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Novel radiation dose calibration methods for Gafchromic film: Exploring Histogram Correlation and Linearisation

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Novel radiation dose calibration methods for Gafchromic film: Exploring Histogram Correlation and Linearisation

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ABSTRACT

Radiotherapy requires quality assurance of patient radiation dose delivery. Gafchromic® radiochromic film is used as a dosimeter to validate these deliveries. This research explores Histogram Correlation as a calibration tool for Gafchromic® radiochromic film in verification of dose, for both magnitude and spatial distribution. This led to the development of a practical method for the use of Gafchromic® radiochromic film for use in Radiotherapy IMRT QA. The basis of this method is that a derived function of the scan data [(Blank/Exposed)-1] is directly proportional to the dose the film has been exposed to. This allows calibration by the definition of only one parameter, the constant of proportionality.

A theoretical model for the observed response is explored. This assumes that the observed optical system response is based on the distribution of the sizes of the particles that constitute the active medium of the film and the optical absorbance properties of the scanner used. The model suggests that film dosimetry should be treated as having two major system components; the conversion of the active medium with dose and the optical response of the scanner taking into account the spectral properties of the film.

The research also explores the theoretical aspects of using general purpose multi-channel scanners for scanning film, in particular, Gafchromic® radiochromic film, where the absorption of the active medium is not constant across the spectral acceptance window for a particular channel.

An explanation is then given for the particular case of the Green channel of the Epson V800® scanner used in transmission mode with Gafchromic® radiochromic film, where it is observed that the optical response is approximately linear with dose. That is, the optical response of the Green channel is approximately uniform such that the simple form of the Beer-Lambert law applies whereby the amount of light transmitted (detector response) decreases as a simple exponential as the amount of active medium converted increases.
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LIST OF PUBLICATIONS

Papers published in peer reviewed journals:


Conference presentations:

Abstracts published:


North Coast Cancer Institute (NCCI) internal publications:


Refer to Appendix 1
GLOSSARY

EBT = External Beam Therapy
Z = Atomic Number
H = Hydrogen
C = Carbon
O = Oxygen
N = Nitrogen
Li = Lithium
Cl = Chlorine
F = Fluorine
Si = Silicon
aSi = Amorphous Silicon
EPID = Electronic portable Imaging Device
OD = Optical Density
Gy = Gray (1Gy = 1 Joule/kilogram)
3D = 3 Dimensional
CRT = Conformal Radiation Therapy
TPS = Treatment Planning System
IMRT = Intensity Modulated Radiation Therapy
SBRT = Stereotactic Body RadioTherapy
SABR = Stereotactic Ablative Body RadioTherapy
RGB = Red Green Blue
1 Introduction

1.1 Background for this research

Radiotherapy is the process of employing ionizing radiation to control diseased tissue, predominantly, forms of cancer. A major goal of radiotherapy is to eradicate cancerous tumour cells while sparing normal tissue. The suitability of radiotherapy to treat a particular cancer type depends on the susceptibility of that cancer type to radiation in comparison to the susceptibility of normal tissues that are critical for patient survival. There are two generalised forms of treatment: (i) where cancer cells are dispersed throughout normal tissue, e.g. breast cancer; and (ii) where the cancer cells are contained within a discrete tumour, e.g. some types of lung cancer, or contained within an organ that is not critical for patient survival, e.g. prostate cancer. For type (i), it is important to deliver a uniform dose that maximises the control of the cancer cells, but limits damage to the normal tissue to an acceptable level. In this case, it is important to control the magnitude of the dose to a high degree of accuracy; the geometric boundary is not critical as the treatment will not significantly harm normal tissue. With type (ii), it is generally important to deliver a dose that will control all cancer cells within the discrete volume of the tumour (or non-critical organ), but not so that the dose is uniform. That is, it can be greater than required, but it is important to control the geometric extent of the beam. Often for types of cancer with discrete volumes, the dose delivered is greater than would cause damage to normal tissue. This is acceptable, as there is no significant normal tissue in the irradiated target volume. However, if there are critical normal tissues in close proximity to the target volume, it is important to control the geometric extent of the dose such that these critical structures receive less dose than they can tolerate (normal tissue sparing).

A radiotherapy procedure in itself does not guarantee any favourable outcome. It is through meticulous planning and careful implementation of the needed treatment that the potential benefits of radiotherapy can be realised (Khan & Potish [29]). An integral part of this process is to verify that the dose distribution that results from the actual delivery of the treatment plan matches the intended distribution as presented in the Treatment Planning System (TPS).
It is now common practice when intensity modulated radiotherapy (IMRT) is being planned and delivered to verify a proposed treatment by generating, from the TPS, a map of the predicted dose to a representative phantom (IMRTCWG [32]; van Dyk [33]; Meyer [34]). The treatment is then delivered to the phantom and a device is used to measure the dose. The map of the measured dose distribution can then be compared to the map of the planned dose. It can then be determined, by IMRT QA analysis, if the treatment delivery system was able to deliver the treatment as planned, within a specified degree of accuracy. With reference to the above, some devices are suited to measurement of dose with a high degree of accuracy but with limited spatial resolution, whereas others are more suited to high geometric accuracy. In particular, Gafchromic® radiochromic film has the potential for high spatial resolution and for determination of the magnitude of dose as a relative measurement, but it is generally considered unreliable to use as an absolute dosimeter. However, the major benefit of film is that it can be placed in a phantom at any orientation, whereas most of the electronic measurement devices available are limited to certain specific orientations.

1.2 Research problem

For a device such as radiochromic film where the response, change in optical density, is not well characterised, there are problems. Some of the issues with currently available radiochromic film, Gafchromic® radiochromic film, are as follows:

(i) Current methods of calibration for Gafchromic® radiochromic film are time intensive.

(ii) Current methods compromise accuracy.

(iii) Current methods provide a limited link to the fundamentals of the process.

This research proposes that problems with calibration of these devices can be addressed by the use of histogram correlation (HC), a novel method developed from the standard image processing method histogram matching, to be summarised in Section 1.5, and explained and discussed in detail in Chapter 2.

1.3 Research questions

In order to address these problems, the following research questions have been formulated:
(i) To what extent does histogram correlation aid in revealing the underlying base response function of Gafchromic® radiochromic film (or any other device)? Are there other advantages of using histogram correlation?

(ii) To what extent can the optical response of Gafchromic® radiochromic film be fitted by a linear function?

(iii) How can the observed response of Gafchromic® radiochromic film be explained?
2 Literature Review

2.1 Literature on devices to be calibrated: Gafchromic® film

There is a significant amount of literature addressing the various iterations of Gafchromic® film, particularly the various versions of EBT, EBT2 and EBT3. Review publications address these various properties, hence this literature review on Gafchromic® film properties is restricted to publications that are relevant to the research undertaken and reported. More emphasis is placed on reviewing histogram correlation techniques as these may be less familiar to the reader and these principles are key to understanding the research associated with Gafchromic® radiochromic film.

The whitepaper from International Speciality Products (ISP [6]) makes several proposals as a starting point for the calibration and use of Gafchromic® radiochromic film scanned on a commercial flatbed scanner as a dosimeter. In particular, it recommends the use of the derived function known as Optical Density as the parameter to calibrate against dose, as follows:

\[ OD = -\log\left(\frac{I}{I_0}\right) \]  

Eqn. 2.1

where \( I_0 \) is the incident intensity of light on the film from the scanner and \( I \) is the transmitted intensity of light received at the detector of the scanner. Log is Base10 logarithm.

This is consistent with the early use of silver halide film for diagnostic use, pre image processing, and either computer based systems or direct analogue systems. It was useful to characterise silver halide film for diagnostic use when it was assessed directly by eye, without any post exposure adjustment (refer to Webb 1988 [18]). Further refer to Webb for established theory of darkening process of silver halide film.

The review paper by Butson et al. in 2003 [7] provides a substantial review of the use of Gafchroomic® radiochromic film, but these authors have chosen to continue the use of derived function Optical Density. This appears to be based on an update of the established theory of exposure of silver halide film, as indicated by the statement: “Note that since \( I_0/I \) has an exponential relationship to the dose, the optical density is appropriately linear with dose” (p.
It is noted that this is a review paper, therefore no direct measurements are offered as evidence, either as to its relevance to silver halide film or to Gafchromic® radiochromic film.

Further, with regard to the optical attenuating properties of the active medium of Gafchromic® radiochromic film and the light properties of commercial flatbed scanners, the Beer-Lambert law of attenuation is reduced to a simple form, that is, simple exponential attenuation (Mayerhöfer et al. [35]). On the other hand, there is justification to apply the complex form which applies to the attenuation of light with a broad spectrum. Note that it may be applied to a mixture of materials that attenuate in different parts of the incident light spectrum, or a single material that has a complex attenuation spectrum. For the active medium of Gafchromic® radiochromic film, the paper describes a complex spectrum. The resulting attenuation relationship to a multi-channel RGB flatbed scanner should be considered in relation to the channel spectrum detector combination. That is, it can be expected that for the complex absorption spectrum of Gafchromic® radiochromic film, the attenuating relationship for the broad spectrum light of commercial RGB scanners will, in general, not be a simple exponential function.

Although Gafchromic® radiochromic film has been considered difficult to work with (Lewis & Chan [8]; Kairn et al. [14]), possibly because it is treated as a direct replacement for traditional wet processed, silver halide, film, it has characteristics that are different. The use of commercially available flatbed scanners to scan this film further differentiates it from the traditional methods used with silver halide film.

General purpose commercial scanners are not optimised for scanning Gafchromic® film for dosimetric purposes because the response of the scanner in the axis perpendicular to the scan direction is non-uniform; this means that the derived doses vary more than the generally accepted tolerances for IMRT QA analysis (Lewis & Chan [8]; Williams et al. [9]; Butson et al. [10]; Alnawaf et al. [11]; Aland et al. [12]).

Furthermore, the active layer of Gafchromic® film is not deposited uniformly, which may result in discrepancies in derived doses that are greater than acceptable (Micke et al. [13]; Kairn et al. [14]). Several methods have been proposed to deal with this including: Micke et al. [13], Kairn et al. [15], Hu et al. [16], Borca et al. [17], Hardcastle et al. [18], and Mendez et al. [19].
An interesting method for low dose exposure is proposed by Gotando et al. [20] which does not use the logarithm of scanner data to obtain optical density (OD). This method is for low dose and it is recognised that at small values a linear response and a logarithmic response have characteristic curves that are similar, suggesting that the use of optical density (OD) is not necessary.

2.2 Review of literature relating to histogram matching

Histogram correlation is based on standard image processing techniques, used to enhance the contrast of an image, in particular histogram matching (Gonzalez & Woods [20]). Histogram matching is a method in image processing of greyscale adjustment of a target image to match the greyscale of a reference image. In image processing it can be a useful technique to normalise images of approximately the same scene, but under different conditions. For example, the subject is illuminated by different lighting conditions or different sensors are used to capture the image. A reference image is chosen and the greyscale of subsequent images is matched to the reference. Fig. 2.1 provides a graphical representation of histogram matching.

With regard to radiotherapy, if the reference image is a dose map created by a TPS and the image to be matched is measured data, such as, data that was obtained by scanning Gafchromic® radiochromic film, formatted such that it is in the same format as a dose map from a TPS, then the matching function that converts the cumulative distribution function (CDF) of the image to the CDF of the dose map is the calibration function.

A method to aid understanding of the histogram matching process is to consider the standard image processing function histogram equalisation (Gonzalez & Woods [30]; Pratt [36]). Histogram equalisation processes an image such that for every grey scale level there is an equal number of pixels. This is often useful for images where there is a large range of values for the data, but the majority of the data lies in a much smaller range. Generally, this type of image would be considered to have low contrast. By applying histogram equalisation, an equal number of pixels are assigned to each grey level. The result is that when the image is displayed the contrast will be improved, as demonstrated in Fig. 2.2.
Fig. 2.1 Graphical example of histogram matching: Cumulative distribution function

Note: Ireference is for the reference image, Iimage is for the image to be adjusted. The matching function converts the Greyscale of Iimage to Ireference.

Fig. 2.2 Example of histogram equalisation

Note: The image on the right, after equalisation, shows an improved contrast, with equal number of pixels assigned to each grey level.
A simple algorithm method for deriving a histogram equalisation transformation is to consider the values for all the pixels in an image, then sort them in order from lowest to highest. The total number of pixels in the image can be divided by the number of grey levels to get the number of pixels to be assigned to each grey level, Ne. Then on the ordered list, the first division of Ne pixels will be assigned the first grey level, the second division of Ne the second grey level, and so on until all divisions have been assigned to their respective grey level. Note that this is not necessarily a computationally efficient method, but for the data sets used in radiotherapy, usually of the order of 250x250 pixels, the ordering can be achieved in a spreadsheet program such as MS Excel® in less than 1 s. It can then be seen that for Histogram Matching, the equalised images of the reference image and target image are equivalent, provided the transformation function is monotonic.

![Image of histogram equalisation](image_url)

**Fig. 2.3 Histogram equalisation**

Note: The reference image, top left, has a different grey scale distribution from the target image, top right. After equalisation, bottom left and bottom right, they are the same.

For the majority of processes in radiotherapy, such as the use of Gafchromic® film, the darkening of the film with dose is monotonic; that is, the film gets darker with more dose, and the image of the dose map generated from the TPS can be considered as the reference image, and the scan image of the Gafchromic® film, measurement device can be considered as the target image. The image of the Gafchromic® film can be considered as a transformed
image of the dose map from the TPS, the transformation being the response function of the medium to the dose.

<table>
<thead>
<tr>
<th>Calculated Data</th>
<th>Median (56 104 140 90 59)</th>
<th>Histogram Equalised Grey Level</th>
<th>Median (106 176 215 158 111)</th>
<th>Measured Data (43 108 198 104 52)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D data array</td>
<td>converted to 1D</td>
<td>Then sorted by value low to high</td>
<td>2D data array converted to 1D</td>
<td>Then sorted by value low to high</td>
</tr>
<tr>
<td>column</td>
<td>23 23</td>
<td>24</td>
<td>25</td>
<td>29</td>
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<td>21 92 202 87</td>
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<td>25 74 145 71</td>
<td>25 25</td>
<td>25</td>
<td>25</td>
<td>29</td>
</tr>
</tbody>
</table>

Note when data is sorted, the median value of a division is the centre value of that division.

![Transformation Function Between Calculated data and Measured data](image)

Fig. 2.4 Example of HC process for a simple 5x5 data set
As illustrated in Fig. 2.4, an algorithm to provide a transformation function can be described as follows [30]:

From a simple treatment plan, the dose distribution is calculated to a quality assurance (QA) phantom. A simple treatment plan is one that when delivered to a virtual QA phantom, the dose distribution can be derived with a high degree of confidence. The plane of interest of the dose distribution can then be exported as a dose plane file and saved in a standard format, e.g. 250x250 pixels. This is the reference data.

In the real QA phantom, the film is inserted at the plane of interest and exposed by delivering the treatment plan using the Linac system.

The film is then scanned and processed and the measured data saved in same format as the reference data.

Both datasets are then ordered into 1 dimensional arrays from lowest to highest.

A sample consisting of a determined number of pairs of data points from the matched 1 D arrays is taken. For example, for 250x250 pixels, this would give a total of 62,500 points. If it was determined that 100 points were sufficient to define a transformation function, then each segment would be 625 points. The centre point of the division is used as this is the median value. Therefore, the first pair of points would be at position 313 and then every position plus 625. This would give 100 pairs of points that would define the transformation function.

Then, for a subsequent patient QA assessment, a film would be exposed using the actual patient treatment plan with the film in the QA phantom. The film would be scanned and processed and saved. This data can now be converted to dose by applying the transformation function. The dose derived in this manner can then be compared with the dose as derived by the TPS and the quality of the plan assessed.
3  Histogram Correlation

3.1  Introduction

This section provides the generic method that was used to derive a calibration for film. It is presented here as a generic method. Chapter 6 provides specific details related to the implementation of this method for clinical use.

Histogram correlation is proposed as a method to achieve a practical method of calibration. By correlating the histogram of the planned dose map with the histogram of the measured dose map, a calibration curve can be obtained that has a high probability of predicting the dose at a measured point. It is the general case in radiotherapy that a dose distribution is calculated using a TPS. The histogram of this calculated (predicted) dose distribution is compared (correlated) with the histogram of the measured dose distribution to derive a calibration. One common problem is that it is not practical to establish a calibration that is generally valid. Examples are Gafchromic® radiochromic film or amorphous silicon electronic portal imaging (aSi EPID) devices, in particular when used for dosimetry (VanEsch et al. [21]; Parent et al. [22]) and GEL for 3D dosimetry (Baldock et al. [23]; Oldham et al. [24]).

Note that this method may be applied to any image data where a calculated dataset has previously been derived. Again this is often the case for imaging in radiotherapy, such as the comparison of a portal EPID image with the pre-calculated digitally reconstructed radiograph (DRR).

3.2  Method used to implement and evaluate histogram correlation

The reference data set, in general calculated by the TPS, should have a range of values that covers from the lowest to the highest expected values for the measured data. In the case of IMRT exposures for Gafchromic® radiochromic film, there are certain common fractionation schedules. For example, the most common fractionation is 2 Gy per fraction in radiotherapy. Further, an allowance should be made for possible hot spots, then further allowance for the actual dose that will be delivered in the phantom, as opposed to that expected in the patient. Generally, the phantoms used are not quite as large as a patient’s external outline, therefore the dose in the phantom is greater for the same treatment plan, as there is less material to attenuate the beams. Therefore, a range from 0 to 3 Gy would be suitable for this
fractionation dose. The plan (beam arrangement) should be composed of simple beams so that there is high reliability that the TPS can calculate the dose to the phantom accurately.

For this project, simple combinations of a 6 cm by 10 cm field were chosen. The 10 cm axis was aligned longitudinally and the 6 cm transversely. Nine different angular positions were chosen. This plan resulted in a reasonably even spread of dose values in the transverse plane. However, the dose distribution was approximately constant in the longitudinal alignment. This allowed for small errors in the longitudinal setup not to make a significant difference in the transverse plane.

The setup parameters for some common calibration ranges are tabulated. Note that 0 – 3 Gy covers the common 2 Gy per fraction schedule (see Table 3.1). 0 – 15 Gy is generally useful for hypo-fractionated SBRT/SABR treatments (see Table 3.2). For example, at North Coast Cancer Institute (NCCI) it is common to use dose per fraction schedules of approximately 10 Gy per fraction. 0 – 40 Gy (see Table 3.3), covers single fraction SBRT/SABR and most other single fraction treatments.

<table>
<thead>
<tr>
<th>Beam Number</th>
<th>Gantry Angle</th>
<th>Field Size X</th>
<th>Field size Y</th>
<th>MU/Fraction</th>
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<td>1</td>
<td>290</td>
<td>6</td>
<td>10</td>
<td>10</td>
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<tr>
<td>2</td>
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<tr>
<td>9</td>
<td>70</td>
<td>6</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 3.1 Beam setup for calibration to cover range 0 - 3 Gy

A TPS plan was prepared for the reference beam arrangement. This included scanning the IMRT phantom (IBA ImRT®). Importing the CT data into the TPS and creating a plan and assigning the beams as shown in Table 3.2.

The TPS plan was then calculated and the dose plane, which corresponded to the position of the film for measurement, was exported. This dose plane is the reference data.
Table 3.2 Beam setup for calibration to cover range 0 - 15 Gy

<table>
<thead>
<tr>
<th>Beam Number</th>
<th>Gantry Angle</th>
<th>Field Size X</th>
<th>Field size Y</th>
<th>MU / Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>290</td>
<td>6</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>6</td>
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<td>30</td>
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<tr>
<td>9</td>
<td>70</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.3 Beam setup for calibration to cover range 0 - 40 Gy

<table>
<thead>
<tr>
<th>Beam Number</th>
<th>Gantry Angle</th>
<th>Field Size X</th>
<th>Field size Y</th>
<th>MU / Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>290</td>
<td>6</td>
<td>10</td>
<td>15</td>
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<tr>
<td>2</td>
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<tr>
<td>8</td>
<td>60</td>
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<td>10</td>
<td>30</td>
</tr>
<tr>
<td>9</td>
<td>70</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

For Gafchromic® radiochromic film, the measured data set is the array of values measured by the film scanner and saved as a computer file. To prepare a film for exposure and subsequent scan, a standard 254 mm x 203 mm sheet of film should be selected. Due care should be used such that the film is not damaged or unwanted marks left on the film. The film should be marked to maintain orientation and any other identifying marks added. It is recommended by the manufacturer (ISP [6]) to scan the film prior to exposure. Several procedures require the unexposed Blank scan of the film, this cannot be obtained after the film is exposed and therefore if it is being considered to use the unexposed blank scan, then it
has to be obtained prior. The film should then be inserted into the IBA ImRT® phantom. The phantom is then positioned on the treatment couch and the reference treatment plan delivered. Fig. 3.1 illustrates the simple plan on a TPS.

Fig. 3.1 Example display screen in TPS for calibration plan

Note: The figure demonstrates the simple beam geometry and displays the calculated dose distribution for a simple plan.

3.3 Practical example using Excel® spreadsheet

A sheet of Gafchromic® radiochromic film was exposed to several beams such that a range of exposures was produced. The film was then scanned. The numerical data was then copied into a spreadsheet program, for this project, MicroSoft (MS) Excel® was used. Numerical data can be saved to a data file then loaded into a spreadsheet program, such as Excel®.

Fig. 3.2 is a graphical display of measured film data and Fig 3.3 is a numerical representation of the data in a spreadsheet. Note that exposed areas are dark, indicating low raw optical value from the scanner, and unexposed areas are light, indicating high values.
Fig. 3.2 Green channel data of scanned film presented as an image

Note: Dark areas represent the high dose regions and light the low dose regions. The image displayed is 254x203 pixels which corresponds with the film dimensions of 254x203 mm.

Fig. 3.3 Green channel numerical data of scanned film loaded into spreadsheet program
The dose plane data exported from the TPS can be displayed as an image. Fig. 3.4 is a graphical display of calculated TPS data, and Fig 3.5 is a numerical representation of the data in a spreadsheet. Note that when data is raw, the image is the negative of the scan of the film. That is, regions of high dose are light (high numerical values), and regions of low dose are dark (low numerical values).

**Fig. 3.4** Treatment planning system data presented as an image

Note: Light areas represent the high dose regions and dark the low dose regions. The image displayed is 254x203 pixels which corresponds with the film dimensions of 254x203 mm.

**Fig. 3.5** Treatment planning system data in numerical form loaded into spreadsheet program
The 2 dimensional arrays are then transposed into two 1 dimensional (column) arrays. Fig 3.6 demonstrates the data prior to sorting. The correlation of the data shown in the 2 columns is effectively random. Each column can then be sorted using the Excel® sort function.

The random data is then converted to correlated data to give the calibration graph displayed in Fig. 3.7. The correlated data is then the transformation (calibration) function that would convert the measured data histogram to the calculated (TPS) data histogram. It is the calibration function which, when applied to measured data will give an estimate of the dose for the pixel value given.
Fig. 3.6 Histogram correlation data prior to sorting
Fig. 3.7 Histogram correlation data post sorting
3.4 Histogram correlation method applied to patient QA data

The calibration defined by histogram correlation can then be applied to a set of measured data for a patient QA treatment. The application of the calibration converts the raw data to data calibrated as Dose (cGy). This data can be loaded into an IMRT analysis program along with the calculated (TPS) data for analysis. Fig. 3.8 presents a flow chart for the HC process.

Fig. 3.8 Process flow chart for histogram correlation process

The calibration is derived from the comparison (Histogram Correlation) of the simple plan TPS data verses the measured data. The calibration is then applied to the measured data for an actual Patient plan. The calibrated measured data can then be analysed in an IMRT analysis program by comparison to the TPS data for the patient plan.

3.4.1 Histogram correlation – Auto method

The Auto method developed here used the Patient data directly to derive a calibration. It used the calculated data from the TPS and the measured data from the Patient QA treatment delivery. This calibration function is specific for the data set. It is independent of the
amplitude scale of the data, therefore the transformed data is not in Dose (cGy), but is relative to the planned data. It is useful because it preserves spatial information. Therefore, if the two planned and measured datasets are correlated, then when analysed, they will return a result that indicates this. Fig. 3.9 presents a flow chart for the Auto process.

Fig. 3.9 Process flow chart for histogram correlation – Auto method

It is used to derive a calibration by direct comparison of the Patient QA calculated and measured data. The data is analysed by comparison of the measured and plan data. Note that the scale is relative but position information is preserved.

### 3.4.2 Histogram correlation – Adjustment method

The Adjustment method seeks to constrain the possible scale error of the Auto method. This is done by comparing the calibration derived by the Auto method to the calibration from the simple plan method at a given time point. By applying a curve fitting routine the adjustment can be determined. If the adjustment is within an expected range, it will give confidence in the result. This applies to dosimeters such as Gafchromic® radiochromic film where it continues to darken after exposure. Fig. 3.10 presents a flow chart for the Adjustment process.
3.5 Conclusions

While histogram correlation can provide a quick and effective method of deriving a calibration function, the following considerations are important:

The reference exposure should be of an IMRT style, but composed of fields that a modern TPS can calculate and give confidence in the result. An IMRT style has a reasonable continuous spread of data values from low to high. The range of values should exceed the expected range of the patient data.

For dosimeters such as Gafchromic® radiochromic film where the response changes continuously with time, it will only provide a calibration function at the equivalent time point to the reference measurement. Note that as the method is quick, it is practical to derive several calibrations, one for each common time point of patient QA measurement.

The Auto method is of interest, as it will consistently give excellent matching results for data sets that have a good correlation, independent of the time point of the measurement. It is noted that it is a relative calibration, but it should be possible to reference it to an absolute calibration by a single independent measurement, e.g. ion chamber measurement. This requires further work to establish. Nevertheless, for medium such as film, it is generally considered that the characteristic of high spatial resolution is more important than absolute dose measurement. It is noted that spatial information is preserved in the Auto process.

The Adjustment method provides, in the absence of an independent measurement, a means to constrain the error by comparison to the calibration derived from the reference exposure. The reference exposure is traceable through the machine calibration to an absolute reference. Again it is useful for medium such as Gafchromic® radiochromic film where the response changes continuously with time. Where the approximate characteristic of the medium is known, then the amount the reference calibration is adjusted can be reported and compared.
against the values expected. If it is within the range of expected values, then the adjusted calibration can be used with the error limit set from the range of expected values. For example, if Gafchromic® radiochromic film is scanned at a time point where it is known the response can change in range 1%-4%, the adjusted calibration may return an indicated 2.2%. The adjusted calibration can then be used, with additional error of 4%.

Histogram correlation is a versatile method that allows the response function of the dosimeter array to be presented for comparison to the calculated array and in the process derive a transformation function, the calibration. For example, using a 3 channel RGB scanner to scan Gafchromic® radiochromic film, there are effectively 3 sets of data, one for each channel of the scanner. Anyone or all of these channels can be compared against the calculated array and a response function derived. Further, if the response data is processed by taking a function of that data, for example, logarithm, then the transformation function will reflect that function by incorporating the inverse of that function. In the case of logarithm, the inverse is exponential.
4 Linear response of Gafchromic® Radiochromic film

4.1 Introduction

When reviewing data for Gafchromic® radiochromic film, it was noted that the transformation function associated with using the derived function Optical Density (OD) versus calculated data, appeared to have the characteristic of an exponential function (see Fig. 4.1). It should be noted that Gafchromic® radiochromic film refers to a range of products manufactured by Ashland Speciality Ingredients (see Technical Acknowledgements). The active medium is a formulation of Di-acetylene (ISP [6]) and is common to the range of film products. The products used are specified in the Clinical Results (section 6.2).

It was then considered that the logarithm function applied in optical density may be redundant. Histogram correlation was then used to compare the quotient of the raw optical value for film having received no exposure, divided by the raw optical value for the exposed film against the calculated data. The transformation function in this case then appeared reasonably linear. In particular, the function for the Green channel appeared to be linear to within a few percent (see Fig. 4.2). The detailed analysis is provided in Figure 4.8.

It is noted that on the simple ratio graph (Fig. 4.2), \((I_0/I)\) verses Dose that the curve is offset by unity from the origin. A further derived function \(((I_0/I) - 1)\) was plotted against Dose (see Fig. 4.3). In the following figures, GAF refers to Gafchromic® radiochromic film, R refers to Red, G refers to Green and B refers to Blue.
Fig. 4.1 Dose vs Optical Density (OD)

Note: Comparison of the R G B Channel data for a Range of 0 - 50 Gy dose to GAF film. Data is the Optical Density \( OD = -\log_{10}(I/I_0) \) for each channel of the RGB scanner.

Fig. 4.2 Dose vs \((I_0/I)\)

Note: Comparison of the R G B Channel data for a Range of 0 - 50 Gy dose to GAF film. Data is the Ratio of \((I_0/I)\) for each channel of the RGB scanner.
Fig. 4.3 Dose vs \(((I_0/I) - 1)\)

Note: Comparison of the R G B Channel data for a Range of 0 - 50 Gy dose to GAF film. Data is the Ratio of \(((I_0/I) - 1)\) for each channel of the RGB scanner.

The use of the derived function \(((I_0/I) - 1)\) is justified on basis that for regions of the film that were not exposed to any Dose, the film would be the same as when scanned prior to exposure. As the values are the same, \(I = I_0\) then the ratio \((I_0/I)\) would be equal to one. Therefore, if one is subtracted from the ratio, then for the Derived function verses Dose, a value of zero is then associated with a Dose of zero. This data is displayed in Fig. 4.3. It would indicate that the derived function \(((I_0/I) - 1)\) is directly proportional to Dose for the Green and Blue channels of the RGB scanner, though not for the Red channel.

4.2 Theoretical basis for linear response

From the model proposed in the Gafchromic® whitepaper (ISP [6]), a further approximate equation can be derived that would demonstrate the linear property seen in Fig. 4.3. The following derivation was introduced in a paper by the author (Bennie & Metcalfe [1]).

In general, and specifically for the scanners used, the system response (pixel value) with respect to an absorbed dose at a specified point of the film, and for a single channel of a RGB scan, was modelled by a 3 term hyperbolic function; see the Gafchromic® whitepaper (ISP [6]).
\[ P_x(D) = \frac{(a + bD)}{(c + D)} \]  

**Eqn. 4.1**

where \( P_x(D) \) is the raw pixel value from the scan, \( D \) is the dose the pixel has been exposed to, \( a, b, c \) which are constants, then for an unexposed Blank film, \( D=0 \), giving

\[ P_x(0) = \frac{a}{c} \]  

**Eqn. 4.2**

For a saturated film exposed to a very high dose, Limit as \( D \to \infty \)

\[ P_x(\infty) = b \]  

**Eqn. 4.3**

If \( b \) and \( c \) are small then this function may be approximated by a simple hyperbolic such that when the unexposed “Blank” is divided by the “Exposed” scan, the result is a function that is approximately linear for a small \( c \) and \( b \):

\[ \frac{P_x(0)}{P_x(D)} \approx 1 + \frac{D}{c} \]  

**Eqn. 4.4**

Then the function is derived further:

\[ \frac{P_x(0)}{P_x(D)} - 1 \approx \frac{D}{c} \]  

**Eqn. 4.5**

So that it is directly proportional to dose, \( D \).

Note that in normal usage, the quantity that we wish to estimate is the Dose (Gy), which in this case is the inverse of the function above, that is, the Dose is equal to the derived function multiplied by a constant:

\[
\text{Derived function} = \left( \frac{P_x(0)}{P_x(D)} \right) - 1 = \left( \frac{10}{I} \right) - 1
\]  

**Eqn. 4.6**

\[
\text{Dose} = (\text{Derived function}) \times \text{Constant}
\]  

**Eqn. 4.7**
For the Green and Blue channels of RGB data this relationship holds reasonably well for most scanners. The relation does not match well for the Red channel.

For the Blue channel, the system sensitivity was notably less than the Red or Green channels. It was noted that the Gafchromic® marker dye is active in the Blue channel. Therefore, the Green channel was considered the most suitable to use with this method.

4.3 Assessment of optical response data

Data was collected for each channel (RGB) for a range of available scanners.

The scanners assessed were: Epson V800®, Epson V700®, Epson V37® series, specifically a V370® and a Canon multi-function office printer/scanner.

The Epson scanners have 16 bit RGB resolution, the Canon has 8 bit RGB (Red Green Blue) resolution, and the V800® and V700® allow scanning in transmission mode. The V700® uses an Epson White Cold Cathode Fluorescent Lamp; the recently released V800® uses an Epson LED (Light Emitting Diode) light source, while the V370® series uses a reflective mode and the Epson LED light source.

The data for each channel RGB was processed as above, that is:

\[
\text{Derived function} = \left( \frac{\text{Blank}}{\text{Exposed}} \right) - 1 = \left( \frac{10}{I} \right) - 1
\]

Eqn. 4.8

\[
\text{Dose} = \left( \frac{\text{Blank}}{\text{Exposed}} \right) - 1 \times \text{Constant}
\]

Eqn. 4.9

In the following figures, Processed Measured Data refers to the Derived Function in the formula above.

Note that data presented is multiplied by 1000 to preserve resolution if data is converted to integer.
Fig. 4.4. Epson V800® Plot Dose vs System response (Film + Scanner) 3 Channels (Processed) RGB

Fig 4.5. Epson V700® Plot Dose vs System response (Film + Scanner) 3 Channels (Processed) RGB
Fig 4.6. Epson V370® Plot Dose vs System response (Film + Scanner) 3 Channels (Processed) RGB

Fig 4.7. Canon MFP Plot Dose vs System response (Film + Scanner) 3 Channels (Processed) RGB
4.4 Discussion of optical response data

The graphs in Figures 4.4 through to 4.7 demonstrate that various scanners have different system response functions. They can also be seen on the reproduction of the scanned image. However, this may depend on the quality of the print and the actual observer because they are general purpose scanners optimised for general office and photographic applications, and often with significant cost constraints. This means they are generally used to copy a document or photograph that when evaluated by eye, the copy seen on a computer monitor appears to be similar to the original. It must be noted that in modern dosimetry, assessment is based on the numerical data evaluated in a computer system; evaluation is almost never done by eye. Gafchromic® film is not optimised to the human visual system, such as certain silver halide films were, so direct visual assessment should not be attempted without careful consideration. The spectrum output of the light source and spectral response of the detectors used in these systems were not optimised for Gafchromic® film.

For each scanner considered, the system response of the Green channel was a well-behaved function and for most, it was approximately linear with dose. With the V800®, the response was close to linear, from 0 to greater than 50 Gy. The specific definition being the error associated with any deviation from linearity would not result in a significant error for IMRT analysis.

For scanners that operate in transmission mode (Canon and V370®), the graphs were best fit and did not indicate the amount of system noise, so the usable range of the V370® was from 0 to approximately 20 Gy and the Canon from 0 to approximately 3 Gy. Nonetheless, since the most common fraction dose in radiotherapy is 2 Gy, these scanners can still be considered useful.

It was noted that the system response of the Red channel for those scanners that operated in transmission mode (V800® and V700®) was generally greater than for the Green channel. However, a pure system response is not as important as the resulting signal to noise ratio. This system has 2 major components, the film and the scanner, both of which are sources of noise. The noise associated with the scanner can be reduced by increasing the sample time. If the resulting increase in scan time is not significant, to achieve the same signal to noise ratio for the Green channel as for the Red channel, then the greater sensitivity of the Red channel should not be a major consideration in the overall choice.
4.5 Assessment of linearity of optical response of Green channel data from an Epson V800® scanner

For the data presented in Fig 4.8, the straight line fit was derived using the MS Excel® function LINEST. The function was constrained to calculate a straight line through the origin. The value of the gradient derived, \( m_0 = 1.4838 \). The value of the coefficient of determination derived, \( r^2 \) correlation = 0.9999. This value being approximately 1 within four significant figures, gives confidence that the straight line model, \( Y = mX \), is appropriate for this data.

![Epson V800 Green channel data](image)

Fig 4.8. Epson V800® Green channel data (linear fit)

Note: Plot Dose vs System response (Film + Scanner) comparison to straight line fit to data \( Y = mX \)

Note that in clinical practice it would be normal for the dose to be derived from the measured data. Therefore, if a film has been exposed and scanned and processed (Green channel data, (unexposed/exposed)-1) the dose can be derived by multiplying the processed measured value by a constant, which equals 673.9 cGy, as presented in Fig. 4.8 (note 673.9 = 1000/1.4838).
4.6 Derivation of scanner optical response of Gafchromic® Radiochromic film

The data presented above indicates that for the Green channel of RGB data for the Epson V800® scanner, the derived function is directly proportional to Dose. A proposed explanation for the non-linear response of the Red channel data and data from alternative scanners, is provided in Chapter 5.

\[
Dose = \left( \frac{Blank}{Exposed} \right) - 1 \times Constant
\]  
Eqn. 4.9

Note that this data covered the range 0-15 Gy; it is recognised that in the range 0-2 Gy a small correction is required of the form known as Gamma correction often used in electrical systems [30]:

\[
Gamma = \frac{\log \text{Vout}}{\log \text{Vin}}
\]  
Eqn. 4.10

and can be expressed as a fitting function

\[
y = Ax^B, \quad \text{where} \quad B = Gamma
\]  
Eqn. 4.11

This is known as power function in the image processing program, ImageJ (see Technical Acknowledgements).

This is not the case for the Red channel data for the Epson V800®, or the data of the other scanners assessed. As it was the same sheet of film that was scanned by each of the scanners, the difference in response function can be attributed to the scanner and the channel (RGB) used. That is, there are two major components to the optical system response. The first part is the conversion of the active medium of the Gafchromic® radiochromic film from the transparent to the non-transparent state by the absorbed dose. Note that it is a convenience to refer to the states as transparent and non-transparent, as the transparent state is not 100% transparent and the non-transparent state is not 100% opaque. The second part is the attenuation of the light of the RGB channel, as registered at the detector, of the scanner used.

The attenuation of a scanner in transmission mode is given by the Beer–Lambert law. In the simple form this states the attenuation is exponential:

\[
I = I_0 \exp(-OM)
\]  
Eqn. 4.12
where \( OM \) is the optical mass of the active medium creating the attenuation.

This assumes the spectrum of the scanner light is attenuated uniformly by the active medium.

For the case of the Green channel of the V800® scanner, it would suggest that the conversion of active medium of the film responded as a function such as:

\[
OM_c = OM_i \ln(1 + \alpha X)
\]  
Eqn. 4.13

Such that when substituted into Eqn. 4.12, it can be expressed as:

\[
I = I_0 \times (1/(1 + \alpha X))
\]  
Eqn. 4.14

which can be rearranged to express dose as:

\[
X(Dose) = (1/\alpha) \times (I_0/I) - 1
\]  
Eqn. 4.15

That is, the linear relation expressed in Eqn. 4.9, above.

To investigate this process further a sheet of film was divided into segments and the segments exposed to known doses to a maximum of 500 Gy.

4.6.1 Method

Film was exposed to known dose. Optical response was measured using an Epson V800® scanner. The scanner was used in transmission mode, 48bit RGB. The Green channel data was extracted and analysed using ImageJ.

4.6.2 Results

The film was scanned on an Epson V800® scanner, processed using ImageJ and values tabulated for the Green channel of the data. The raw data is presented in Fig. 4.9, normalised data has been plotted and presented in Fig. 4.10, and the derived function, \( 1/(1 + \alpha X) \), is presented in Fig. 4.11. Alpha is a constant. The value of \( \alpha \) in Fig 4.10 was derived from the linear regression of the transformed function.
<table>
<thead>
<tr>
<th>Gy</th>
<th>Green</th>
<th>(G0/G)-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>38130.0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>28760.0</td>
<td>0.326</td>
</tr>
<tr>
<td>4</td>
<td>23110.0</td>
<td>0.650</td>
</tr>
<tr>
<td>6</td>
<td>19670.0</td>
<td>0.938</td>
</tr>
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</tr>
<tr>
<td>500</td>
<td>1158.0</td>
<td>31.927</td>
</tr>
</tbody>
</table>

Fig. 4.9 Image of composite sheet of Gafchromic® radiochromic film exposed to range of dose from 0 to 500 Gy

Fig. 4.10 Normalised Green channel data compared with simple hyperbolic function $1/(1 + \alpha X)$, $\alpha = 0.16$
Fig. 4.11 Gafchromic® radiochromic film – Processed value \((\frac{I_0}{I}-1)\) directly proportional to Dose to 100 Gy.
4.6.3 Discussion

As shown in Fig. 4.11, at exposures greater than 100 Gy the graph tends to a saturation value, but it does not appear to saturate in the same way as silver halide film. Silver halide film reaches a saturation value quickly, whereas Gafchromic® radiochromic film only trends to a saturation value slowly, and does not reach a saturation at the maximum practical exposure, which is approximately 100 times the value that would saturate clinical silver halide film.

The linear portion of the graph shown in Fig 4.11, from 0 – 100 Gy, would suggest that the conversion of the active medium followed a function such as:

\[
\text{Optical Mass} = \ln(1 + \text{Constant} \times \text{Dose})
\]

Eqn. 4.16

Substituting this into the equation for exponential optical attenuation (Beer-Lambert Law, Eqn. 4.12), will result in the raw optical output decreasing as a simple hyperbolic function as the dose increases. It can be seen from Fig. 4.10 that a match is obtained with the hyperbolic function:

\[
\frac{1}{1 + \alpha X}
\]

Eqn. 4.17

where \(\alpha = 0.16\)

If the value of the transmission for the unexposed film is known, then the hyperbolic function can be manipulated to give the processed value expressed in Eqn. 4.15.

This can be explained as follows:

For the active medium of Gafchromic® radiochromic film the equivalent of the grains in silver halide film are the crystals of Di-acetylene [6], but these crystals are not of equal size. An exponential type distribution is expected as related to the grain size distribution. The progression of the conversion of the active medium starts predominantly with the larger crystals, which contain a large proportion of the total mass, then progresses with the smaller crystals which contain a smaller proportion of the total mass. The overall result is that the progression is similar to the \(\ln (1+\alpha X)\) function.
5 Derivation of Linear Response

5.1 Model for system response based on exponential distribution of particle size

It is proposed that in a specified volume (voxel) the particles of the active medium can be grouped such that the total mass of each group is equal, for example:

(i) Group 1 contains 1000 particles of mass 100 units -> total mass in group 100,000 units.

(ii) Group 2 contains 10,000 particles of mass 10 units -> total mass in group 100,000 units.

(iii) Group 3 contains 100,000 particles of mass 1 units -> total mass in group 100,000 units.

Then as the probability of conversion with dose is proportional to particle size, the particles in Group 1 are 10 times more likely to be converted than Group 2 and 100 times more likely than Group 3.

Then if a dose of 10 units is sufficient to convert 90% of Group 1, it will convert 9% of Group 2 and 0.9% of Group 3.

An additional dose of 90 units would convert 90% of Group 2, and a further 900 units would convert 90% of Group 3.

Therefore, approximately, the conversion of the mass of active medium (Optical Mass) is proportional to the Logarithm of the dose the medium has been exposed to. Note that the use of function $\ln (1+\alpha X)$ is such that response for zero dose equals zero. See Fig. 5.1.

<table>
<thead>
<tr>
<th>Dose Units</th>
<th>$\ln(1+\alpha X)$</th>
<th>Total Optical Mass Converted</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>2.398</td>
<td>100</td>
</tr>
<tr>
<td>100</td>
<td>4.615</td>
<td>200</td>
</tr>
<tr>
<td>1000</td>
<td>6.909</td>
<td>300</td>
</tr>
</tbody>
</table>

Fig 5.1. Total optical mass converted vs $\ln (1+\alpha X)$

Note that the above explanation is simplistic. The particle size distribution is continuous, at least in context that there is a finite, but very large, number of particles. There may be a
practical upper limit of size, and also a lower limit, where particles below a certain size do not polymerise. Despite this, it can be considered valid to subdivide much further such that an actual distribution is better represented.

Then for each group the conversion function,

\[ OM_e = OM_i \times (1 - \exp(-K_n \times X)) \]

Eqn. 5.1

where:

- \( OM_i \) is the total optical mass initially in each group,
- \( OM_e \) is the optical mass converted in each group, and
- \( K_n \) is a constant for group \( n \) and \( X \) is dose,

can be applied for each group, then the total optical mass converted is the sum of all groups. The result of the model calculation and comparison to the \( \ln (1+\alpha X) \) function is presented in Fig. 5.2. It indicates that there is good agreement over a significant range.

![Comparison of Model of Response of Exponential distribution vs Ln(1+X) Function](image)

Fig 5.2. Comparison of model of Response of exponential distribution vs \( \ln (1+\alpha X) \)

The result appears to be valid for the Green channel of an Epson V800® scanner. It is an important result, as it allows for a simple and effective method for using Gafchormic® radiochromic film for dosimetry in radiotherapy. In particular, the practical range, 0 - 100 Gy,
allows for a single method to cover all current dose measurements, from low dose scatter to lens of eye, approx. 1 cGy per fraction, to single fraction SABR, where the target dose in the measurement phantom may be greater than 4000 cGy.

In the present study, for the scanners evaluated, it was only the Green channel of the Epson V800® that gave good agreement. Even then it was noted that when used in the dose range below 2 Gy a correction should be applied to achieve current acceptable levels of accuracy for IMRT analysis. This correction was attributed to the spectral properties of the light source / detector combination and how it was affected by the absorbance spectra of the Gafchromic® radiochromic film.

5.2 Model of scanner response from absorbance spectra

The above derivation assumes the simple form of the Beer-Lambert law, where the attenuation follows a simple exponential decrease with thickness. In the case of Gafchromic® radiochromic film, the thickness equates to the amount of active medium that has been converted to the non-transparent state. The term attenuation refers to the loss in response by any means and the term absorbance refers to loss in response by the absorption of the light by the active medium of the film.

It is known that the absorbance spectra of Gafchromic® radiochromic films are complex (Fig. 5.3). It is the combination with the channel light / detector system that will result in the channel response.
Fig. 5.3 Visible absorption spectra of EBT2 film before and after irradiation (ISP [6])

To derive the scanner response, the response for an ideal absorber where there is uniform absorption across the active spectral window of a source/detector combination, should first be demonstrated (Fig. 5.4).

Fig 5.4. Optical Mass converted (OMc) vs Dose modelled as ln(1 + alpha * X)
For Gafchromic® radiochromic film modelled as:

\[ OM_c = OM_i \times \ln(1 + \alpha X) \]  

Eqn. 4.13

\( \alpha = 0.16 \) which is the approximate value derived for Gafchromic® radiochromic film Green channel data (Fig 4.9).

The term OM (optical mass) is the mass of active medium in a voxel of the film. \( OM_i \) is the initial value prior to exposure. \( OM_c \) is the amount of active medium in converted state post exposure.

Note as outlined above, that the function \( \ln (1 + \alpha X) \) is an approximation suitable to be used in the Dose range 0 to 100 Gy. It is noted that \( \ln (1 + \alpha X) \) tends to an infinite value as the Dose tends to an infinite value, whereas there is a finite amount of active medium; once all has been converted, there is no more to convert. Therefore, the Y-axis does not have a relative scale to an absolute amount of the active material in a voxel of Gafchromic® radiochromic film.

This relation can be substituted into the response for an ideal absorber. An ideal absorber system is one that follows simple form of Beer-Lambert law, i.e. a simple exponential, where there is uniform absorption across the active spectral window of the source/detector system.
Fig 5.5. System response vs Dose modelled by substituting OMc into scanner function

Note: The scanner in this case is assumed to follow simple form of Beer-Lambert law, that is, simple exponential attenuation. Note that for this case the system response is a simple Hyperbolic $1/(1 + \alpha X)$.

The system response for this case (Fig. 5.5), can be shown to be a simple hyperbolic function, $1/(1 + \alpha X)$ as follows:

Scanner response is modelled as:

$$\frac{I}{I_0} = \exp(-OMc)$$  \hspace{1cm} Eqn. 5.2

Then using Eqn.4.13 for OMc

$$\frac{I}{I_0} = \exp(-\ln(1 + \alpha X)) = 1/(1 + \alpha X)$$  \hspace{1cm} Eqn. 5.3

This simple Hyperbolic function can be inverted to relate Dose in terms of the derived function ($I/I_0$-1) to give Eqn. 4.7:

$$Dose = (Derived \ function) \times \text{Constant}$$  \hspace{1cm} Eqn. 4.7
Fig 5.6. Derived function \((I_0/I)-1\) vs Dose. Demonstrates linear response

Plot of derived function \((1/\alpha) what follows?
scanner response is exponential, then taking the logarithm is effectively removing the scanner response from the system response.

It is noted that the logarithm function is a difficult function to fit using a multi term polynomial. The logarithm function can be shown to expand as an infinite series of polynomials. Therefore, it cannot be exactly estimated from a finite series. Any limited approximation will only be valid for the specified range. The fitting function is to the inverse. As explained above, it is normal to derive Dose from optical response, that is, optical response on the X-axis and Dose on the Y-axis. The result is a function that is approximately exponential. Again, the exponential function can be expanded as an infinite series of polynomials. With regard to errors, it can now be seen that errors expand exponentially. That is, if optical density is chosen as the derived function of optical response, then the errors in the estimated dose will expand exponentially with the errors in measured optical response.

This is a significant problem with Gafchromic® radiochromic film as it continues to darken after it is exposed. The difference between the value for dose derived at 1 hour post exposure and 24 hours post exposure may be as much as 10%. It should be noted that the shape of the conversion curve remains the same, but with a different value of $alpha$.

If optical density is used as the derived function, the error in the fitting function results in a non-linear response (exponential) as the errors are expanded. These errors cannot be corrected by a simple scaling factor.

On the other hand, if $((I_0/I) - 1)$ is used as the derived function, this results in a linear response with a different gradient. This error can be corrected by a scale factor. This allows patient data to be analysed in relative mode. This is demonstrated in Fig. 5.7.
Fig. 5.7. Derived function \((I_0/I)-1\) vs Dose

Note: Demonstrates linear response scales as constant alpha

5.3 Model of system response for absorbance spectra with 2 distinct bands

The model for an absorber can now be considered as having two distinct spectral components with respect to the source/detector combination, one where absorbance is high and accounts for a large proportion of total at low exposure. In the other band, the absorbance is low and at low exposure only accounts for a small fraction of total, but at high exposure, as the contribution of the band with high absorbance has diminished such that it is now insignificant, this band now accounts for the major portion of the total. This approximates to the Red channel response of the Epson scanners when used with Gafchromic® radiochromic film. There is a high absorbance band associated with the distinct absorbance peak at approximately 636 nm (see Fig. 5.3); (ISP [1]), and a low absorbance band at wavelengths greater than 660 nm. The bi-exponential function is a reasonable approximation to the scanner Red channel response to Gafchromic® radiochromic film. Note that it is recognised...
as an approximation, as the actual spectral response associated with the Red channel is a continuous function.

The system response is modelled by substituting $OMc = \ln (1 + alpha X)$ into the model of a scanner with two distinct bands. A high value of $alpha$ is used for the high absorbance band and a low value of $alpha$ is used for the low absorbance band. The sum of the scanner response is no longer a simple hyperbolic (see Fig. 5.8).

![System response vs Dose](image)

**Fig. 5.8.** System response vs Dose for a system with 2 distinct absorbance bands

Further, the derived function $(I_0/I)-1$ can be plotted vs dose (see Fig. 5.9). Note that for this system, the derived function $(I_0/I)-1$ is not linear with dose. Of note is the effect of the low absorbance component, which has a significant effect on the non-linear shape of the curve.
Fig. 5.9. Derived function \((I_0/I)-1\) vs Dose for system with 2 distinct absorbance bands

Note: The derived function \((I_0/I)-1\) is not linear for this system.

This does not exclude the use of the Red channel data for dosimetry. It is recognised that for low exposures the sensitivity of the Red channel is superior to the other channels. This is mainly due to the high absorbance peak at 636 nm. However, applying the above process, such that errors do not expand exponentially and the result can be scaled by a linear constant, requires that the Red channel scanner response function be removed from the system response data, leaving the response curve of the active component of the Gafchromic® radiochromic film. The active component varies as \(\ln (1 + \alpha \text{Dose})\) Therefore to get relation in terms of Dose requires that the exponential function is applied and unity is subtracted. This is a difficult process, as the model of a bi-exponential is for the scanner raw value as the independent variable, whereas it is required to be inverted and the function derived with the scanner raw value as the dependent variable. For any given scanner, this should only have to be derived once, and it may be the case that for a particular model of scanner the response function is defined by hardware properties that do not change, either from unit to unit, or significantly over time, such that it is only required to be derived once for all units of a particular model of scanner.
If this method is used, the end result will be a process where the errors are linear, and can be corrected by applying a scale factor, that is, suitable to be analysed in relative mode.

Note that it is recognised that for the other channels, Green and Blue, the simple application of the Beer-Lambert law as a simple exponential is an approximation. It may be a good approximation for the Epson V800® scanner, such that the resultant errors are small in comparison to the assessment criteria for IMRT dosimetry. Therefore, a valid analysis can be made. It would also be appropriate to derive the scanner response function for the Green channel and apply as above.

5.4 Discussion

The results above are derived based on observed measurements of the optical system of the scanner. Supporting data has been obtained from Ashland, manufacturers of Gafchromic® radiochromic film. See Fig. 5.10, which is a particle size analysis for a particular Lot (070516) of Gafchromic® radiochromic film. It is noted that the particle size distribution may be different for different lots and further that an underlying theory to explain why the particle size (mass) approximates to an Exponential distribution has not been developed. The test data was collected from several lots of Gafchromic® film, both EBT2® and EBT3®, all of which demonstrated approximate linear response.

In general, the results demonstrate that film dosimetry should be treated as having two major components: the conversion of the active medium with dose; and the optical response of the scanner taking into account the spectral properties of the film. For a good quality scanner, it would be reasonable to assume that the scanner optical properties are stable, both from unit to unit within a model range and over an extended time period. If this can be demonstrated to be the case, then even if it is a significant effort to derive the scanner response function (inverse), it will only have to be done once for a particular model of scanner. The scanner response function can then be removed from the raw data, which would then effectively leave a map (distribution) of the amount of active medium converted. The dose can then be derived by applying the model of the conversion of active medium with dose, \( \ln (1 + \alpha X) \). What may need to be evaluated is whether the spectral response varies significantly over the area of the flatbed scanner; in particular, the response in the lateral axis may exhibit such a response due to the internal optics of the scanner.
Fig. 5.10 Particle size analysis for active medium of Gafchromic® radiochromic film

However, for the particular case of the Green channel of an Epson V800® scanner used in transmission mode with Gafchromic® radiochromic film (Gafchromic® EBT2® and EBT3®)
were used), the optical response of the channel appears to approximate to a simple exponential attenuation. There is no need to add the extra complexity and the system can be treated as a simple system, which provides a level of accuracy suitable for use with IMRT QA. It may be the case that if higher accuracy was required, then this could be achieved by applying equivalent corrections. It is noted that the response of the Green channel is not perfectly uniform across its spectral window; it appears uniform to an extent that the optical attenuation is approximately a simple exponential function.

It is also noted that for low dose exposures, less than 3 Gy, the Red channel of an Epson V800® is dominated by the high absorbance band, and as a result can be treated in a similar manner to the Green channel. The result is close to linear such that it can be corrected by a simple Gamma correction of approximately 6%. This may be useful, as it is recognised that the signal to noise ratio of the film/scanner system is superior using the Red channel compared to the other channels (Bennie & Metcalfe [1]).
6 Implementation of Novel Gafchromic® Radiochromic Film Calibration Methods for IMRT QA Dosimetry

6.1 Implementation

The information in this chapter is published in part in the paper, *Practical IMRT QA dosimetry using Gafchromic film: A quick start guide* (Bennie & Metcalfe [1]):

A summarised form is presented in Appendix A3.

This chapter provides a documented procedure for the use of Gafchromic® radiochromic film by the process developed in this thesis for use in clinical dosimetry.

The internal North Coast Cancer Institute document, *GAF Film Procedure.pdf: Appendix I*, provides specific procedure documentation on the use of:

- The XiO® and Monaco® Treatment Planning systems in the preparation of QA plans to be evaluated by measurement with Gafchromic® radiochromic film
- The IBA ImRT® phantom with film
- The Elekta Linac Treatment system for the delivery of the QA plan to the film in the phantom
- The SNC Patient® program for the analysis of the processed film data

The document, *GAF Film Processing using ImageJ.pdf, Appendix I*, provides specific procedure documentation on the use of:

- The ImageJ macro programs to process the scan data and provide measured dose planes in a suitable format for SNC Patient® (IMRT analysis program)

ImageJ is an image processing package available from the National Institutes of Health, Bethesda, Maryland, USA, web site: http://imagej.nih.gov/ij (Rasband [20]; Abràmof et al. [21]).

The radiochromic film used in this project was supplied from Ashland Speciality products, Wayne, NJ. The products were Gafchromic EBT2 and EBT3.
6.2 Clinical results

The results presented here demonstrate the practical implementation of the process developed in this study. A selection of test radiotherapy beam arrangements, which have been planned on the Elekta Monaco® TPS used at NCCI, Lismore are presented. These demonstrate specific aspects of QA using film. The two current types of Gafchromic® radiochromic film, EBT2® and EBT3®, are represented, and different scanners, Epson V700® and Epson V800® have been used.

The following representative selection of actual Patient plans (anonymised) have been transferred to a IBA ImRT® film phantom and the dose distribution calculated. These have been chosen to demonstrate utility for a range of IMRT treatment types and different range of dose per fraction. For example, Elekta dMLC® IMRT, Elekta VMAT, SBRT and SABR. The dose per fraction ranges covered are from 1.8 Gy/Fx to 40 Gy/Fx.

The analysis was performed using the application from Sun Nuclear, Patient®. This program compares the processed measured data (film) with the calculated data from the TPS. It allows adjustment of parameters for Gamma analysis (Low et al. [16]) which are applied in the global sense (VanDyk et al. [15]). Gamma analysis is a tool that allows the quantitative comparison of dose distributions. Prior to comparison the datasets to be compared are renormalised by dose and distance criteria. The renormalisation allows the dose distribution comparison to be conducted simultaneously along dose and distance axis. It is in effect an extension of the VanDyk criteria for IMRT patient QA. The VanDyk criteria were developed to give a meaningful comparison for machine QA data, in particular water tank profile data. In the central area of the profile the dose was reasonably constant and a meaningful comparison using only magnitude could be made. In the high dose gradient regions it is necessary to include a distance to agreement criteria in order that a meaningful comparison can be made. Gamma analysis extends this concept to patient QA, which is generally 2 dimensional, but can be 3 or 4 when datasets at different time points are included. In the original paper (Hu et al. [16]) it is suggested that criteria of 3% and 3mm are typical of clinical use. These are still common criteria for general measurement devices used in radiotherapy. However, an advantage of film is higher spatial resolution. It is therefore often used in situations where high spatial resolution is required to be assessed and generally a less stringent requirement for the magnitude of the dose. As such, at NCCI for IMRT patient QA, criteria of 4% and 2mm is used for film analysis. Note that a physicist making an analysis is
not restricted to these criteria, and should they deem it beneficial to use different criteria, they may choose to do so.

All of the results presented have been analysed with parameters 4%/2mm with a threshold of 10%. This is normal at NCCI for film analysis, where geometric resolution is given higher importance than amplitude (dose) resolution. For each analysis, three screen captures have been presented. The histogram screen presents the measured data in the top left, the calculated data in the top right, the calculated gamma index (Low et al. [16]) in the bottom left, and a histogram of the gamma index values is presented in the bottom right. On the right hand side bar are presented the percentages passing for the gamma analysis with the total number of points analysed, the number passing and the number failing. The Xprofile screen presents a profile plot of both measured and calculated data in the X-axis; the pink line is measured data, and the black line is calculated (TPS) data. This is with reference to the film. As described earlier, an advantage of film is that it can be positioned in any orientation. For the analyses in this study, the film is in either the coronal or sagittal plane with respect to the patient frame of reference. The Yprofile screen presents the same for the Y-axis.

Generally, one standard sheet (25x20 cm) of film was used, but for SBRT treatments where the target is reasonably small and there is a requirement to measure in both the coronal and sagittal planes, then a half sheet (12.5x20 cm) was used for each plane. This is sufficient to evaluate all areas of interest and saves on the total amount of film used for a patient QA analysis.

The following notes are provided as a guide to the data analyses represented in Figures 6.1a through to 6.13c. Descriptive particulars are noted under each figure.

Figures 6.1a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure what is effectively a depth dose curve for the Y-axis and a dose profile for the X-axis. Generally, this would be considered one of the simplest beam arrangements to be tested in external beam radiotherapy (EBRT). Despite this, it is useful, as it demonstrated direct compatibility with other measurement method such as a rectilinear scanning water tank. Note good agreement over the area of assessment, the gamma analysis indicates 99.2% of points passing at criteria of 4% and 2mm. In general, this can be interpreted as the measured data is within 4% of the calculated data, and in the regions of high dose gradient, where the dose difference is greater than 4%, points of agreement can be identified within a radius of 2mm.
Figures 6.2a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by the standard simple beam combination for range to 15 Gy (see Table 3.2). In this example the film used was Gafchromic EBT2® and the scanner used was an Epson V700®. Note good agreement over the area of assessment, the Gamma analysis indicates 99.6% of points passing at criteria of 4% and 2mm. Note some regions of the measured data have what appears to be areas of small random errors, generally this is attributed to the EBT2 film used, which was an early version and quality may not have been as good as the later version EBT3.

Figures 6.3a – c: The analyses displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by the standard simple beam combination for range to 15 Gy (see Table 3.2). In this example the film used was Gafchromic EBT3® and the scanner used was an Epson V700®. Note good agreement over the area of assessment, the gamma analysis indicates 100% of points passing at criteria of 4% and 2mm.

Figures 6.4a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by the standard simple beam combination for range to 15 Gy (see Table 3.2). In this example the film used was Gafchromic EBT3® and the scanner used was an Epson V800®. Note good agreement over the area of assessment, the gamma analysis indicates 100% of points passing at criteria of 4% and 2mm.

Figures 6.5a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by the standard simple beam combination for range to 3 Gy (see Table 3.1). In this example the film used was Gafchromic EBT3® and the scanner used was an Epson V800®. Note good agreement over the area of assessment, the gamma analysis indicates 99.9% of points passing at criteria of 4% and 2mm.

Figures 6.6a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by the standard simple beam combination for range to 50 Gy. In this example the film used was Gafchromic EBT3® and the scanner used was an Epson V800®. Note good agreement over the area of assessment, the gamma analysis indicates 100% of points passing at criteria of 4% and 2mm.
Figures 6.7a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by a VMAT plan to treat a pelvic node. For this case the target dose was 3 Gy/Fx. Note good agreement over the area of assessment, the gamma analysis indicates 100% of points passing at criteria of 4% and 2mm.

Figures 6.8a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by a VMAT plan to treat a prostate. It is now standard practice at NCCI, Lismore to treat prostates with 45 fractions of 1.8 Gy, to give total of 81 Gy. Note good agreement over the area of assessment, the gamma analysis indicates 100% of points passing at criteria of 4% and 2mm.

Figures 6.9a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by a VMAT plan to treat a lung tumour. For this case the target dose was 10 Gy/Fx. This is considered a SABR (Stereotactic Ablative Body Radiotherapy) treatment. Therefore, there is a requirement to ensure the geometric accuracy of the dose distribution. That is, the very high equivalent biological dose is such that it will sterilize all cells in the target volume, but it has the potential to do serious damage to normal tissues if the delivery it not geometrically accurate. Note that with good agreement over the area of assessment, the gamma analysis indicates 100% of points passing at criteria of 4% and 2mm.

These figures show the transverse orientation. For these SBRT cases it is normal to measure in two planes, transverse and sagittal. Note only a half sheet (12.5 x 20 cm) is used for each orientation. Generally, the target with a SABR treatment is small, so will fit on a half sheet.

Figures 6.10a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by a VMAT plan to treat a lung tumour. For this case the target dose was 10 Gy/Fx. Note good agreement over the area of assessment, the gamma analysis indicates 99.9% of points passing at criteria of 4% and 2mm. This is the same treatment plan as for Figures 6.9a – c, but measured in the sagittal orientation. The sagittal orientation is useful in assessing the extent of the dose delivered in the Gun/Target axis. This can be problematic with Elekta Linacs where this motion may be over 1.5 mm. For these SBRT cases it is normal to measure in two planes, transverse and sagittal.
Figures 6.11a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by a VMAT plan to treat a Lung tumour. For this case the target dose was 8 Gy/Fx. Good agreement over the area of assessment, the gamma analysis indicating 98.6% of points passing at criteria of 4% and 2mm, should be noted. Note however, the small discrepancy seen on the Xprofile, in the transverse orientation.

Figures 6.12a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by a VMAT plan to treat a Lung tumour. For this case the target dose was 8 Gy/Fx. Note good agreement over the area of assessment, the gamma analysis indicates 98.6% of points passing at criteria of 4% and 2mm. Note the small discrepancy seen on the Xprofile. However, it is not as noticeable on this, the sagittal, as it is on the transverse orientation. This demonstrates the better amplitude (dose) resolution in the transverse orientation.

Figures 6.13a – c: The analysis displayed in these figures demonstrates the utility of the method to accurately measure the dose distribution produced by a VMAT plan to treat a Lung tumour. For this case the target dose was 40 Gy/Fx. Note this is a test patient plan, no NCCI patients have been treated with a single fraction. Note that a maximum of 150% is allowed, therefore the maximum could be 1.5 x 26 = 39 Gy, hence evaluation to 40 Gy. Note good agreement over the area of assessment, the gamma analysis indicates 100% of points passing at criteria of 4% and 2mm.
Fig. 6.1a. Data analysis: Single 10x10 beam: Histogram

EBT2 film, Lot # A02171102. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.2%
Fig. 6.1b. Data analysis: Single 10x10 beam: Xprofile

EBT2 film, Lot # A02171102. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.2%
Fig. 6.1c. Data analysis: Single 10x10 beam: Yprofile

EBT2 film, Lot # A02171102. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.2%
Fig. 6.2a. Data analysis: Simple 9 field calibration to 15 Gy: Histogram

EBT2 film, Lot # A02171102. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.6%
Fig. 6.2b. Data analysis: Simple 9 field calibration to 15 Gy: Xprofile

EBT2 film, Lot # A02171102. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.6%
Fig. 6.2c. Data analysis: Simple 9 field calibration to 15 Gy: Yprofile

EBT2 film, Lot # A02171102. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.6%
Fig. 6.3a. Data analysis: Simple 9 field calibration to 15 Gy: Histogram

EBT3 film, Lot # 07281402. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.3b. Data analysis: Simple 9 Field Calibration to 15 Gy: Xprofile

EBT3 film, Lot # 07281402. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.3c. Data analysis: Simple 9 field calibration to 15 Gy: Yprofile

EBT3 film, Lot # 07281402. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.4a. Data analysis: Simple 9 Field Calibration to 15 Gy: Histogram

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.4b. Data analysis: Simple 9 Field Calibration to 15 Gy: Xprofile

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.4c. Data analysis: Simple 9 Field Calibration to 15 Gy: Yprofile

EBT3 film, Lot # 07281402. Epson V700® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.5a. Data analysis: Simple 9 field calibration to 3 Gy: Histogram

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.9%
Fig. 6.5b. Data analysis: Simple 9 field calibration to 3 Gy: Xprofile

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.9%
Fig. 6.5c. Data analysis: Simple 9 field calibration to 3 Gy: Yprofile

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.9%
Fig. 6.6a. Data analysis: Simple 10 field calibration to 50 Gy: Histogram
EBT3 film, Lot # 02181401. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.6b. Data analysis: Simple 10 field calibration to 50 Gy: Xprofile

EBT3 film, Lot # 02181401. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.6c. Data analysis: Simple 10 field calibration to 50 Gy: Yprofile

EBT3 film, Lot # 02181401. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.7a. Data analysis: Sample patient, pelvic node, VMAT, 3 Gy: Histogram

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.7b. Data analysis: Sample patient, pelvic node, VMAT, 3 Gy: Xprofile

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.7c. Data analysis: Sample patient, pelvic node, VMAT, 3 Gy: Yprofile

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.8a. Data analysis: Sample patient, prostate, 7 Field dMLC, 1.8 Gy: Histogram

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.8b. Data analysis: Sample patient, prostate, 7 Field dMLC, 1.8 Gy: Xprofile

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.8c. Data analysis: Sample patient, prostate, 7 Field dMLC, 1.8 Gy: Yprofile

EBT3 film, Lot # 07281402. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.9a. Data analysis: Sample patient, lung SBRT1, VMAT, 10 Gy, transverse: Histogram

EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.9b. Data analysis: Sample patient, lung SBRT1, VMAT, 10 Gy, transverse: Xprofile
EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.9c. Data analysis: Sample patient, lung SBRT1, VMAT, 10 Gy, transverse: Yprofile

EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.10a. Data analysis: Sample patient, lung SBRT1, VMAT, 10 Gy, sagittal: Histogram

EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.9%
Fig. 6.10b. Data analysis: Sample patient, lung SBRT1, VMAT, 10 Gy, sagittal: Xprofile

EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.9%
Fig. 6.10c. Data analysis: Sample patient, lung SBRT1, VMAT, 10 Gy, sagittal: Yprofile

EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 99.9%
Fig. 6.11a. Data analysis: Sample patient, lung SBRT2, VMAT, 8 Gy, transverse: Histogram

EBT3 film, Lot # 04201501, Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 98.6%
Fig. 6.11b. Data analysis: Sample patient, lung SBRT2, VMAT, 8 Gy, transverse: Xprofile

EBT3 film, Lot # 04201501, Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 98.6%
Fig. 6.11c. Data analysis: Sample patient, lung SBRT2, VMAT, 8 Gy, transverse: Yprofile
EBT3 film, Lot # 04201501, Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 98.6%
Fig. 6.12a. Data analysis: Sample patient, lung SBRT2, VMAT, 8 Gy, sagittal: Histogram

EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 98.6%
Fig. 6.12b. Data analysis: Sample patient, lung SBRT2, VMAT, 8 Gy, sagittal: Xprofile

EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 98.6%
Fig. 6.12c. Data analysis: Sample patient, lung SBRT2, VMAT, 8 Gy, sagittal: Yprofile

EBT3 film, Lot # 04201501. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 98.6%
Fig. 6.13a. Data analysis: Sample patient, lung SBRT3, VMAT, 40 Gy, transverse: Histogram

EBT3 film, Lot # 02181401. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.13b. Data analysis: Sample patient, lung SBRT3, VMAT, 40 Gy, transverse: Xprofile

EBT3 film, Lot # 02181401. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
Fig. 6.13c. Data analysis: Sample patient, lung SBRT3, VMAT, 40 Gy, transverse: Yprofile

EBT3 film, Lot #02181401. Epson V800® scanner. Percent points passing Gamma Criteria 4%/2mm: 100%
7 Summary of Conclusions and Suggested Future Work

Histogram correlation was demonstrated to be a fast, effective and accurate method to determine a calibration for measurement devices that collect an array of data and a TPS is available that can provide a corresponding calculated array of data for comparison. This is generally the case in radiotherapy.

The first research question for this study was:

(i) To what extent does histogram correlation aid in revealing the underlying base response function of Gafchromic® radiochromic film (or any other device)? Are there other advantages of using histogram correlation?

To address this question, with regard to Gafchromic® radiochromic film, histogram correlation allowed the observation that the optical response of this film scanned on a 3 channel RGB flatbed scanner in transmission mode was approximately directly proportional to the dose the film had been exposed to.

\[ Dose = (\text{Derived function}) \times \text{Constant} \]  
Eqn. 4.7

In particular, for the Green channel data of an Epson V800 scanner, this relation was found to hold to a high degree over the range 0 to 100 Gy. It is noted it is approximate and for the dose range 0 to 3 Gy a gamma correction of approximately 3% \cite{1} is required to achieve the accuracy to meet general criteria for IMRT QA analysis. Note at the North Coast Cancer Institute (NCCI) it is normal to use 3%/3mm for general IMRT analysis and 4%/2mm when using film when a higher specification for geometric error is required. The action level is 95% of points passing, but it is normal to achieve >99% of points passing using the method developed. Note that in addressing the second part of the research question, histogram correlation is a fast and effective tool to derive a calibration when both a measured and calculated dataset are available. With regard to assessing the correction, if required, it is a suitable tool.

The second research question was:

(ii) To what extent can the optical response of Gafchromic® radiochromic film be fitted by a linear function?
To address this question, it was found that the system optical response of Gafchromic® radiochromic film, scanned on a flatbed scanner, is, in general, not linear. However, if the optical response of the scanner can be approximated by the simple form of the Beer-Lambert law, i.e. simple exponential attenuation, then the combined system response will be linear. For the particular case of the Green channel of the Epson V800® scanner, this appears to be the case. The response is linear over a large range and only requires a small correction for low dose, <3Gy.

This then led to the derivation of the underlying process of the conversion of the active medium of Gafchromic® radiochromic film from the transparent to non-transparent state. That is, it responds as the function ln (1 + alpha X). This addresses the third research question:

(iii) How can the observed response of Gafchromic® radiochromic film be explained?

This led to a better understanding of the optical response of a scanner where the absorbance spectrum is not uniform and as a result the application of the Beer-lambert law has to be in the complex form, that is, the integral over the spectrum associated with the channel (source/detector response) used. It allowed an understanding of the particular case of the Green channel of an Epson V800® scanner, which appeared to have a uniform response and so was suitable to be modelled by the simple form, that is simple exponential attenuation. This was found to be valid in the range 0 to 100 Gy.

With regard to the method implemented, the division of the Blank (scan prior to exposure) by the Exposed (scan post exposure) addresses some other problem aspects of Gafchromic® radiochromic film scanned using a general purpose flatbed scanner, namely, the scanner uniformity and the film uniformity. The scanner uniformity is the effect, particularly in the transverse axis of the scanner, where response varies with distance from central axis. This is generally attributed to the optical path with in the scanner, but is exacerbated by the channel RGB response associated with Gafchromic® radiochromic film. It is noted that each channel of an Epson scanner has a different uniformity. The film uniformity relates to the production process that applies the active medium to the film.

The study has shown that a dosimetry system based on the use of Gafchromic® radiochromic film scanned using RGB scanners and analysed using the method developed is practical. Specifically, it is accurate both geometrically and in magnitude, and it is simple and fast to
use, as it requires the derivation of only one parameter to characterize the response. Further, as the response is linear, corrections can be made by applying a simple constant as a scale factor so that the data can be analysed in relative mode.
Technical Acknowledgements

Image processing package ImageJ available from:

National Institutes of Health
Bethesda, Maryland, USA

Web site: http://imagej.nih.gov/ij

Version used was ImageJ 1.48v

Note some functions may not be available in earlier versions and the authors have no control over future versions of ImageJ.

Gafchromic® refers to a range of Radiochromic film products supplied by:

Ashland Speciality Ingredients
International Speciality Products
1361 Alps Road Wayne · NJ , USA

The Epson range of scanners was supplied by:

Seiko Epson Corp.Nagano, Japan

The IMRT evaluation program used was SNC Patient v6.5 supplied by:

Sun Nuclear Corporation, Melbourne, FA, USA
References


Appendix 1

The internal North Coast Cancer Institute document:

**GAF Film Procedure.pdf**

Provides specific procedure documentation on the use of the XiO and Monaco Treatment Planning systems in the preparation of QA plans to be evaluated by measurement with Gafchromic® radiochromic film.

Provides specific procedure documentation on the use of the IBA ImRT® phantom with film.

Provides specific procedure documentation on the use of the Elekta Linac Treatment system for the delivery of the QA plan to the film in the phantom.

Provides specific procedure documentation on the use of the SNC Patient® program for the analysis of the processed film data.

The internal North Coast Cancer Institute document:

**GAF Film Processing using ImageJ.pdf**

Provides specific procedure documentation on the use the ImageJ macro programs to process the scan data and provide measured dose planes in a suitable format for SNC Patient (IMRT analysis program)

ImageJ is an image processing package available from the National Institutes of Health, Bethesda, Maryland, USA,

web site: http://imagej.nih.gov/ij  (Rasband [20], Abràmof et al. [21]).

Included in this appendix is a summary of these two documents that would allow a user to complete a Patient QA procedure as per NCCI protocol with access to NCCI equipment, which includes all TPS software, Record and Verify system, Linac treatment system as well as the QA equipment specifically used at NCCI for routine film analysis.
Workflow Overview

1. Prepare sheet of film:
   - Label
   - Scan prior to Exposure
   - Insert in Phantom

2. Position Phantom with Film in Linac
   - Deliver QA Treatment to Phantom

3. Wait
   - (Recommend 1 hour)
   - Scan exposed Film

4. Process Scanned Film Data
   - (BLANK / EXPOSED)
   - Using ImageJ method
   - To get calibrated dose file in SNC Patient format.

5. Use TPS to Prepare Dose Plane output file for dosimetry plane of interest.

6. Use SNC Patient Application to analyse Film file by comparison to TPS Dose Plane output file
A2 Preparation and Scanning of film

The preparation of a sheet of Gafchromic® radiochromic film, the scan prior to exposure, the installation in phantom and the scan post exposure is detailed in NCCI document GAF Film Processing. It is summarised as follows:

- Remove a sheet of film from packet. Label such that it can be identified and the orientation of the film can be maintained.
- Scan the unexposed film and store image file in working directory. Scanner setup is specified in A5.
- Install sheet of film in phantom.
- Position phantom in treatment unit, as specified by QA plan.
- Irradiate phantom with the treatment plan that is to be evaluated.
- Remove film and store. Note recommendation is 1 hour, unless the treatment was particularly long and different parts of the film were exposed at significantly different times (total time, 1st part exposed to final, greater than 10 minutes).
- Scan the unexposed film and store image file in working directory. Scanner setup is specified in A5.

A3 Processing Scan data

The processing of the scanned film data to produced calibrated (dose) data is done by image processing application ImageJ. The conversion to a data format suitable for use by application SNC Patient is done using a MS Visual Basic (VB) program, RemovePinHoles. This program allows the user to remove significant pin holes left by the IBA phantom and saves data in a format suitable for application SNC Patient.

To run a macro in ImageJ, use:

File -> Open and select the macro (it should be saved with extension .ijm)

The Macro window should open, then from the Menu bar on the Macro window:

Select Macros -> Run Macro
It is assumed the scanned image files (Blank & Exposed) are in the working directory.

Using ImageJ:

Open image file (RGB) of the Pre-Exposure image (Blank).

Run macro:  IJmacro_PreProcess_BLANK.ijm

Open image file (RGB) of the Post-Exposure image (Exposed).

Run macro:  IJmacro_PreProcess_EXPOSED.ijm

The pre-processed but uncalibrated image of the exposed film should be open at this point.

Run macro:  IJmacro_Calibrate_V800_EBT3_LowRange.ijm

This macro applies the blank correction and applies a calibration function. The ImageJ macro then starts VB program, RemovePinHoles. This program allows the user to remove any pin hole artifacts that may have been introduced by the phantom. The program then saves data (calibrated Dose) to a file suitable for use by application SNC Patient.

The output file is:  AP_Processed_Film.txt

Further, if required, the adjustment VB program, GF_Linear_Correct_PFF, can be run to apply a linear correction.

The output file is:  AA_Film_File.txt

These data can then be analysed by application SNC Patient.

A4  Film processing software installation

The software to process the scanned data files and produce a file suitable for SNC Patient software is stored on the NCCI Physics server:

To load this software:

(Note instructions assume user is familiar with the Microsoft Windows operating system as installed at NCCI)
Copy the dir NCCI_GAF_v23_win7_IJ to C: drive under dir !Data.

For the standard IT configuration at NCCI, the dir !Data is the read/write/execute directory of the C: drive.

It should be checked that all users have full read/write/execute privilege to this dir.

Files in the directory are:

- **GF_Linear_Correct_PFF** VB exe for scaling dose file.
- **GF_Extract_subset_of_MapCheck_File** VB exe to extract subset of TPS file
- **GF_RemovePinHoles_1016x812** VB exe to remove pin hole artefacts
- **AA_RemovePinHoles** BAT file used to activate above.
- **Add_Header_to_csv_file** BAT utility to add a header to a csv file.
- **Cursor_Shift.txt** Adjustment for cursor select.
- **IJmacros** Directory of IJ Macros
- **IJmacro_PreProcess_BLANK.ijm** Macro to Pre-process RGB to 1016x812 TIF
- **IJmacro_PreProcess_EXPOSED.ijm** Macro to Pre-process RGB to 1016x812 TIF
- **IJmacro_Calibrate_V700_EBT3_HighRange.ijm**
- **IJmacro_Calibrate_V700_EBT3_LowRange.ijm**
- **IJmacro_Calibrate_V800_EBT3_HighRange.ijm**
- **IJmacro_Calibrate_V800_EBT3_LowRange.ijm**
All programs can be started by a double click on the executable file. However for, GF_RemovePinHoles_1016x812.exe, it is recommended to start using the batch file AA_RemovePinHoles.bat. Using the Windows7 operating system, this file can be activated by selecting the TIF file to be processed, then Right click, then select open with AA_RemovePinHoles.bat. The name of the TIF file to be processed is passed to the BAT file, which then activates the EXE with correct parameters. Note AA_RemovePinHoles.bat is activated at completion of the ImageJ calibration macros, by using the ImageJ exec command to activate the BAT file, in similar manner.

Add_Header_to_csv_file.bat is a utility that can be used to add a header to an image file in csv format. The csv file is created from a Text file output of ImageJ, by opening the text file in MS Excel, then saving as format csv. This allows the data to be read by application SNC Patient, by specifying “Planned Data” type “XiO”.
A5 Parameters for scanning software

EPSON Scan® is a software program provided by Epson Corporation to interface a computer to any of the Epson scanners used to scan the Gafchromic® radiochromic film.

It has been observed that the response of the scanner can be unstable and measures have to be taken to alleviate this issue. The method chosen for this film procedure is to scan at a very high resolution (recommend 1016dpi, 40dpmm). This slows the acquisition of a 20x25cm film to approximately 1 minute. This method also has the additional benefit that subsequently, when the data is processed, the system noise is reduced.

- Define the Main Screen EPSON Scan settings as shown below
  - Press **File Settings**: Little Icon just above Close button and define the File Save Settings as shown below.
○ Select TIFF Options -> Select “PC”
- Press Configuration. Ensure the settings in each tab are the same as the following four screenshots
• To acquire an image, Select “Preview”

Note: The image should appear as below, note position and orientation of written text and alignment mark.

• Check Alignment of film by using mouse/cursor to draw a selection box. Align side of box with 2 longitudinal pin holes in film. If pin holes are not aligned, then adjust film on scanner and repeat.

• When alignment is good, click the MARQUEE button to reset selected area to all of film.

• Click SCAN, to initiate scan
  o Note TIFF file should be saved as type “PC”.
Scan should take approximately 1 minute.

When finished it should store scanned data file in specified directory. This file is approximately 120Mb in size. It is recommended that the specified store directory in the configuration of the Epson scanner application is set to the same disk as the film processing directory. This allows a move of data from store to film processing directory. Otherwise a copy is required, which may take several minutes.

- Transfer scanned file to film processing directory.

Note after processing, a processed file is created which is significantly smaller, approximately 4Mb. Therefore, the large scanned data file can be deleted to conserve disk space. The processed file being kept is required for records.

Product references:

_Gafchromic, Ashland Speciality Ingredients_

_International Speciality Products, GafChromic White Paper: GAFCHROMIC® EBT2, SELF-DEVELOPING FILM FOR RADIOTHERAPY DOSIMETRY, Feb 2009_

_Epson V700 & V800 flatbed scanner with Transparency attachment. Seiko Epson Corp. Nagano, Japan_

_Sun Nuclear Corporation, MapCHECK (Patient) software_

_IBA Dosimetry, I’mRT Phantom_