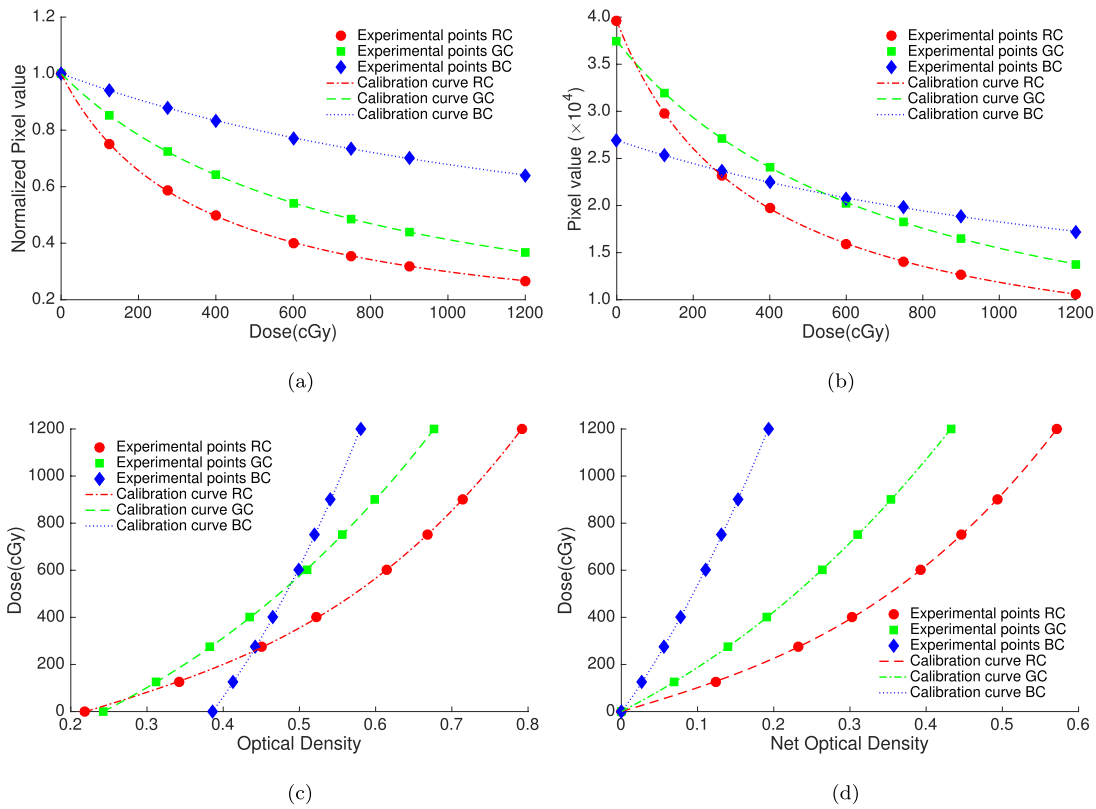

Figure 1. Lot calibration curves in the three color channels for the investigated dosimetry protocols. These curves are obtained with the calibration sheet from the lot #01171702 read in the EPSON 10000XL scanner. RC, GC and BC stand for red, green and blue channels respectively. The error bars corresponding to one standard deviation in dose (1.2%) and film responses in the ROIs (1%) can not be correctly visualized due to its small size. The R^2 values are higher that 0.98 for all the lot calibration curves in the study regardless of color channel or dosimetry protocol. (a) First protocol. (b) Second protocol. (c) Third protocol. (d) Fourth protocol.

As widely described in Ruiz-Morales *et al* (2017), the re-calibrated function is expressed as $y = f(x; \lambda_i * a_i)$, in which the parameters are re-scaled by the factors λ_i. These factors are obtained by minimizing the sum of squared differences between the measured values and the values predicted by the new function in the re-calibration strips.

As described in Ruiz-Morales *et al* (2017) and Lewis *et al* (2012), the efficient protocol works with a rational lot sensitometric curve that relates the normalized responses in the pieces of the calibration film with the absorbed doses to which these pieces were exposed. When another film from the same lot is analyzed, usually several days after the lot calibration has been performed, two or more recalibration strips from this film are exposed to known doses and read together with the rest of the film where the unknown dose distribution has been irradiated. So, a particular sensitometric curve for the evaluated film is obtained by relating the film readings in the re-calibration strips and the lot sensitometric curve through a linear relationship. The coefficients of this linear relationship may be obtained from a least square minimization between the known and the calculated doses in the control strips.

It should be noted that the first and second dosimetry protocols are quite similar. In fact, they are straightforward compared in some results, since both protocols work with the raw pixel values to obtain the dose estimate. The major difference between them is that the first protocol employs the EP recalibration method while the second protocol employs the PE one. So, while the EP recalibration method only may be implemented with the first protocol, the PE recalibration method is intended to work with any sensitometric magnitudes and is employed with the second, third and fourth dosimetry protocols.

2.3. Recalibration assesment

2.3.1. Overview of the problem. The concept of intrinsic film calibration

The relationship between film responses and absorbed dose in a particular film may differ substantially from the lot calibration curves, giving rise to inaccurate dose estimates. The intra-lot variability, i.e. differences in the active layer thickness of sheets from the same lot, or the inter-scan variability, i.e. differences in the reading process, may be responsible for the incorrect dose estimates. But also the interval of days between the lot calibration and the exposition of the particular film should be considered due to self-development of the films and possible storage conditions impact on the film response.

Ideally, the variabilities could be avoided and accurate absolute RCF dosimetry could be accomplished with the use of the intrinsic film calibration (IFC). This calibration is performed with pieces from the same film sheet in order to avoid the intra-lot variability. Also, these calibration pieces should be exposed to known doses at the same time than the rest of the film as well as stored and read together with the rest of the film in order to avoid the inter-scan variability, self development of the film and impact of the ambient storage condition. In this way, it is clear that the most accurate dose estimates with a film should be obtained with the IFC curves, since they are free from the aforementioned variabilities.

However, the former ideal solution should not be usually carried out. On one side, due to the finite extension of the films it is not always possible to cut eight calibration pieces and have enough space in the rest of the film for the evaluation of the unknown dose distribution. On the other, due to the finite extension of the scanner bed, it may not be possible to set all the pieces centered in the scanner bed along the light source moving direction in order to avoid the lateral scanning artefact.

At this point, it should be noted that two, three or maybe four strips may be cut from the film and exposed to known doses and read with it. These values are not enough to perform an IFC but may be employed together with the lot calibration curves to obtain re-calibrated curves that mitigate the effect of the variabilities. In fact, as demonstrated in Ruiz-Morales *et al* (2017), the use of these re-calibrated curves leads to an improvement in the accuracy of the dose estimates. With this in mind, the remaining questions are how many strips and what exposure doses should be considered.

Regarding the exposure doses employed for the recalibration strips, it has been a common practice in the works of Ruiz-Morales *et al* (2017) and Lewis *et al* (2012) to employ two strips, an unexposed strip and another strip exposed to a dose higher than the one expected in the rest of the film sheet with the unknown dose distribution. As may be seen in the aforementioned works, the employment of these two strips leads to an improvement in the accuracy of the RCF dosimetry protocols. Two reasons may be mainly argued for such a choice of the exposure doses. First, the unexposed film sheets show a great variability in their readings that lead to an increase in the uncertainty of dose estimates as shown by Saur and Frengen (2008) and proved by Ruiz-Morales *et al* (2017) for the EBT3 films. Second, when working with radiochromic films, extrapolations beyond the lot calibration curves should be avoided as stated by Lewis *et al* (2012). It should be reminded that film readings may get saturated in some color channels depending on the exposure dose, thus extrapolations are strongly discouraged in RCF dosimetry. So, in this work the use of new recalibration strips with exposure doses in the dose interval between the unexposed and the maximum exposure dose, as well as their impact on the global accuracy is investigated.

2.4. Design of the experiment

The key of the experiment is the knowledge of the doses delivered to every strip from every sheet in the study. This knowledge allows us to quantify the accuracy of the re-calibration methods. It also should be remembered that the exposure doses are distributed along the whole calibration range.

The first film of each lot was used to obtain the lot calibration functions. Once these functions were obtained, these films were no longer used. For the other films from each lot, the IFC curves as well as several re-calibration curves were obtained. So, the performance of the different re-calibration methods with different number of re-calibration strips could be compared to the IFC curves, i.e. the curves that lead to the most accurate dose estimates.

So, by altering the number of control strips used in the recalibration and the exposure doses of these strips, different options are tested with all the dosimetry protocols:

- Two-level recalibration: the re-calibration is performed with the control strips corresponding to the highest exposure dose and the unexposed one.
- Three-level recalibration: the lot calibration is recalibrated using the lowest and the highest dose level and one of the six intermediate ones, giving rise to six different re-calibrations possibilities. Dose levels in figures 5–8 correspond to percentages of maximum dose of 11%, 25%, 36%, 55%, 68% and 82% respectively and named also by 2,3,4,5,6 and 7. The strip 1 is the unexposed strip, while the numbered as 8 is the one exposed to the maximum dose.
- Four-level recalibration: for recalibrating the lot curve, the lowest and the highest levels are fixed. Then, the other two recalibration levels are chosen between the 15 possible combinations obtained with the six intermediate levels, 2–7.

In order to quantify the accuracy of the IFC and re-calibrated curves, the mean absolute deviation (mAD) was calculated for every curve in every channel,

$$mAD = \frac{\sum_{i=1}^{N} |D_i - \hat{D}_i|}{N}, \quad (1)$$

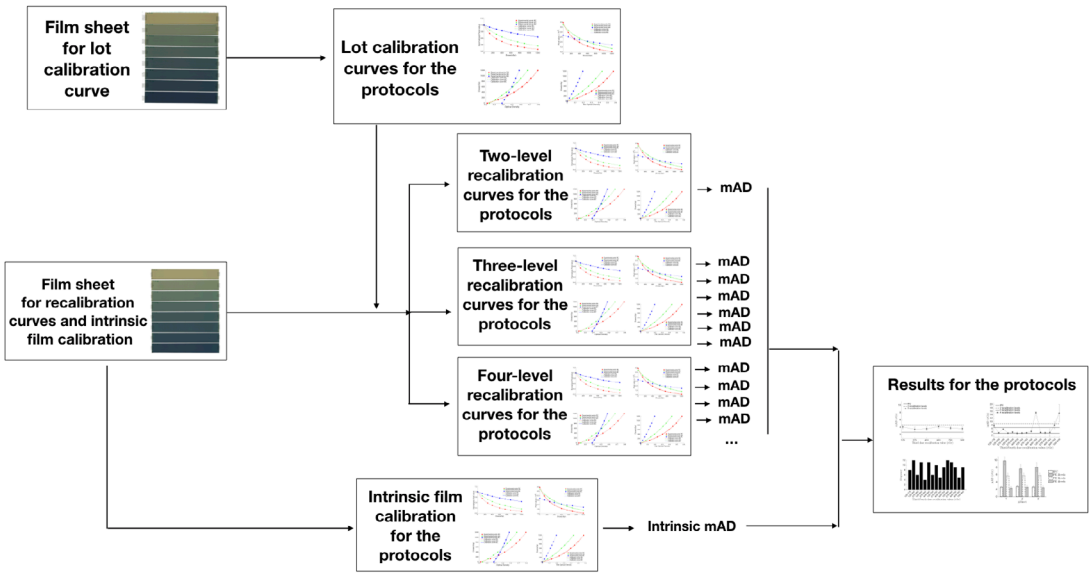

Figure 2. Scheme of the workflow followed in this work.

where $N = 8$ is the number of strips, D_i are the known doses to which the film pieces were exposed and $\hat{D}_i$ are the dose estimates obtained with the IFC curves or with the different dosimetry protocols and the recalibrated curves. Also, the average of the three mADs (one per channel) was computed. Finally, the workflow followed with every film in the study is summarized in figure 2

2.5. General considerations

As expected and seen in figure 3, the recalibration curves and the IFC curves are closer to the known absorbed doses in all film pieces than the lot calibration curve. Ideally, the IFC and the re-calibrated curves should coincide and, in this case, both curves would produce the same mAD value. However, the most common situation is to obtain similar values of the mAD for the re-calibrated and the IFC curves. This means that both curves are close between them and close to the known film responses to exposure dose. Even it is possible to find mAD values of the recalibrated curves lower than those of the IFC curves and this may be explained by the fact that the IFC curves are obtained by a least squares fitting procedure while the mAD computes absolute deviations.

From the inspection of the lot calibration curves shown in figure 1, it may be seen how the three color channels show different behaviour. The blue channel is the less sensitive to exposure dose, the red channel shows high sensitivity to low doses below 4 Gy and the green channel shows the highest dynamic range beyond 6 Gy. Thus, for every dosimetry protocol, different optimal re-calibration schemes may be found depending on the color channel considered, but this is not acceptable, since the point is to obtain optimal re-calibration schemes that simultaneously yield to accurate dosimetry protocols in the three color channels in order to be able to employ multichannel protocols. In this way, once its goodness is tested, the average of the three color channel mAD is considered to characterize the global achievable accuracy.

In summary, different recalibration methods are inter-compared in this work. Also, each method is compared against a reference method, supposed to represent the highest accuracy level achievable with a film from the lot. In this way, it is determined what methods reach the accuracy of the reference method. The whole procedure has three steps:

1. IFC is considered the reference method. So the IFC of each sheet in the study is obtained for the four dosimetry protocols evaluated.
2. A criterion to decide if a recalibration reaches the accuracy of the reference method is established. This criterion states that if differences in the three channel averaged mAD are lower than a small positive value ϵ, $mAD_{recalibration} \leqslant mAD_{IFC} + \epsilon$, the accuracy of both methods can be considered the same.
3. Finally, the recalibration methods and the configurations of the re-calibration strips (number and exposure doses) that reach the accuracy of the reference method are determined. Also, the frequency of the re-calibration configurations and methods that yield the same accuracy level is studied. It should be noted that the six films from the two analysed lots are read in two different scanners, so for every recalibration method and configuration a sample of twelve elements is available.

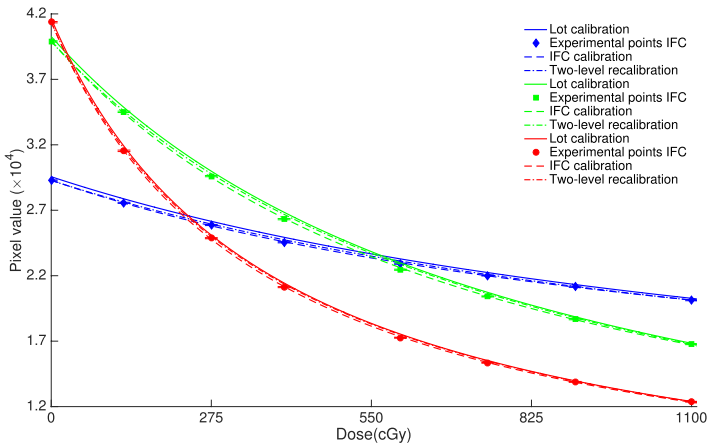

Figure 3. The recalibration curves and IFC curves in this figure correspond to the readings of film 1 from the first lot read with the 10000XL scanner. Also, the lot calibration curves are plotted. The dosimetry protocol is the second one and the PE method is employed to obtain the recalibrated curve. The error bars corresponding to one standard deviation in dose (1.2%) and film responses in the ROIs (1%) can not be correctly visualized due to its small size.

In this work, the criterion $\epsilon = 0.5$ cGy is taken from the 90 percentile found in the experimental sample of the $mAD_{recalibration}$ values that are lower than those of its corresponding $mAD_{reference}$.

Lastly, we would like to mention that this work is intended to provide recalibration strategies to improve the whole accuracy of the dose estimates in the three color channels simultaneously. In this way, once the three channels have been recalibrated, the multichannel algorithms may be employed and the estimated doses may improve their accuracy due to the use of the recalibrated curves. As may be seen in figure 4, the performance of the multichannel algorithm of Mayer *et al* (2012) yields to more accurate dose estimates, and when recalibration algorithms are employed, there is an improvement in the accuracy with single channels as well as with multichannel algorithms. In order to perform this evaluation, the multichannel algorithm was implemented via an in-house software.

3. Results

3.1. Averaged channel mAD

Figure 5 shows the mAD between calculated doses and known doses for one film using the three-level recalibration. The mAD values using three-level recalibration for the four dosimetry protocols and the two recalibration methods are plotted for the single channel dose estimates and for its average. Similar results to these are found in the other films in the study. Also, as may be seen, the averaged channel mAD is a good indicator for the global accuracy of the re-calibration procedure in the three color channels simultaneously.

3.2. Two-level and three-level recalibration

Figure 6 shows the average of the three channels mAD for a second film. In this case, the three-level recalibration (asterisks) results are compared with those of the two-level recalibration (dashed line) and the IFC (solid line) for the four protocols. As may be seen for all the dosimetry protocols, the two level recalibration usually is far from the maximum achievable accuracy, the mAD value of the IFC. Also, depending on the third recalibration level the three-level recalibration may reach the accuracy of the IFC or may lead to worse results than those of the two-level recalibration.

Figure 7 shows the frequency with which the mAD for the three-level recalibration method is lower than the IFC as a function of the third recalibration level and for the four dosimetry protocols with both recalibration methods. As the six films from both lots are read in two different scanners, twelve independent cases are considered. As may be seen, employing a three-level recalibration scheme does not always yield the same accuracy of the IFC, except for the second dosimetry protocol with the fourth recalibration level.

3.3. Four-level recalibration

The mAD results for a third film are shown in figure 8. In this case, four-level recalibration method is used, and the mAD values are compared with those obtained with the two-level method, the three-level method and the IFC. For the three-level method, the intermediate dose level used was the second one (125 cGy = 11% of 1100 cGy) for EP and the fourth one (400 cGy = 36% of 1100 cGy) for all PE cases. Results for all possible combinations of choosing 2 of 6 levels as intermediate levels in the four-level method are shown. As may be seen, the increase of the recalibration levels yields to a general improvement of the accuracy obtained with the recalibrated curves.

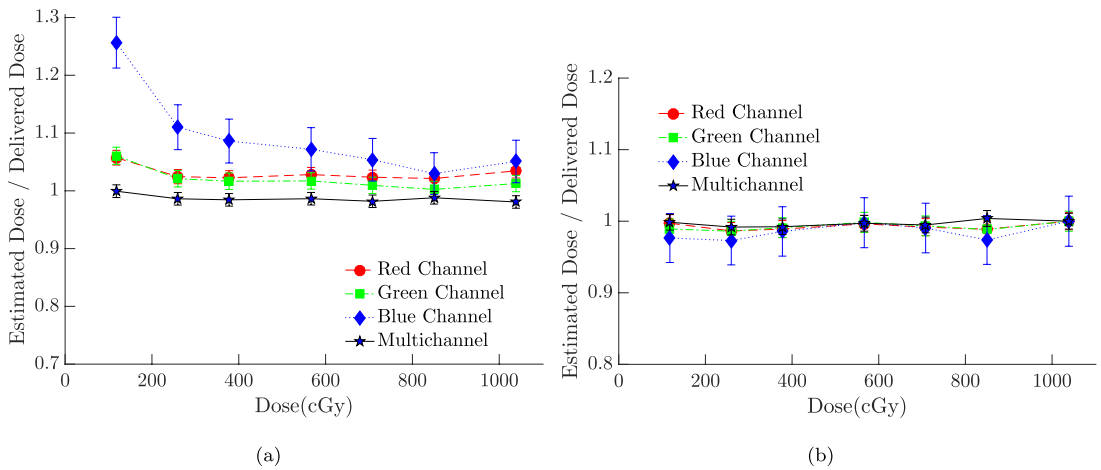

Figure 4. The performance of the recalibration methods with single channel and multichannel algorithms: (a) no recalibration, (b) two levels recalibration with the PE method. The data in this figure correspond to the second film from the second lot in the study read in the V800 scanner, however, the behaviour shown here is totally general. The error bars in the figure correspond to 1σ uncertainty calculated as described in the work of Vera-Sánchez *et al* (2018).

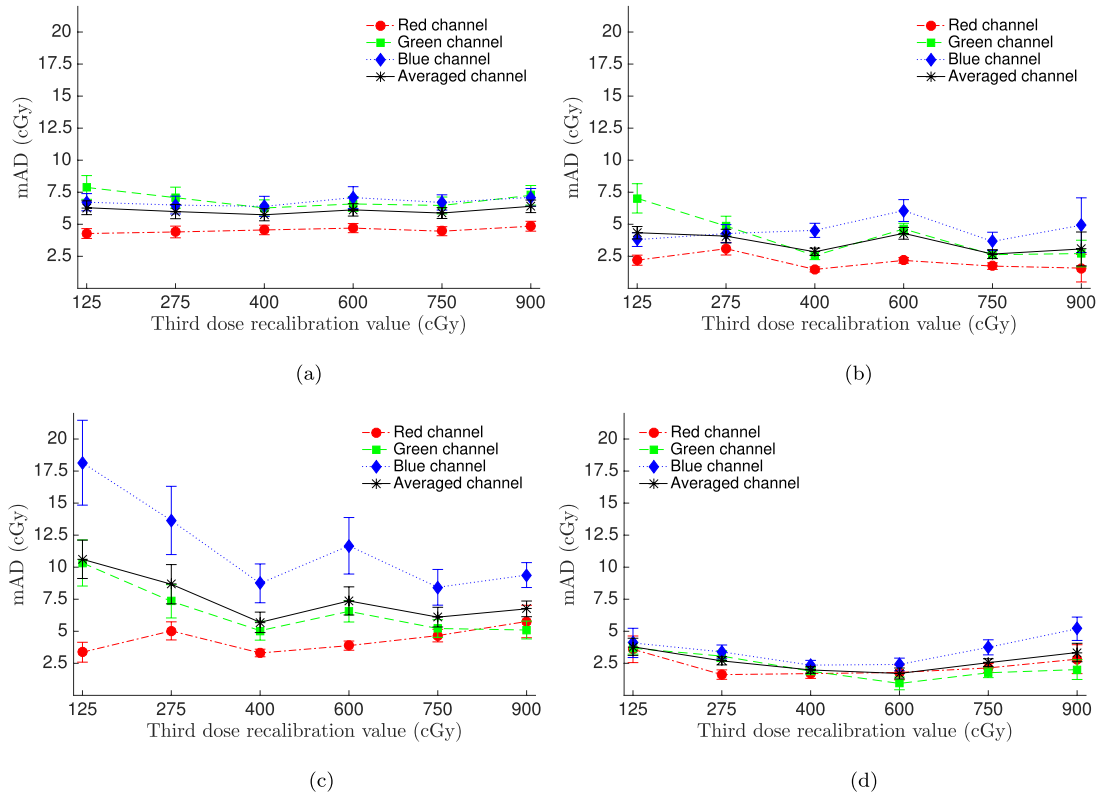

Figure 5. The data in this figure correspond to film 1 from the first lot read with the 10000XL scanner. The horizontal axis represents the third re-calibration dose level employed for the re-calibration, ordered from lower to higher dose while the vertical axis represents the mAD values. The error bars in the figure represent the 1σ deviation found in the experimental data. (a) EP, PV versus D. (b) PE, PV versus D. (c) PE, D versus OD. (d) PE, D versus NOD.

However, some particular configurations may worsen the accuracy of the recalibrated curves, especially for the third and fourth dosimetry protocols.

Figure 9 shows the frequency with which the mAD for the four-level recalibration method reaches the accuracy level of the IFC as a function of the third and fourth recalibration levels and for all the evaluated protocols. As may be seen, in the case of the first dosimetry protocol with the efficient protocol there is no recalibration configuration that always yields the same accuracy level of the IFC. In the case of the second dosimetry protocol with the PE method, the results obtained with second and fourth and with the fourth and sixth levels in addition to the unexposed piece and the piece exposed to the maximum dose yield the same accuracy level of the IFC. For the third dosimetry protocol, three configurations ($1-2-4-8, 1-2-6-8$ and $1-3-6-8$) are found

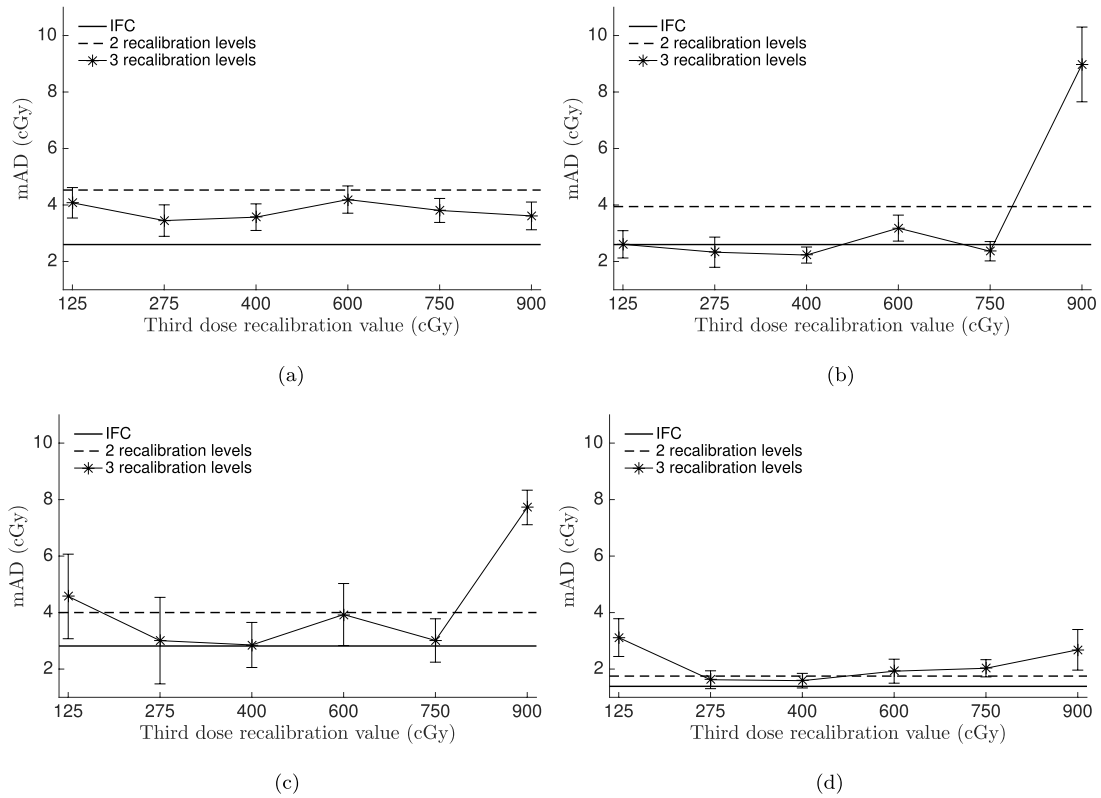

Figure 6. The data in this figure correspond to film 2 from the second lot read with the V800 scanner. Averaged channel mAD results using two and three-level recalibration protocols and the intrinsic film calibration (IFC).The error bars in the figure represent the 1σ deviation found in the experimental data. (a) EP, PV versus D. (b) PE, PV versus D. (c) PE, D versus OD. (d) PE, D versus NOD.

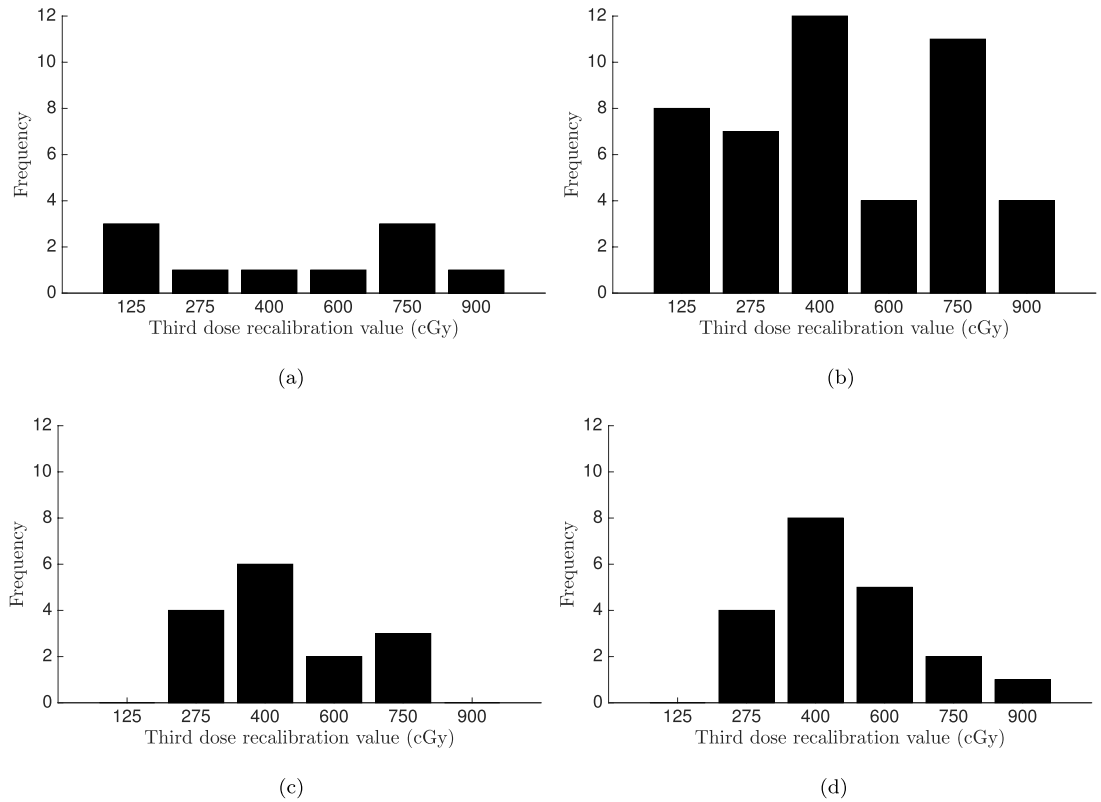

Figure 7. Frequencies with which the three-level method reaches the accuracy level of the IFC. (a) EP, PV versus D. (b) PE, PV versus D. (c) PE, D versus OD. (d) PE, D versus NOD.

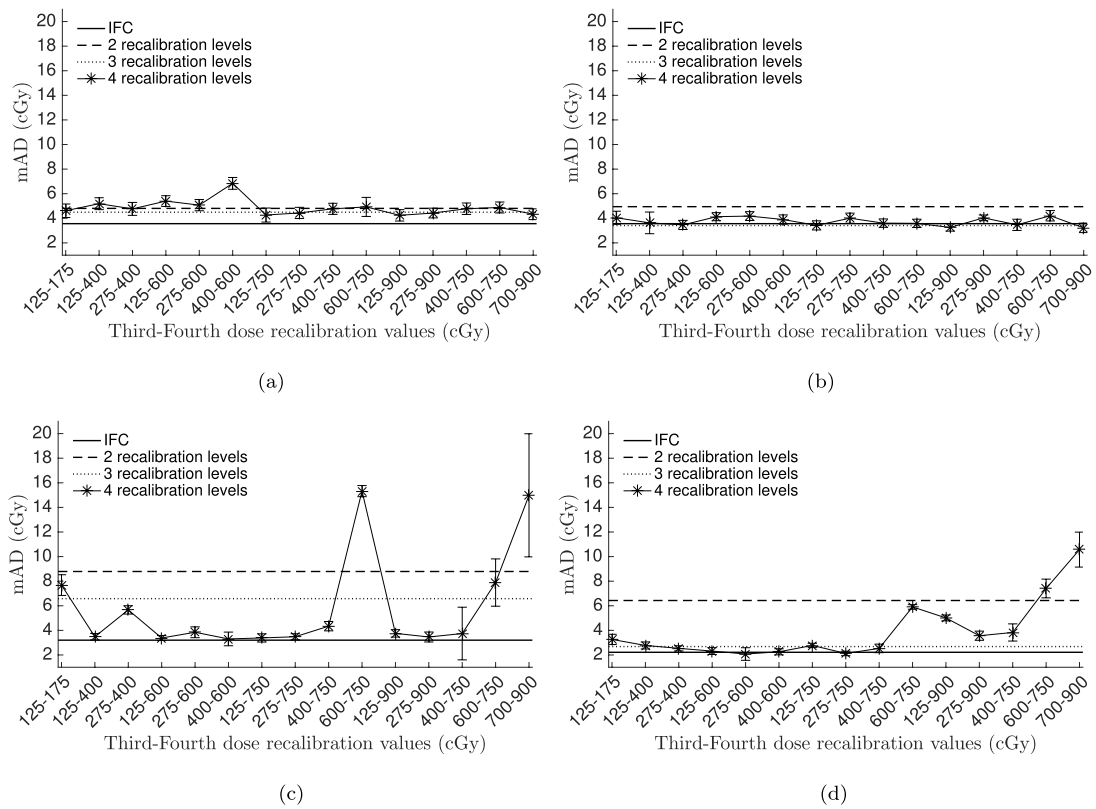

Figure 8. The data in this figure correspond to film 3 from the first lot read with the V800 scanner. mAD values for the four-level recalibration method. Results for the two-level method, the three-level method and the IFC are also shown. The error bars in the figure represent the 1σ deviation found in the experimental data. (a) EP, PV versus D. (b) PE, PV versus D. (c) PE, D versus OD. (d) PE, D versus NOD.

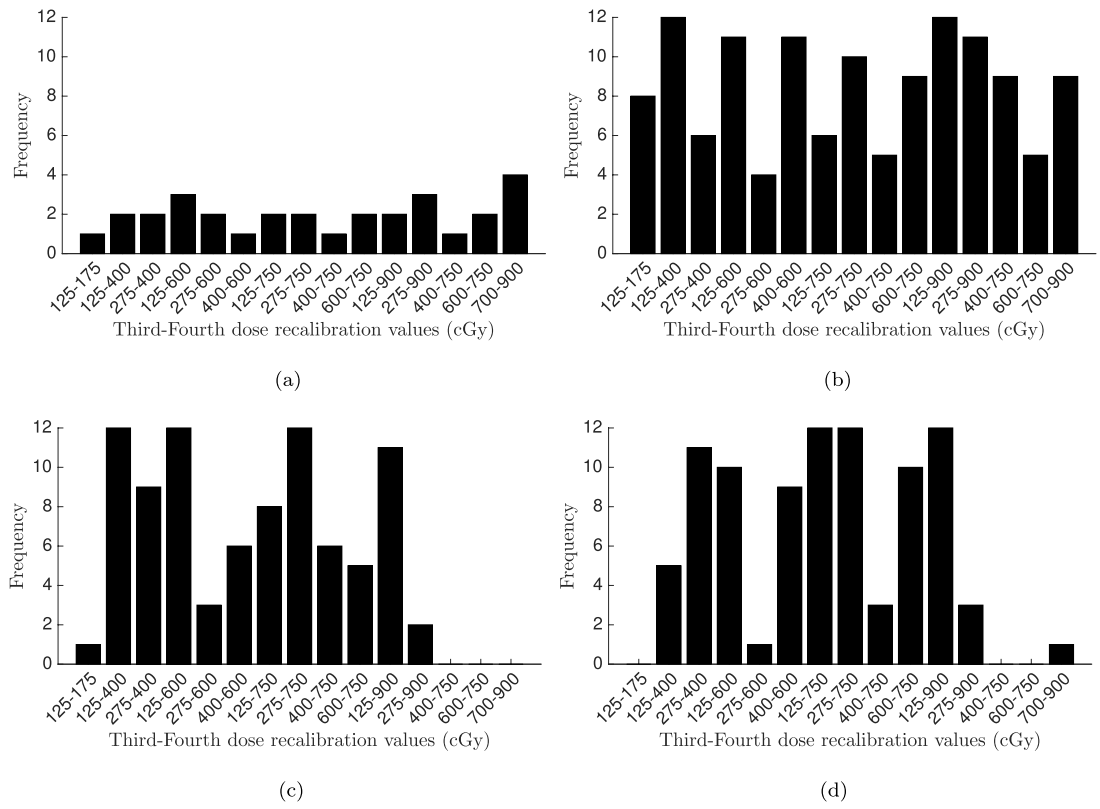

Figure 9. Frequencies with which the four-level method reaches the accuracy level obtained with the IFC. (a) EP, PV versus D. (b) PE, PV versus D. (c) PE, D versus OD. (d) PE, D versus NOD.

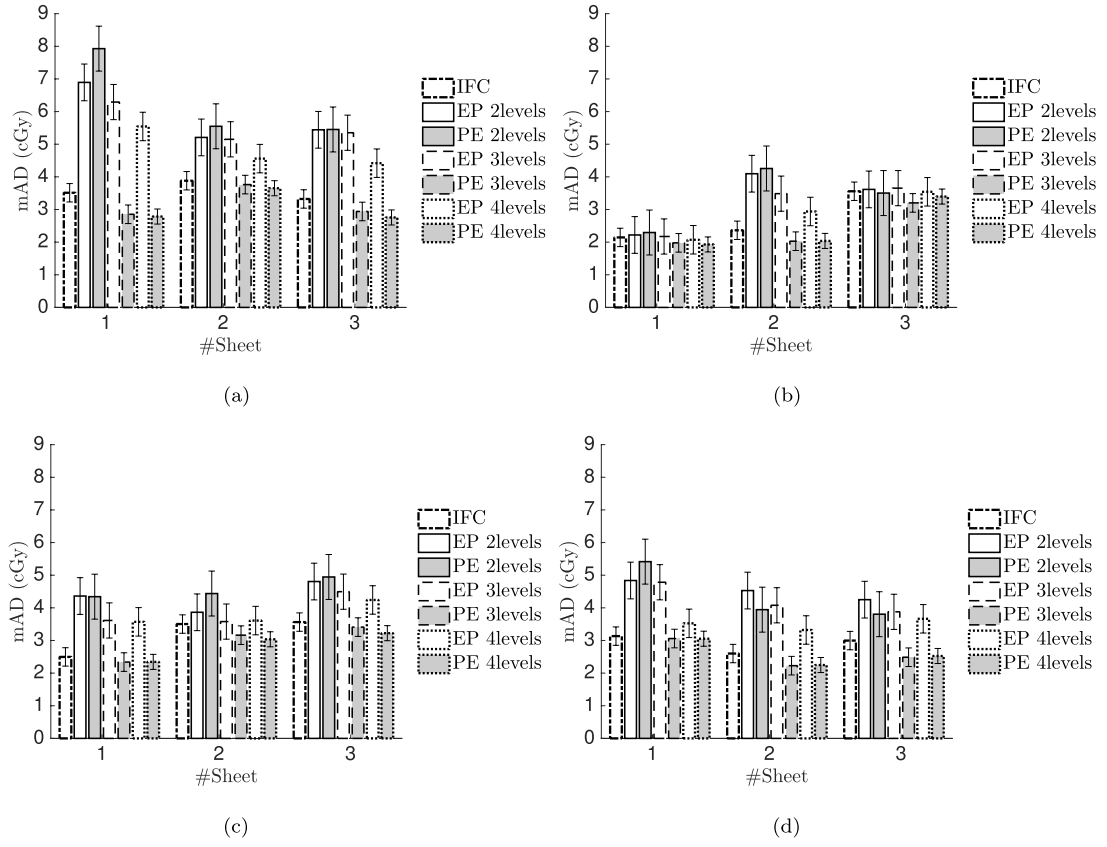

Figure 10. mAD results for all the films, both digitizers, four recalibration protocols and two, three and four-level recalibration methods. The variables used in the lot calibration curves are D and PV, so results of the first and the second dosimetry protocols are shown. The error bars in the figure represent the 1σ deviation found in the experimental data. (a) Lot 1 10000XL. (b) Lot 2 10000XL. (c) Lot 1 V800. (d) Lot 2 V800.

to reach the maximum accuracy level. Finally, for the fourth dosimetry protocol, another three configurations ($1-3-5-8, 1-3-6-8$ and $1-4-6-8$) are found to reach the IFC accuracy level.

3.4. Global accuracy of the dosimetry protocols

All the mAD data generated in this study, i.e. averaged mAD values and the mAD values obtained with the IFC, are provided as tables in the supplementary material (stacks.iop.org/PMB/65/015016/mmedia). Finally, figures 10–12 summarize the mAD results for all film sheets, two digitizers, four recalibration protocols and two, three and four-level recalibration methods.

For the three-level method, strips $1-2-8$ and strips $1-4-8$ are used in the EP and PEs protocols respectively. In the case of the four-level method, the recalibration configuration that produces the best accuracy level is shown. In this way, comparisons were always made with respect to the best possible case obtained with the four-level method.

4. Discussion

In this work, it has been studied the level of accuracy that can be reached with usual RCF dosimetry protocols and recalibration methods. It has been also studied how this accuracy depends on the particular configuration of the recalibration strips, i.e. the number of recalibration strips employed and their exposure doses. The accuracy of the dose estimates obtained with recalibrated curves has been compared to that obtained with the IFC curves, intended to provide the most accurate dose estimates with every sheet in the study. For instance, figure 6 illustrates how accurate the three-level recalibration method can be, compared to the IFC. It also shows the improvement of the three-level method with respect to the two-level one.

As an example of the effect of the particular set-up of a given method, figure 7 shows that for the OD and NOD based protocols, the closer the intermediate level is to the center level, the highest the frequency with which the use of that level minimizes the mAD. The optimal choice in these cases is a three-level recalibration configuration with an unexposed piece, a piece exposed to a dose close to 5.5 Gy and an exposure dose of 11 Gy. The most

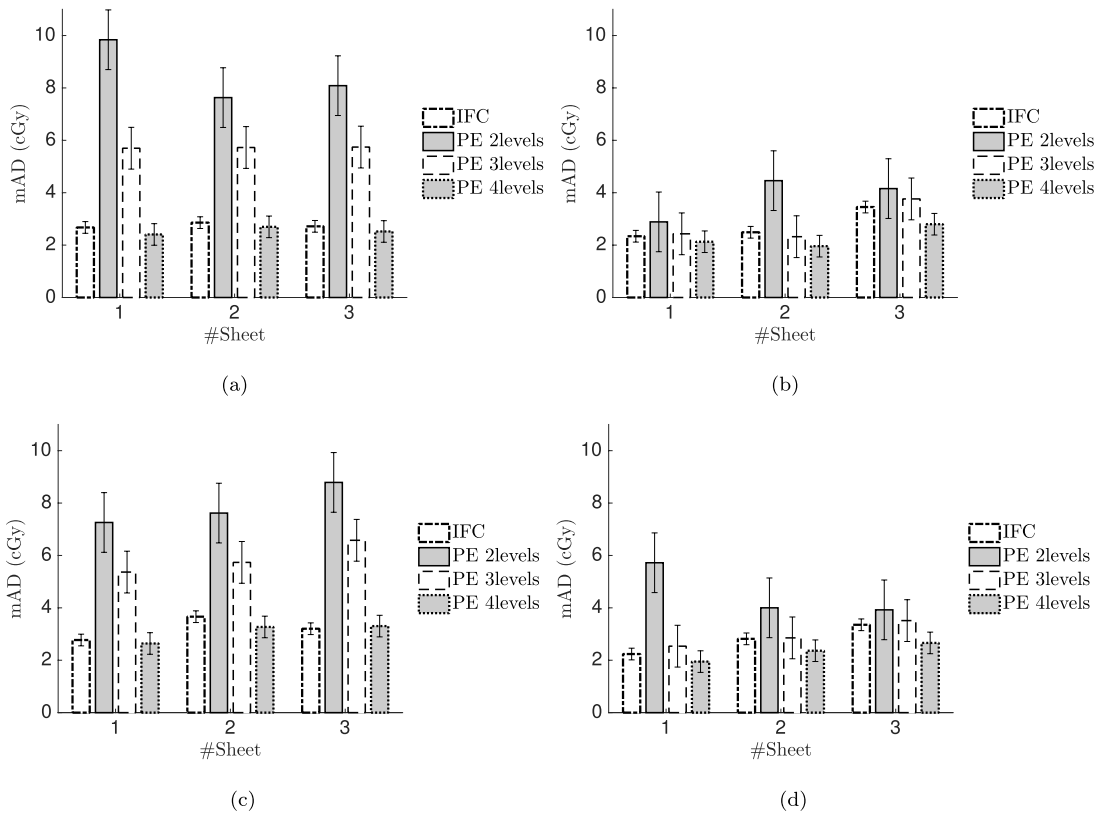

Figure 11. mAD results for all the films, both digitizers, four recalibration protocols and two, three and four-level recalibration methods. The variables used in the lot calibration curves are D and OD, so results of the third dosimetry protocol are shown. The error bars in the figure represent the 1σ deviation found in the experimental data. (a) Lot 1 10000XL. (b) Lot 2 10000XL. (c) Lot 1 V800. (d) Lot 2 V800.

sensitive protocol is the one based on OD. It should be noted that this is the only protocol using a polynomial function as calibration function.

In regard to how much accuracy a given protocol can reach, figure 7 shows that the PE protocol, using D and PV as the variables of the calibration function, is the protocol that comes closest to the IFC, when three control strips are used for recalibration. In particular, when the fourth dose level is used as the third control strip, the three-level method reaches the maximum achievable accuracy level.

Figure 8 shows that increasing the number of control strips from three to four (the case of the four-level recalibration method) does not guarantee an improvement in all cases. For instance, for the film shown in the figure, three-level method using the fourth control strip is clearly better than most of the possible combinations for the four-level method when the PE protocol is used with D and PV as variables.

For PE, figure 10 shows that three-level and four-level recalibration methods, working with D and PV variables, reach quite similar results in all the cases analysed. These results are clearly better than those found by the two-level method. This suggest that no improvement will result of using more than three control strips for recalibration. This figure also shows that increasing the number of control-strips from two to three has a lesser impact in the EP protocol than in the PE one.

The case of PV and D as sensitometric variables includes the first dosimetry protocol with EP as recalibration method and the second dosimetry protocol with PE as recalibration method. As shown in figure 10, the PE method with three-level recalibration has similar results to the IFC in all the films, suggesting that this combination is optimal when variables D and PV are used. The PE method also reaches the accuracy of the IFC with the four-level recalibration. However, the EP method shows more variability in their accuracy results. In general, increasing the number of recalibration levels from to two to three or four has less impact on the accuracy of the dose estimates with this protocol. Also, with this protocol, there are sheets in the study that do no reach the accuracy of the IFC regardless of the number of recalibration strips employed. This may be explained by the fact that the EP method employs a linear relationship between film responses and exposure doses. In contrast, the PE method seeks for a minimization between the known lot calibration curves and the information on the recalibration strips, as widely depicted in Ruiz-Morales *et al* (2017). This different performance for both recalibration algorithms also accounts for the experimental results seen in figures 6–9, while the EP method does not always reach the IFC accuracy, the PE should be employed with intermediate recalibration dose levels in order to

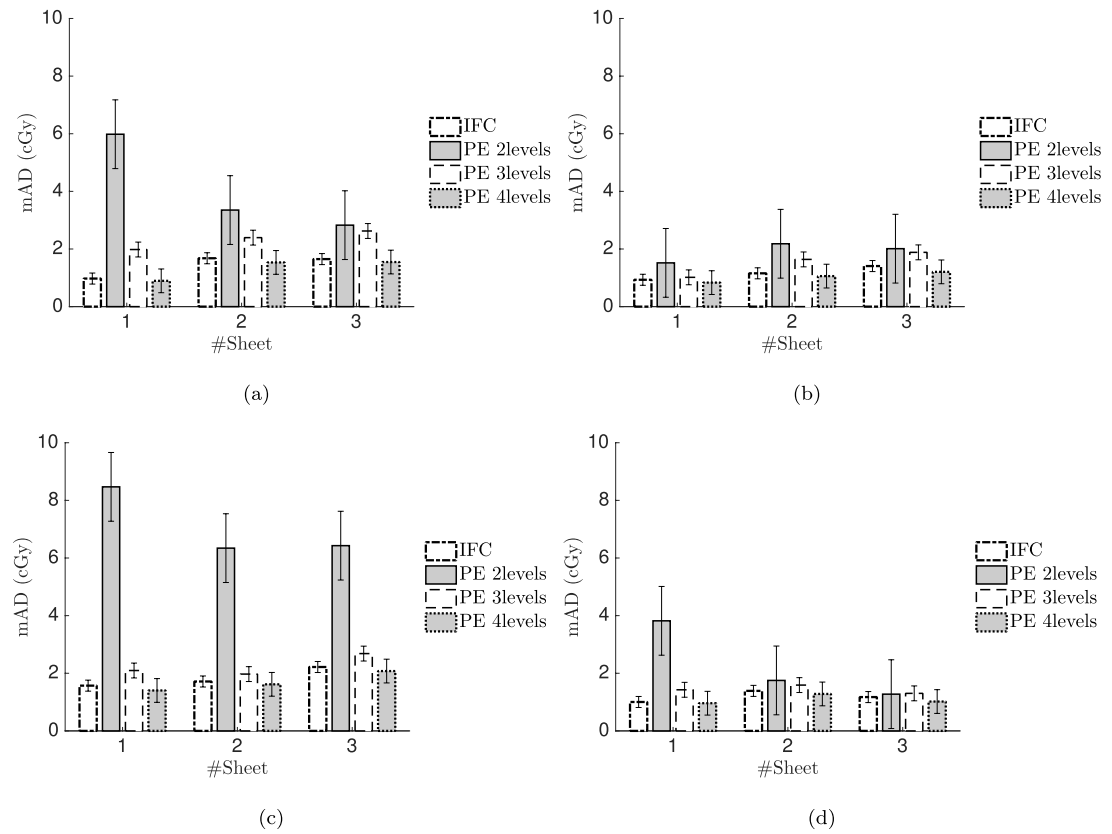

Figure 12. mAD results for all the films, both digitizers, four recalibration protocols and two, three and four-level recalibration methods. The variables used in the lot calibration curves are D and NOD, so results of the fourth dosimetry protocol are shown. The error bars in the figure represent the 1σ deviation found in the experimental data. (a) Lot 1 10000XL. (b) Lot 2 10000XL. (c) Lot 1 V800. (d) Lot 2 V800.

avoid accuracy loss. In this way, it seems a logical solution to feed the optimization process of the PE method with recalibration doses distributed along the whole calibration interval instead of providing recalibration levels close to the interval limits.

In the case of PE using D and OD as variables of the calibration function, figure 11 shows that four-level recalibration is the best option, mAD values obtained by the four-level and the IFC methods are quite similar. Therefore, in this case, the optimization is reached with the four-level method. Also, this dosimetry protocol is the most sensitive protocol to the inter-lot variability. As may be seen, for the second lot a three-recalibration level recalibration reaches the IFC accuracy level.

Figure 12 shows that, when using PE with NOD, the differences found between three-level and four-level recalibration methods are less important than in the case of PE using OD (see figure 11). The mAD values obtained with the three-level method are close to those obtained with the four-level one. Then, although the second method obtains the best results, using the first one only involves a small loss of accuracy.

Other important result shown in figures 10–12 is that reference and optimal mAD values for the PE protocol using D and NOD variables are the smallest of all protocols. Then, the maximum accuracy is reached with this protocol.

In short, some key points of this research should be clear in order to apply this result to the clinical practice. First of all, the lot calibration may be accomplished with doses ranging from 0 to 12 Gy while the recalibration procedure may be accomplished with doses up to 11 Gy in order to avoid extrapolations. Second, an increase in the accuracy of the RCF dosimetry process is obtained when three recalibration strips are employed instead of two, especially with the PE recalibration method. In addition to the unexposed strip and the one exposed to the maximum dose, the third strip should be exposed to an intermediate dose whose exact value depends on the dosimetry protocol considered. Third, when employing D and PV as sensitometric variables with a rational function, the PE recalibration method obtain the maximum accuracy with a three-level recalibration scheme, where the recalibration dose levels are 0%, 36% and 100% of the maximum recalibration dose of 11 Gy. Fourth, for the

protocols that employ OD and NOD as film responses, and polynomial and power functions as lot calibration functions, respectively, the maximum accuracy is obtained with four recalibration strips with exposure doses of 0%, 25%;, 68% and 100% of the maximum recalibration dose of 11 Gy although other configurations are possible for each protocol. Last, the most accurate dose estimates are obtained with a dosimetry protocol that employs D and NOD as sensitometric variables, a power calibration curve and a four-level recalibration configuration with the PE method.

5. Conclusion

As shown in previous works, inter-scan, inter-lot and other variabilities that affect RCF dosimetry make necessary recalibration protocols to accomplish accurate absolute dosimetry. But as shown in this work, the choice of the dosimetry protocol and the recalibration method have a deep impact on the achievable accuracy level.

Based on the dosimetry conditions of this study, it is found that the highest accuracy is reached by the dosimetry protocol that employs a power function relating NOD and D values and the parameter escalation recalibration method with a four-level recalibration. In terms of accuracy, the next protocols and recalibration methods are PE using OD with four-level recalibration and PE using PV with three-level recalibration, that obtain similar results.

Regarding the optimization followed in this work, parameter escalation reaches the accuracy of the intrinsic film calibration with three-level recalibration when the variables are D versus PV, and with the four-level recalibration when the variables are D versus OD and D versus NOD.

Finally, it is found under the conditions of this study, that increasing the number of control strips from two to three always increases accuracy, although this increase is lower for the efficient protocol than for the rest of protocols. Thus, in order to maximize the accuracy of the dose estimates, it should be recommended to employ the parameter escalation method with at least three recalibration levels.

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