The Hague University of Applied Sciences

Graduation

Determination of total uncertainty in dose of the radiochromic film dosimetry method

Author:
Luciën Martijn

Internship coach:
M.C. Vloemans

Friday 30th August, 2013

Abstract

The treatment of tumours in cancer patients have become more advanced and thus more complex. The verification of the dose distribution, calculated by clinical physicists, have thus become more complicated. VSL has started the development on measurements of absolute dose distributions in an antrhopomorphic phantom. One of those developments at VSL is the use of radio chromic dosimetry films (RCFD) to determine a dose distribution in two dimensions. Irradiating films with the double irradiation technique in an anthropomorphic phantom (PMMA) will be used to determine dose distributions that are traceable to primary standard at VSL, the watercalorimeter. Films are read out with a flatbed scanner. The scanning of the film introduces additional uncertainties to the dose determination procedure. The delivered dose on the film in the water phantom is different than the delivered dose in the PMMA phantom. Thefore a conversion factor between these two phantoms is needed and will be investigated in this report. The uncertainties of the scan procedure will also be investigated.

The conversion factor for the delivered dose to film in the PMMA and water phantom for RCFD has been validated by irradiating films in the water phantom and in the PMMA phantom. The ratio of OD ratios, R_{PMMA}/R_{water}, and its uncertainty of these delivered doses has been determined. The calculated reference value of R_{PMMA}/R_{water} is compared with the measured value. The effect of water can have an influence on the active layer of the film, this effect has been investigated and measured. The influence of pre-irradiation dose on film and its uncertainty has been investigated and determined. Experiments that determine the uncertainties of the scanning procedure have been investigated and determined for different components. Due to polarized films and scanner light, an additional source of uncertainty, the polarization effect has also been investigated and determined. As a result of all the measured uncertainties in the whole process of determining the dose distribution with RCF, an uncertainty budget of both the irradiation of films process and the scanning has been partially determined.

The difference between the measured value of the measured and the reference value of R_{PMMA}/R_{water} is -0.4%. The measured and calculated reference value differ too much when looked at the relative standard deviation of the measured value (0.0007). This value is used as an additional uncertainty. The water influence on film is nonexistant, the determined values of the ratio of the optical density between the control group of films and the in water dipped films fall within each others standard devition. When films are pre-irradiated with 0.5 Gy, it has been determined that the relative standard deviation on mean of R is greater than when films are pre-irradiated with 1.0 Gy. The total uncertainty of scanning films has been determined on a relative standard deviation of 0.007. Some physical quantities that can play a role on the process of determining a dose distribution with RCF are yet to be determined. Some physical quantities and its uncertainty of the whole process of determining the dose distribution with RCF are yet to be determined, only when all of the physical quantities have been determined and evaluated is it possible to evaluate if RCFD might be a reliable method to determine an absolute 2D dose distribution.

Abbreviations

PMMA	=	Poly (methyl methacrylate)
^{60}Co	=	Isotope Cobalt-60
Voxel	=	Volume element. Value voxel is average of the cluster pixel values
dpi	=	Dots per inche
RGB	=	Red Green Blue Colour Model
*.mat	=	Matlab file format
*.tiff	=	Tagged image file format
*.csv	=	Comma seperated values file format

List of symbols

SSD	=	Source to surface distance	[mm]
R	=	Ratio of $\Delta OD_2/\Delta OD_1$ of each voxel	[-]
OD	=	Optical Density	[-]
I	=	Intensity	[W m^{-2}]
D	=	Dose	[Gy]=[1 J kg^{-1}]
δ	=	Absorption parameter	[-]
ϕ	=	Orientation angle of film	[°]
$rel.OD$	=	Relative OD	[-]
$k_{D,ref}$	=	Correction factor D_{ref}	[-]
P	=	Polarization effect	[-]
k_{pol}	=	Correction factor polarization effect	[-]
$Rel.s$	=	Relative standard deviation in OD	[-]
t_{irr}	=	Irradiation time	[s]
$\dot{D}$	=	Dose rate	[Gy s^{-1}]
$C_{water,PMMA}$	=	Conversion factor for the secondary standard with RCFD	[-]

Contents

1 Introduction

1.1 Background

Radiotherapy departments of hospitals use ionizing radiation to damage and eradicate further tumour growth in patient's body. The main goal of the radiologists is to target most of the tumour cells and spare the healthy tissue surrounding the tumour. First, the tumour is to be located with the use of a CT scan. After the tumour's location and size is determined, a treatment plan is constructed with a computer (using special treatment planning software) by clinical physicists to ensure that the tumour cells recieve the most part of the ionizing radiation. The resulting 3D distribution is calculated from this plan. The patient is then treated according to the treatment plan.

The source of the ionizing radiation is a linear particle accelerator. This accelerator accelerates electrons at energies between 4 and 25 MeV, yielding X-ray photons with varying energies. The X-ray beam rotates around the patient, so that the tumour can be irradiated from different angles. The intensity of the beam can be modulated at each angle. In addition the beam is subdivided in small parts for which the intensity can be modulated independentely. During treatment planning all modulation parameters are optimized to achieve optimal dose distribution.

Figure 1 – Medical linear accelerator

Since dose distributions have become more and more complex, verification of the calculated dose distribution has become more important and more complicated. Several different techniques have been introduced recently to verify dose distributions in a relative manner. Most of these techniques lack a sufficient high resolution of about 2 mm. In addition, none of the techniques are able to measure an absolute dose distribution. There is a growing need of independent measurements of absolute dose distributions as a result of the ongoing development. For this

reason VSL has started the development on the measurements of absolute dose distributions in an anthropomorphic phantom.

1.2 Purpose of this tesis

Radio Chromatic Film Dosimetry (RCFD) is a measurement method to determine a dose distribution in two dimensions. In the last couple of years the section ionizing radiation of VSL has developed software, procedures and measurement setups to use the RCFD to determine traceable to the primary standard dose distributions accurately as a secondary standard. The primary standard for dose distribution determination is the water calorimeter. The radio chromic films have to be calibrated against this primary standard. The end goal of these developments is to determine an absolute 2D dose distribution in an anthropomorphic phantom with radio chromic films.

To determine a dose distribution, films placed in an anthropomorphic phantom are irradiated with X-ray photons and are scanned with a flat bed scanner afterwards. Specially designed software at VSL use the scan files to construct a 2D dose distribution.

Scanning the films with the flat bed scanner have a few uncertainties: polarization effects, scanning reproducibility, dependency of scan resolution and the non-uniformity of the scanner light. All these uncertainties will be investigated and assessed.

The films are irradiated in an antrhopomorphic phantom (PMMA) instead of a water phantom. The delivered dose on the film in the water phantom is different than the delivered dose in the PMMA phantom. Thefore a conversion factor between these two phantoms is needed. This factor has been determined previously with ionization chambers. However the effects of assumptions in this procedure were unknown. Validation of the indirect method with measurements of film in water and in a perspex phantom will also be investigated and assessed.

The first goal of the graduation internship is to determine the total uncertainty in the scanning procedure of the irradiated films of the radio chromic film dosimetry. The second goal is to determine the conversion factor of absorbed dose in a PMMA phantom to absorbed dose in water with film measurements and to determine the associated uncertainty.

2 Radio Chromic Film Dosimetry

2.1 Measurement Principle

Radio Chromic Film Dosimetry is a method to determine the absorbed dose in a water or in a phantom of any other material by scanning the film pieces in a flat bed scanner. This method is used as a secondary standard. The watercalorimeter is used as primary standard, which determines the dose absolutely by measuring the temperature increase in water. An other secondary standard for the determination of a dose distribution is the absorbed dose in a water phantom which is measured by an ionization chamber. For the chamber, a calibration is required in order to convert the measured electrical charge into absorbed dose in water.

The connection between the primary and secondary standard (of radio chromic film dosimetry) is determined by calibrating a radio chromic film in a water phantom. Radio chromic film dosimetry uses special made films (type EBT2) that are placed in a poly (methyl methacrylate) phantom (PMMA). These films consist of multiple layers, where one layer contains monomer crystals. These crystals undergo a polymerization reaction due to an ionizing radiation beam.

The polymerization process changes a property of the film, the optical density OD. After the films have been irradiated, they are scanned with a flat bed scanner (Epson^{TM} expression 1680 flat bed colour scanner). The created image files (*.tif file) of the films are processed with software that can calculate the absorbed dose distribution of the incident beam in the PMMA phantom. Each cluster of eight pixels of a *.tif file are averaged to one voxel.

2.2 Calibration Procedure

2.2.1 Model of EBT Film

The film that is used today by the department of radiation at VSL is of the type EBT2 of GafChromic. Figure 2 shows the model of the EBT2 film[6] The active layer has a thickness of 30 μm, and consists of monomer crystals (active component embedded in a gelatin matrix). The active layer is coated by a 50 μm polyester overlaminate with a 25 μm adhesive layer in between and a polyester substrate of 175 μm.

When the film is irradiated with ionizing radiation, a chain of ionizations by electrons is induced. Ionization of one of the monomer molecules induces a polymerization reaction. The polymerization reaction changes the optical density of the film (also called absorbance). The optical density is a logarithmic ratio between the intensity of an incident light beam and the intensity of the transmitted light beam[2]:

$$OD = \log \frac{I_0}{I_t} \tag{1}$$

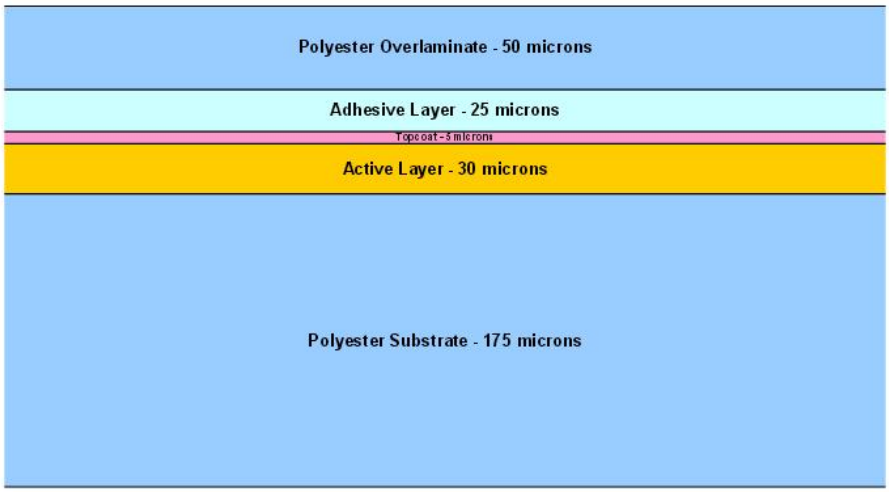


Figure 2 – Configuration of GafChromic EBT2 film

Where I_0 and I_t are the incident radiation beam and the transmitted radiation beam respectively. The change in optical density is dependent on the wavelength of the incident light beam.

2.2.2 Double Irradiation Technique

The films are not perfectly homogeneous in terms of monomer crystal concentration and/or a film thickness in the active layer. Points on the film with a different concentration of monomer crystals and a different film thickness will have a slightly different OD value when irradiated with the same dose. The resulting sensitivity of the film at that point will be different for the same absorbed dose. The inhomogeneity in OD over different points on the film contributes to an additional contribution to uncertainty and can be in the order of 1-2%. To reduce this uncertainty the double irradiation technique is applied.

The double irradiation technique is a technique that performs the irradiation twice on the film, with a development time in between. The development time is applied to allow remaining polymers reaction to complete. The time between the two irradiations on the film is kept at 144 hours [6]. After this time period, the change in OD per day is smaller than 0.06% [1].

The net optical density ΔOD is calculated as follows with use of equation 1 [5]:

$$\Delta OD^i = OD^i_{irr} - OD^i_{unirr} \tag{2}$$

$$= \log \frac{I^i_{unirr} - I^i_{zero}}{I^i_{irr} - I^i_{zero}} \tag{3}$$

Where ΔOD^i is the net OD value of one voxel, i, (scanned film piece) of an irradiated film, OD^i_{unirr} is the OD value of that same voxel of an unirradiated film and OD^i_{irr} is the OD value of the same voxel of that same film. I_{zero} is the light intensity value of that same voxel of a zero

scan (see section 2.2.5)[1].

First, the unirradiated film is scanned and OD^i_{unirr} per voxel is calculated with equation 1 from the relative intensities of the red channel, (see section 2.2.5) of the *.tif file with the matlab routine ReadOD[1] (see section 2.2.6). Then, the film is pre-irradiated with a known dose D_1. After the film has been pre-irradiated, ΔOD_1 per voxel is determined. Then 24 hours later, the film is irradiated again with a calibration or unknown dose D_2 and ΔOD_2 per voxel is determined as well.

The ratio $R = \Delta OD_2/\Delta OD_1$ of each voxel is used to determine D_2 of each voxel and thus the dose distribution. Taking this ratio will reduce the uncertainty contribution of the inhomogeneity in OD over the film.[1]

A relation between the absorbed dose and change in optical density has been derived[2].

$$OD = OD_\infty(1 - \exp(-\delta D)) \tag{4}$$

Where OD_∞ is the OD after infinite dose, D the dose and δ the absorption parameter. OD is dependent on the concentration of monomer crystals and the thickness of the film. Whereas the δ parameter is independent of the monomer concentration and thickness of the film.

The pre-irradiation dose that is given to the film is 1 Gy. It is not possible to give precisely 1 Gy to the whole film, due to the irradiation timer which can only set time with 2 digits accuracy. Another contribution to the given dose uncertainty is the beam field (flat dose plane) which has a small inhomogeneity. Due to these inhomogeneities, a correction is neccesary for the measured ratio $R(D_1, D_2) = \Delta OD_2/\Delta OD_1$. The corrected ratio is $R(D_1, D_2) = \Delta OD_2/\Delta OD_{1,ref}$. The following equation calculates the reference optical density:

$$\Delta OD_{1,ref} = \Delta OD_1(D_1)\left[\frac{1 - \exp(-\delta D_{1,ref})}{1 - \exp(-\delta D_1)}\right] \tag{5}$$

Where the fraction is correction factor $k_{D,ref}$:

$$k_{D,ref} = \left[\frac{1 - \exp(-\delta D_{1,ref})}{1 - \exp(-\delta D_1)}\right] \tag{6}$$

$\Delta OD_{1,ref}$ is the ΔOD_1 if the reference dose $D_{1,ref}$ was given to the film.

δ is a parameter that represents the amount of dose absorption (see equation 4). It is obtained by a fit of calibration data of film pieces, irradiated once, using equation 4. The value of δ is determined as 0.3. The OD correction is not very sensitive to the value of δ.[2]

2.2.3 Calibration Curve and Dose Determination

To determine the calibration curve of the film, the ΔOD^i_1 and ΔOD^i_2 values of each voxel of the film are determined with the matlab program ReadOD (see section 2.2.6). With ΔOD^i_1 and

$\Delta OD^i_{2,i}$ determined, R_i is calculated. In the calibration curve graph of each voxel, R_i is plotted against the total dose $D_{tot,i}$ for each voxel. The total dose is the sum of $D_{1,i}$ and $D_{2,i}$. The calibration curve R for all voxels is fitted with a 3$^{\text{rd}}$ order polynomial, $R = f(D)$, to this dataset.

The unknown dose or the calibration dose per voxel is determined by using the ratio $R_i = \Delta OD^i_2 / \Delta OD^i_{1,ref}$ to read the corresponding $D_{tot,i}$ of that voxel. $D_{2,i}$ is determined by substracting $D_{tot,i}$ from $D_{1,i}$.

2.2.4 Dose measurement equation

When films have been irradiated by the use of the double irradiation technique and have been scanned, the ratio R is calculated.(see section 2.2.2):

$$R = \frac{\Delta OD_2}{\Delta OD_1 k_{D,ref}} \tag{7}$$

$k_{D,ref}$ is calculated with equation 6.

The delivered dose to an EBT2 film piece in a water phantom under reference conditions is calculated as:

$$D_{film,water} = t_{irr,water} \dot{D}_{water} \tag{8}$$

Where $t_{irr,water}$ is the irradiation time of the radio active source to the water phantom and $\dot{D}_{water}$ the dose rate. Since dose calibration with film pieces is performed with a PMMA phantom, the equation is written as the following:

$$D_{film,water} = t_{irr,PMMA} \dot{D}_{water} C_{water,PMMA} \tag{9}$$

Where $C_{water,PMMA}$ is a conversion factor for the secondary standard with radio chromic films. More information on this in section 3.

The calibration curve is plotted as a function with R against the irradiation time $t_{irr,water}$ in the PMMA phantom, $R = f(D)$. Where $f(t_{irr}\dot{D}) = g(t_{irr})$ and g are a third-order polynomials. The inverse of this polynomial gives the following expression for the determined dose:

$$D_{film,water} = g^{-1}(R) \dot{D}_{water} C_{water,PMMA} \tag{10}$$

The uncertainty of physical quantity $C_{water,PMMA}$ determined by step 1 and the uncertainty of physical quantity of R determined by step 2 is listed in the uncertainty budget at section 5.4.

2.2.5 Scanning Procedure

Films are scanned with an Epson$^{\text{TM}}$ expression 1680 flat bed colour scanner. Films are scanned in the 48-bit RGB mode (16 bit per colour) at a resolution of 200 dpi (voxel size is 0.127 mm).

The area of the flat bed is 31 × 31 cm^2. The scans are saved as *.tif files.[1]. Silverfast Ai v5.1.2 software is the application that performs the scanning of films, with all the image enhancement options and filters turned off. Transmission mode is used to read out all three colour channels of the charge-coupled-device (CCD) of the scanner. The scanning procedure of films is performed as following:

1. Prescan 3 times to warm up the scanner
2. Make two zero scans (scan of the empty flat bed)
3. Place film and prescan again
4. Scan the film in RGB 48 bit mode
5. Place other film and prescan again
6. Scan the film in RGB 48 bit mode again, et cetera for all films
7. Make two zero scans again

This procedure is performed for each scan of a film piece in the double irradiation technique: (1) Scan of unirradiated, (2) pre-irradiated and (3) irradiated films.

Zero scans are performed to reduce the influence of non-uniformity of the lamp intensity and to correct for defective voxels.[5]

Figure 3 shows that the peak in the absorption spectrum of the active layer of the EBT2 film is located at wavelengths of the red part (636 nm) of visible light. Therefore the flatbed colour scanner gets the best response for the EBT2 film from the red colour channel[1][4]. Each film is consistently placed on the same position on the flat bed scanner in order to reduce the positioning of the film variation. The scanner response is not uniform for films over the whole flat bed. This nonuniformity is corrected by a correction factor, which resulted in a great reduction of nonuniformity[1]. Even though a correction factor is used to correct for position dependency, it is recommended to place each film at the same position.

2.2.6 Image Processing and determination dose distribution

The output images of each step of the double irradiation technique are imported into MATLAB software for processing and analysis. The software consists of three routines[1]:

ReadOD

Imports the saved *.tif files from the scanning procedure. Each voxel of these files has a relative light intensity. The routine converts these intensities into optical density voxel per voxel in a

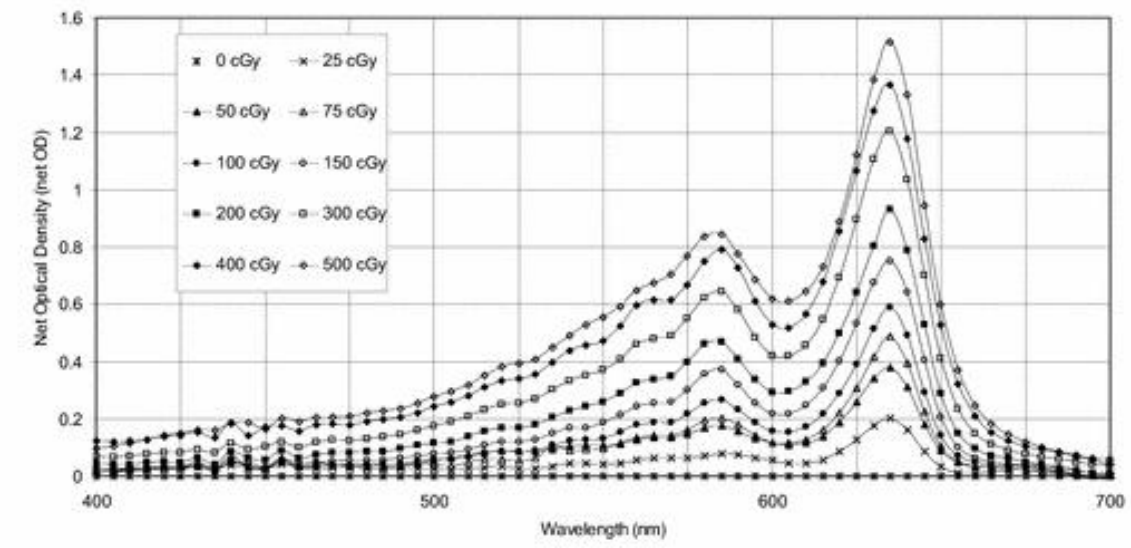


Figure 3 – Net absorption spectrum EBT2 RCF

region of interest of 20 × 20 mm^2 of the film by using equation 1. Then both the pre-irradiated optical density $OD_{irr,1}$ and the irradiated optical density $OD^i_{irr,2}$ are substracted from the unirradiated optical density OD^i_{unirr}, yielding ΔOD^i_1 and ΔOD^i_2 for a film piece that has been irradiated twice. Outputs are two matrices, a matrix of ΔOD_1 per voxel value and a matrix of ΔOD_2 per voxel value in a *.mat file for each film piece.

Fit:

Uses the *.mat file generated by ReadOD of each film piece and calculates a calibration fit. Then uses the data to correct ΔOD_1 to $\Delta OD_{1,ref}$ (see section 2.2.2) and calculates the ratio $R = \Delta OD_2$ / $\Delta OD_{1,ref}$ as function of D_{tot}. Output is a *.mat file that contains the fit parameters for the third order polynomial that is used to generate the curve.

OD2D:

OD2D calculates the dose distribution, D_2, delivered to the film piece in the form of a matrix. This calculation requires the fit parameters as input of the Fit routine output and the data from ReadOD output for the corresponding film piece. OD2D calculates D_2 voxel per voxel as following: by determining the D_{tot} from the ratio $R = \Delta OD_2$ / $\Delta OD_{1,ref}$, D_{tot} is substracted with $D_{1,ref}$ voxel per voxel.
Output is a *.csv file which can be imported into Excel.

3 Conversion Dose on Film in PMMA to Dose on Film in Water

In section 3 the role of the conversion factor, $C_{water,PMMA}$ is explained. The material irradiation conditions in the PMMA phantom and the water phantom differ slightly: depth, attenuation per path length and electron stopping powers. All these properties will lead to a different irradiation time to give a certain dose. A conversion factor between the water phantom and using an ionisation chamber the PMMA phantom has already been determined. An assumption was made that the material properties of the water phantom do not influence the relative electron energy spectrum inside the ionization chamber cavity of the PMMA phantom and water phantom [1].This conversion factor is used to calculate the irradiation time in an PMMA phantom needed to give a certain dose to the film.

An excel sheet has been developed by the department of radiation at VSL to calculate the irradiation time for a certain dose in water (and PMMA). This excel sheet needs certain parameters like a conversion factor between water phantom and anthropomorphic phantom, SDD, depth of object, temperature, pressure, date of time (for radioactive decay correction of the Co-60 source) to determine the irradiation time in water. The current version of the excel sheet contains the conversion factor determined previously with ionisation chamber measurements.

To determine this conversion factor, Two sets of films are pre-irradiated in the PMMA phantom and one set of films in the PMMA phantom and the other set in the water phantom. The irradiation time for precisely 2.0 Gy in both the water and PMMA phantom, has been determined with the use of the excel sheet. In-depth explanation about the direct determination of the conversion factor for the secondary standard with radio chromic film pieces is shown in 3.1

3.1 Direct determination of ratio dose to film in PMMA and water phantom

For the determination of the ratio dose to film in the PMMA phantom and water phantom, $C_{water,PMMA}$, 20 films were cut from a sheet, 10 films for irradiating in PMMA and 10 films irradiating in water. A special holder was developed for the measurements of film in water. To fit in this holder, the 20 films were cut with the dimensions 4.2×4.5 mm^2.

The excel sheet was used to calculate the irradiation time for both in the PMMA phantom and water phantom. An assumption was made that the reference depth of the film in the PMMA phantom was 4.00 cm (this was measured when ionisation chamber measurements were performed) and the measured depth when irradiating films in PMMA was assumed 4.02 cm.

First, all 20 films were pre-irradiated in PMMA at a reference depth of 4.00 cm (measured depth 4.02 cm) with a dose of 0.995 Gy. 4 days of developing time between the following up irradiation

and the films were scanned. Then, 10 films were irradiated in PMMA at 4,02 cm depth again and the other 10 films were irradiated in water at a reference depth of 5 cm, both with 2.000 Gy. Both the films were scanned again after 4 days of developing time. The scan files are processed with the MATLAB software ReadOD.

The reference depth in the PMMA phantom with the ionisation chamber and the measured depth in the PMMA phantom for films was measured again to check if the depths really were 4.00 cm and 4.02 cm respectively at the time of irradiating the films. This measurement was performed with an interferometer. The real measured reference depth and measurement depth yielded 3.92 cm and 4.03 cm respectively. This difference in depths yields a different delivered dose on the film in PMMA. Thus the reference ratio of dose to film in PMMA and water phantom is not expected to be 1.00. To check the measured value with the reference ratio, the reference ratio has to be corrected. The reference ratio is calculated as follows.

The reference ratio dose to film in the PMMA phantom and the water phantom R_{PMMA}/R_{water} is calculated using equation 4:

$$R_{water} = \frac{OD_{2,water}}{OD_{1,PMMA}} = \frac{OD_{\infty}(1 - \exp(-\delta(D_{2,water} + D_{1,PMMA}))}{OD_{\infty}(1 - \exp(-\delta D_{1,PMMA}))} \tag{11}$$

Where $OD_{2,water}$ is the optical density after irradiating the film with a calibration dose in water and $OD_{1,PMMA}$ is the optical density after pre-irradiating the film with a pre-irradiation dose in PMMA.

$$R_{PMMA} = \frac{OD_{2,PMMA}}{OD_{1,PMMA}} = \frac{OD_{\infty}(1 - \exp(-\delta(D_{2,PMMA} + D_{1,PMMA}))}{OD_{\infty}(1 - \exp(-\delta D_{1,PMMA}))} \tag{12}$$

Where $OD_{2,PMMA}$ is the optical density after irradiating the film with a calibration dose in PMMA. The ratio R_{PMMA}/R_{water} is calculated as follows:

$$\frac{R_{PMMA}}{R_{water}} = \frac{1 - \exp(-\delta(D_{2,PMMA} + D_{1,PMMA}))}{1 - \exp(-\delta(D_{2,water} + D_{1,PMMA}))} \tag{13}$$

Because of a different irradiation time, due to the depth in PMMA measurement, a correction factor a has to be introduced. a is determined by the difference in attenuation correction at a reference depth of 4.00 cm and the attenuation correction at the new measured reference depth of 3.92 cm. The corrected ratio R_{PMMA}/R_{water} is calculated as follows:

$$\frac{R_{PMMA}}{R_{water}} = \frac{1 - \exp(-a\delta(D_{2,PMMA} + D_{1,PMMA}))}{1 - \exp(-\delta(aD_{2,water} + D_{1,PMMA}))} \tag{14}$$

This calculated reference ratio dose to film in PMMA and water phantom will be used to compare it with the measured ratio.

Results and conclusions of the measurement are shown in section 5.2.1

3.2 Water effect on Film

When measurements of film in water are performed, the film lies in the water for roughly 180 seconds. During this time, the water enters in the sides of the film and possibly influences the optical density of the film. If there is a noticable difference due to the water entering the active layer, a correction factor, k_{water}, for all the films irradiated in the water phantom is required. The correction will have influence on the measured ratio dose to film in PMMA and water phantom.

The procedure on determining the effect of water on the film was executed as followed:

1. Two sets of each 10 unirradiated films of the size 5 $\times$ 5 cm^2 where cut out of single sheet.
2. One set was used as control group and was not dipped in water, the other set was used to dip it in water
3. Each film of both sets was scanned three times with the flat bed scanner.
4. Then, each film of the second set was dipped in its own plastic cup of demi water for roughly 3 minutes.
5. 4 Days of wait time for both sets, same wait time as is done in the experiments shown in section 3.1.
6. The films of both sets are scanned again with the flat bed scanner.

The scan files are processed with the MATLAB software ReadOD. With the data, OD matrix, of the *.mat file produced by readOD is used to calculate the mean of the OD matrix of the films of the control group and the films of the water group. The mean OD of the first and second scan of the water group are divided, yielding a ratio of a before mean OD (before films were dipped in water) and an after mean OD (after films were dipped in water. The same calculation was done for the control group, except the films weren't dipped in water. Then the mean of the 10 ratios and the standard deviation over the 10 ratios for both the groups were calculated.

Results and conclusions of the water effect on the film are shown in section 5.2.2

3.3 Influence of Pre-Irradiation dose on uncertainty

With the double-irradiation films are pre-irradiated first. It takes time to irradiate a lot of films to determine a calibration curve. Lower pre-irradation dose can lessen the time required to calibrate. This experiment uses a lower pre-irradiation dose of 0.5 Gy. The pre-irradiation dose of 0.5 Gy is compared with the standard pre-irradiation dose of 1.0 Gy. The question is if the uncertainty in the double irradiation technique is different with a pre-irradiation of 0.5 Gy.

The calibration curve is determined as follows: multiple films have to be pre-irradiated with the same dose and irradiated with different doses (see section 2.2.3), from 1.0 Gy to 4.0 Gy.

Two calibration curves are plotted in figure 10. In total 40 films have been pre-irradiated in PMMA: 20 films pre-irradiated with 0.5 Gy and 20 films pre-irradiated with 1.0 Gy. The results of these measurements are shown in section 5.3.

4 Determination of uncertainties

4.1 Uncertainties Scan Procedure

When scanning films with the flat bed scanner, certain effects like the polarization effect, reproduciblity of scans and other effects contribute to the total uncertainty. All these uncertainties will be explained in the subparagraphs below.

4.1.1 Polarization Effects

Background Polarization Effects

The flat bed scanner uses polychromatic light to illuminate the film which is partially polarized. The polarization direction of the scanner light is unknown and a part of the light might be absorbed by the film that is scanned. A polarization effect then can influence the value of the optical density of the film.

When the film is placed, the monomer crystals of the film will often not exactly be parallel with the polarization direction of the light. This might give rise to polarization effects [7]. This means that the polarized light might be absorbed partally by the film monomer crystals. The polarization effect is less if the monomer crystals in the film have undergone a polymerization reaction [3].

Placement and Orientation of Film

When the films are cut out from a larger film sheet into squares (5×5 cm^2), the edges of the squares are not perfectly parellel with each other and also not parallel with the long monomer crystal chains.
If the films are placed perfectly in line with the scanner light polarization direction, the chain of monomer crystals don't have to be in line with the polarization direction of the light. The angle between the polarization direction and the long polymer strings can have a different value, due to the film cutting process.

Determination Polarization Uncertainty At Small Angles

To determine the effect of the polarization in numerical quantity, films at different orientation angles are scanned with the scanner. First, five films are scanned five times at an orientation angle of 90 ° and 0 °. Then, five films with each five varying orientation angles between 10 and 0 ° are scanned five times for each angle. Figure 4 shows the orientation of the films at two orientation angles ϕ.

(a) $\phi = 0°$ **(b)** $\phi = 90°$

Figure 4 – Film orientation angle as shown by the *.tif file (not the top view of the film placed on the scanner) at 0 and 90 °.

The output *.tif files of the scanner are then processed with the ReadOD MATLAB routine. The data of the output of readOD, ΔOD_1 and ΔOD_2 and the coordinates of the film vertices, are used to calculate two quantities: orientation angle of the film ϕ (i.e. the angle between the lower film edge and the orientation of the CCD array) and the correction factor $k_{pol} = \frac{\Delta OD(\phi=0)}{\Delta OD(\phi}$ for the polarization effect. This correction factor corrects for the polarization effect. The polarization effect is expressed as following:

$$P(\phi) = |k_{pol}(\phi) - 1| \tag{15}$$

Where $P(\phi)$ is the polarization effect and $k_{pol}(\phi)$ is the correction factor for the polarization effect. The polarization effect is the strongest at 90 °, where k_{pol} has the highest value. All ΔOD value of each voxel of the OD matrix create a vertical point cloud at one angle. The length of this vertical point cloud is a measure for the spread in k_{pol}.

The correction factor k_{pol} per voxel for each orientation ϕ is averaged over all voxels of one film. This is done for five films of both the 0-10° and 90° rotated films. The five averages of the correction factor of each orientation angle ϕ are then averaged again to one value, $\overline{\overline{k}}_{pol}$.

The relative uncertainty in the polarization effect is determined differently. This determination is not based on multiple data, which will yield a reproducibility uncertainty (Type A uncertainty [9]). The following equation is based on the assumption that the relative uncertainty on polarization effect is constant for angles between $\phi = 0°$ and $\phi = 90°$.

$$u(\overline{\overline{k}}_{pol}(\phi)) = u(\overline{\overline{k}}_{pol}(\phi = 90°))\frac{(\overline{\overline{k}}_{pol}(\phi) - 1)}{\overline{\overline{k}}_{pol}(\phi = 90°) - 1} \tag{16}$$

Where $u(\overline{\overline{k}}_{pol}(\phi))$ is the standard deviation in the correction factor and $\overline{\overline{k}}_{pol}(\phi = 90°) - 1$ the effect of the polarization effect in respect to normalized value of $\overline{\overline{k}}_{pol}$.

The determined relative uncertainty of both irradiated and unirradiated films at orientations between 0 and 10 ° are shown in chapter 5 Results.

4.1.2 Reproducibility of the Scanner

In order to determine the stability and reproducibility of scanning a film with the flat bed scanner, the relative standard deviation per voxel of film in the reproducibility was determined. To determine the relative standard deviation per voxel in reproducibility of the scans, four types of reproducibility scans were performed, with for each scan type the scan was repeated 20 times in a row. 20 scans is sufficient to get a reliable relative standard deviation in reproducibility of the scanning process. Several steps in the scanning process contribute to the overall reproducibility. Therefore four different types of reproducibility measurements have to be performed. For each type of scans, the same three films (labeled as a7, a8 and a9) are used. These four types of reproducibility are:

Normal Scans

A film is placed on the flat bed scanner at an orientation of $\phi = 0°$ and is not moved throughout the scanning procedure.

Open/Close Scanner Door Scans

A film is placed on the flat bed scanner at an orientation of $\phi = 0°$. Between each scan, the door of the scanner is opened and closed. These type of scans are done, because when one has to place another film, whether the opening of the door has influence on the standard deviation of the scanning.

Reposition of Film Scans

A film is placed at 20 different positions throughout the scan session. The door of the scanner has to be opened and closed each time to reposition the film. The orientation of the film stays the same ($\phi = 0°$). Each position is scanned once. Figure 5 shows the placement of films in an area of 10 x 10 cm:

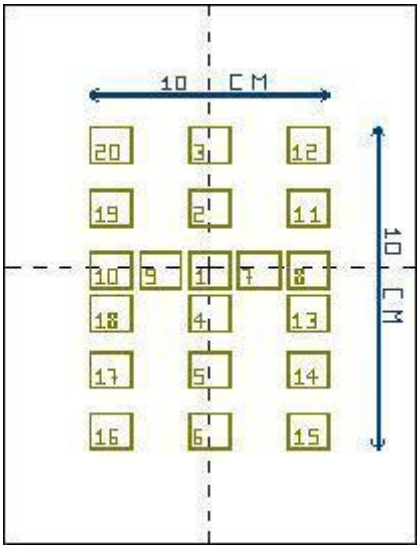


Figure 5 – 20 Placements of film on flat bed scanner throughout a scan session. Not scaled correctly

1 Minute Wait In Between Scans

A film is placed on the flat bed scanner at an orientation of $\phi = 0°$. In contrast with the normal scans (see Normal Scans), the wait time between scans is 1 minute instead of continueous scans. The 1 minute wait type of scans is to check if the scan temperature plays a role in the standard deviation of the scans. The scanned films for each types of scan measurements were unirradiated and were the size of 5 x 5 cm^2.

These four types of actions are investigated on reproducibility, because these action occur when films are scanned by the standard scanning procedure. When one film piece is scanned, the door of the scanner is opened first, a new film piece is placed on the flat bed and the door is closed. This usually takes roughly one minute and the next film is going to get scanned.

4.1.3 Determination of Reproducibility of Scanning Process

Figure 6 shows a schematic of multiple scans of one film piece and its voxel dimension coordinates. To determine the reproducibility of the scanner as used in the standard procedure, the standard deviation is used as an estimate.
The standard deviation of OD, s_{rep}, is calculated over 20 scans of the same voxel (from voxel 1,1,1 to 1,1,20) of each scan (OD matrix). The standard deviation calculation is done for all the other voxels of each scan (from voxels 1,2,1 to 1,2,20 and 2,1,1 to 2,1,20 and et cetera). The result is a 2D matrix consisting standard deviations for each voxel. Then all the standard deviations of each voxel are averaged to one standard deviation, $\overline{s_{rep}}$.The average OD value of each voxel over 20 scans, $\overline{\overline{OD}}$ is calculated in the same way as the standard deviation $\overline{s_{rep}}$.

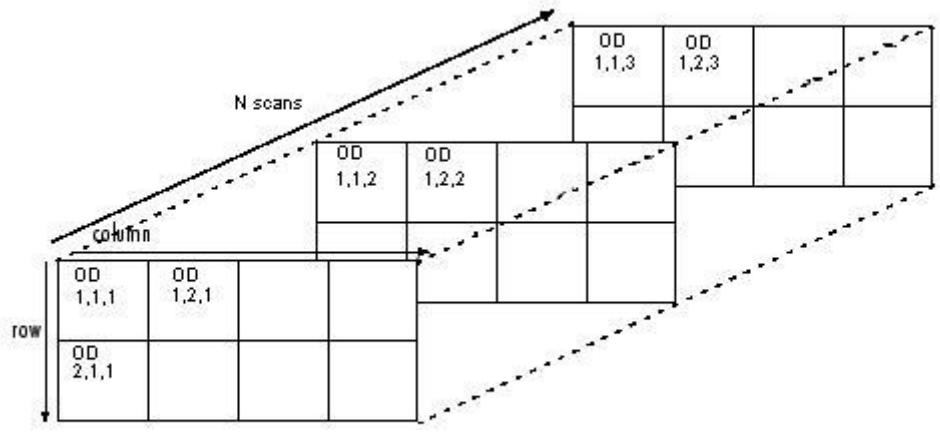


Figure 6 – Example of a schematic of multiple scans as OD matrices. Dimension coordinates are shown in each cell of each matrix.

The averaged standard deviation $\overline{s_{rep}}$ is then divided by the average OD value per voxel over 20 scans, $\overline{\overline{OD}}$, to calculate the relative standard deviation of OD.

$$Rel.s = \frac{\overline{s_{rep}}}{\overline{\overline{OD}}} \tag{17}$$

All the calculations and creations of matrices are performed with MATLAB using the output *.mat files of ReadOD.

4.1.4 Dependency Resolution Scanner

When films are scanned at a lower or higher resolution, the volume of pixels changes. Since the results of the film position detection algorithm is dependent on the scan resolution, matching of films scanned at different positions is influenced by the scan resolution. In theory would scanning at a higher resolution yield more accurate results. The same pixel of both the unirradiated scan and irradiated scan would have more accurately the same coordinates in the OD matrix. Conclusion if this is true, it will be observed in the standard deviations of a film scanned at three different resolutions.

In the standard procedure, the films are scanned at a resolution of 200 dpi. In this experiment films were scanned at a scanner resolution of respectively 150 and 250 dpi. The change in resolution changes the OD matrix in size. Three films were scanned at 150 dpi, 200 and 250 dpi.

Each film piece was scanned 20 consecutive times, without repositioning the film between scans, at all the resolutions. The scan files are processed with the MATLAB software ReadOD (the resolution parameter had to be corrected for 150 and 250 dpi, standard=200 dpi). The results are shown in the results section 5.1.3

4.2 Total Uncertainty Calculation

4.2.1 Uncertainty Budget

All contributions of uncertainties in the processes of practicing film dosimetry at VSL are listed in table 6. The total uncertainty of these processes is determined by evaluating uncertainties in physical quantities or procedures that contribute to the calibration procedure and the dose determination with radiochromic film. The calibration procedure and dose determination at VSL consists of two processes: irradiating film pieces with gamma rays and scanning them with a flat bed scanner. For the first process only the uncertainty contribution of the conversion factor was investigated. The uncertainty associated with $\dot{D}_{water}$ is given by the uncertainty for the primary standard and amounts 1.0% (k=2) [9].

5 Results Uncertainty Scan Procedure and PMMA to Water Conversion

5.1 Uncertainties Scan Procedure Measurements and Analysis

All the results of the determined uncertainties in the scan procedure are shown in the next subparagraphs. The results of the PMMA to Water Conversion are shown in section 5.2.1.

5.1.1 Polarization Effects

Figure 7 shows the determined values of the correction factor k_{pol} at different orientations of one radio chromic film, labeled as a4.

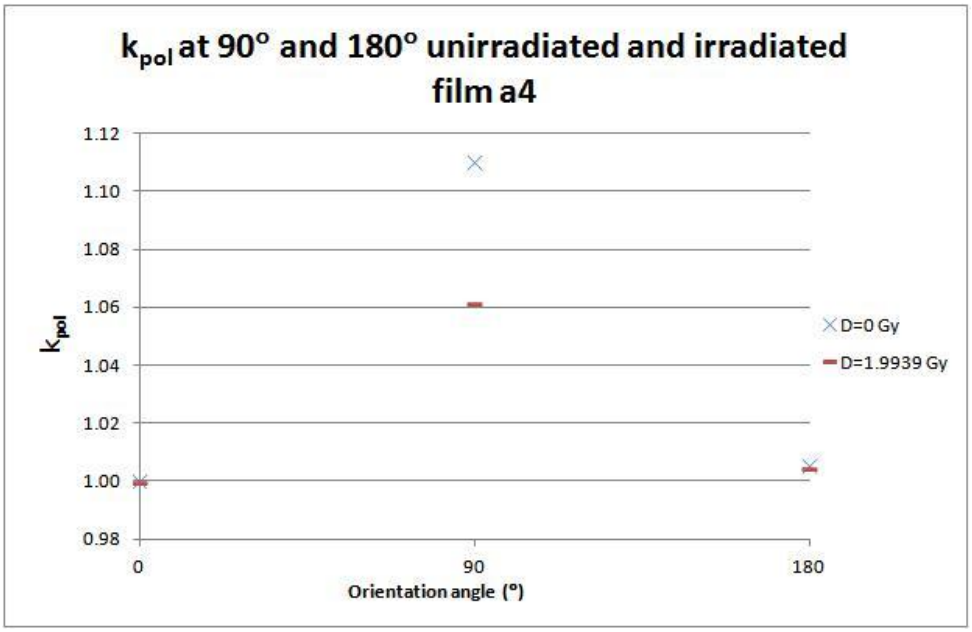


Figure 7 – Correction factor k_{pol} at different orientation angles ϕ.

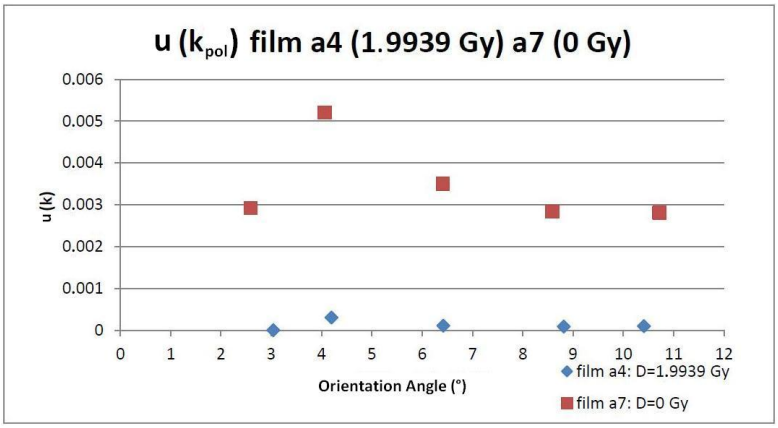
The graph in figure 7 shows that k_{pol} at orientation angles of 0 and 180° is 1 or close to 1. At an orientation angle of 90°, the correction factor is higher, ranging at 1.10 for unirradiated films and 1.06 for irradiated films.

Figure 8 shows the calculated values of the relative standard deviation in the correction factor k_{pol} at different orientations of three radio chromic films. Two series are shown in the graph, irradiated films and unirradiated films.

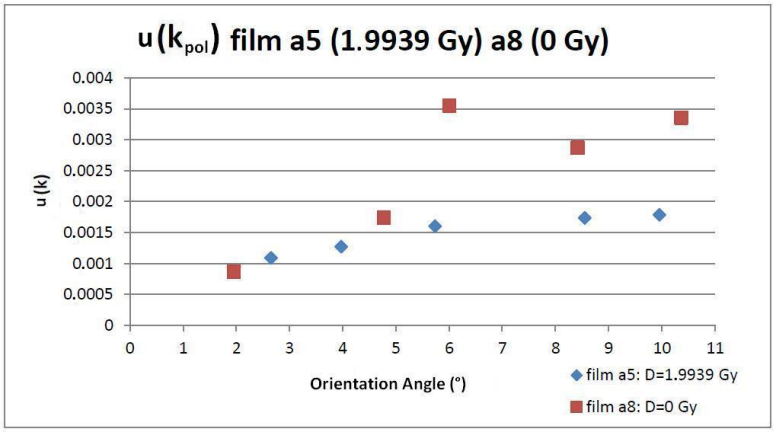
The graphs in figure 8 overall show that the relative standard deviation in k_{pol} in the unirradiated

films is higher than the irradiated films. The values of the relative standard deviation of k_{pol} of the unirradiated films are ranged between 0.0005 and 0.0050 and of the irradiated films between 0.0003 and 0.0017.

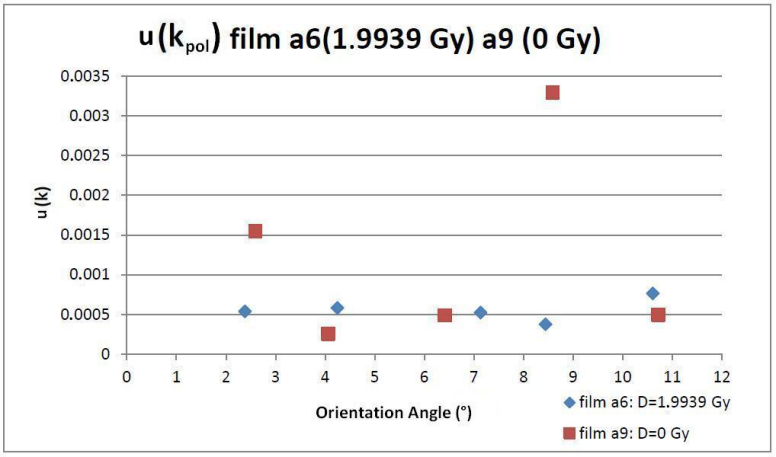
$u(k_{pol})$ of the unirradiated film is greater than the irradiated film, due to the fact that the polarization effect of unirradiated films is bigger than irradiated films. A possible explanation might be that the polymer crystal orientation of irradiated films is less alligned in the direction of the incedent scanner light due to the polymerization process. The measured OD values do not contain solely the uncertainty of polarization effects. Other effects like the temperature due to cooling down of the scanner can contribute to the total determined uncertainty of the polarization effect measurements. This explains the wide variety in $u(k_{pol})$ of all the unirradiated and irradiated films at angles of ϕ ranging between 0 and 10°.



(a) film a4 (D=1.9939 Gy), film a7 (D= 0 Gy)



(b) film a5 (D=1.9939 Gy), film a8 (D= 0 Gy)



(c) film a6 (D=1.9939 Gy), film a9 (D= 0 Gy)

Figure 8 – Graphs of standard deviation in k_{pol} of different films, both irradiated and unirradiated

5.1.2 Reproducibility Scanner

Four types of reproducibility scans (normal, repositioning, 1 minute and open/close door of scanner scans) have been performed as explained in section 4.1.2 and the results are shown below. All the scanned films were unirradiated. The relative standard deviation *Rel.s* in the reproducibility of the normal scans are shown in figure 9a, repositioning scans in figure 9c, 1 minute wait scans in figure 9d and open/close of door scanner scans in figure 9b respectively.

Each three colour points represent one film. The middle point is the average rel. S, heighest and lowest point the maximum and minium rel. S respectively.

The graphs shown in figure 9 show that the repositioning of the film between scans is the biggest factor in reproducibility of scanning with an average value of the relative standard deviation ranging between 0.0072-0.0075. While the average of the relatieve standard deviations of the other three reproducibility type scans have a value ranging between 0.0023-0.0027.

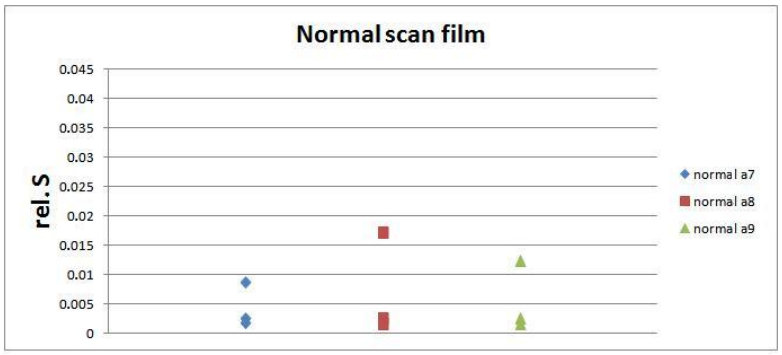
As explained in section 4.1.2, has the standard scanning procedure a sequence of four sources of reproducibility: (1) scanning the film, (2) opening the scanner door and closing it, (3) placing a new film on the scanner and (4) whole process of placing new film takes roughly one minute.

Source (1) is the primary source of reproducibility. Source (2) has the added effects of sources (2), (3) and (4) and et cetera.

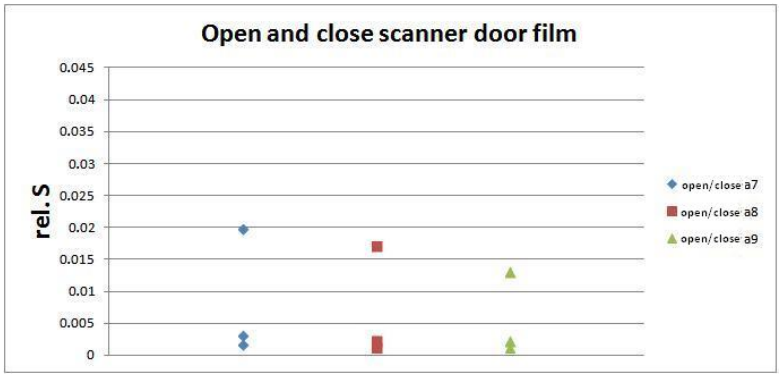
Table 1 shows the average rel. S of each reproducibility scan type and the added effect of other scan type on other scan types.

Table 1 – Reproduciblity standard deviation for each scan type

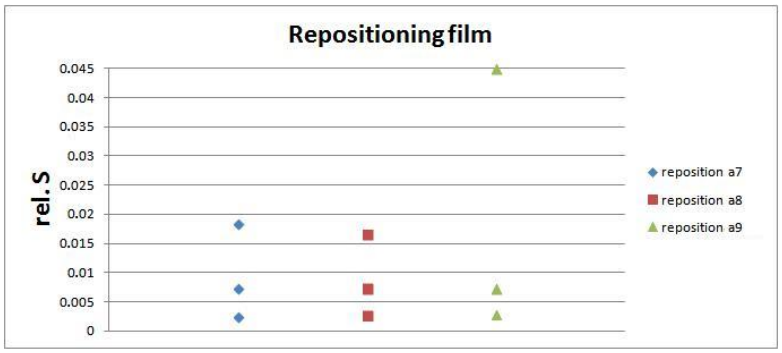
Type scan	rel. s (OD)	Added effect
1. Normal Scan	0.00271	
2. Open/Close Door	0.00259	Source (2), (3) and (4)
3. Repositioning	0.00734	Source (3) and (4)
4. One Minute Wait	0.00223	Source (4)



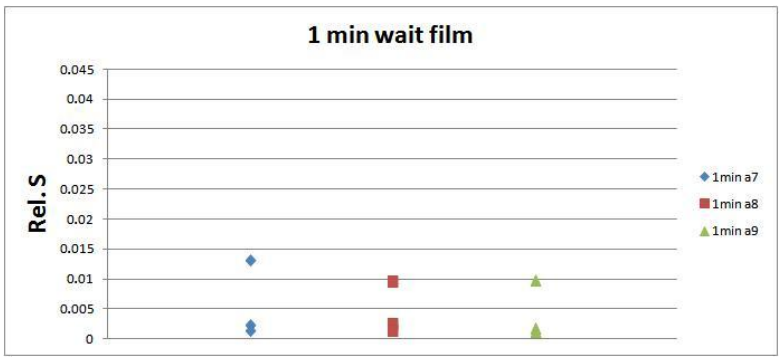
(a) Unirradiated film a7, a8, a9 scanned 20 times.



(b) Unirradiated film a7, a8, a9 scanned 20 times.



(c) Unirradiated film a7, a8, a9 scanned 20 times.



(d) Unirradiated film a7, a8, a9 scanned 20 times.

Figure 9 – Graphs of the four types of reproduciblity scans. Each three colour points represent one film. The middle point is the average rel. S, heighest and lowest point the maximum and minium rel. S respectively.

5.1.3 Dependency Resolution Scanner

Three film pieces were scanned at a resolution of 150, 200 and 250 dpi. Each film piece was scanned 20 consecutive times. All the scanned films were unirradiated. The mean value $\overline{\overline{OD}}$ and standard deviation, s_{rep} of each film piece was calculated using the equations of section 4.1.3. Table 2 shows the experimental values of the mean value and its absolute standard deviation of each film at three different scanner resolutions:

Table 2 – Scanner Resolution Dependency Results

	Resolutie (dpi)		
	200	150	250
Mean OD			
a7	0.2241	0.2267	0.2329
a8	0.2223	0.2275	0.2349
a9	0.2244	0.2275	0.2349
Mean Std. Dev			
a7	0.0007	0.0007	0.0008
a8	0.0005	0.0009	0.0007
a9	0.0005	0.0007	0.0008

The standard deviation values of each film at different resolutions do not change much. This implies that scanning with a higher resolution is not more accurate than with a lower resolution. The average optical density value does have a difference between different resolutions.

5.2 Conversion Dose on Film in PMMA to Dose on Film in Water

5.2.1 Direct determination of ratio dose to film in PMMA phantom and water phantom

The ratio dose to film in PMMA phantom and water phantom is determined as explained in section 3.1. The ratio R_{Pmma}/R_{water} has been determined directly by experiment and compared to the calculated reference ratio (calculated by 14. Table 3 shows the determined and the calculated value of the ratio:

Table 3 – Ratio dose to film in PMMA phantom and water phantom, measured and calculated reference value with the excel sheet (corrected to the correct reference and measured depth, see section 3.1)

R_{PMMA}/R_{water} (measured)	R_{PMMA}/R_{water} (reference)	Deviation (%)
1.0020 ± 0.0007	0.9979	-0.4%

The measured and calculated reference value differ too much when looked at the relative standard deviation of the measured value. This can be explained by certain correction factors like k_{fl},k_{wall} and k_{cel} and parameters like the electron energy spectrum of the stopping power ratios of both water and PMMA, that have been simplified in the derivation process of the equations in the Rapport Radio Chromic Film Dosimetry [1]. The experiment results indicate that these simplifications might not be justified and can cause a deviation between the calculated and measured determined value of the ratio dose to film in PMMA phantom to water phantom.

5.2.2 Water effect on Film

The water effect experiment was performed as explained in section 3.2. Table 4a and 4b show the average optical density of the first scan and the second scan for both sets of films.

Table 4 – Water Effect Results

(a) First set of films where films weren't dipped in demi water. This set of films was used as control group

	Mean OD		**Ratio**
Film	Scan 1	Scan 2	Scan 2/ Scan 1
1	0.1929	0.1948	1.0098
2	0.1931	0.1951	1.0101
3	0.1936	0.1957	1.0106
4	0.1947	0.1955	1.0042
5	0.1942	0.1958	1.0078
6	0.1955	0.1963	1.0039
7	0.1952	0.1964	1.0059
8	0.1940	0.1953	1.0068
9	0.1939	0.1954	1.0079
10	0.1944	0.1958	1.0070
		Mean	1.0074
		std. dev	0.0007

(b) Second set of films where scan 1 represents the scan before dipping the films in demi water and scan 2 the scan after the films were dipped in water

	Mean OD		**Ratio**
Film	Scan 1	Scan 2	Scan 2 / Scan 1
1	0.1945	0.1960	1.0076
2	0.1949	0.1954	1.0106
3	0.1939	0.1960	1.0106
4	0.1941	0.1967	1.0132
5	0.1945	0.1945	1.0003
6	0.1940	0.1955	1.0077
7	0.1945	0.1965	1.0105
8	0.1944	0.1930	0.9927
9	0.1947	0.1959	1.0062
10	0.1955	0.1967	1.0059
		Mean	1.0057
		std. dev	0.0019

The standard deviation shown in table 4 is the standard deviation of the mean value of the ratio of Scan 2/ Scan 1 for both groups.

The values of the ratios of both the film sets are within eachothers standard deviation. This implies that the water that enters the film from the sides does not influence the optical density value when scanning the film. No extra correction factor has to be introduced for measurements of film in water.

5.3 Calibration Curve and Influence of Pre-Irradiation on Uncertainty

Two calibration curves of two sets of film pieces have been determined by using the double irradiation technique. One calibration curve was determined by :

pre-irradiating 18 films of this set with 0.5034 Gy, iirradiating 3 film pieces with 0.5016 Gy, 4 pieces with 0.9995 Gy, 4 pieces with 1.4974 Gy, 3 pieces with 2.0031 Gy and 4 pieces with 2.5009 Gy.

The other calibration curve was determined by: pre-irradiating 19 films of the other set with 1.0030 Gy, 4 film pieces with 0.5016 Gy, 4 pieces with 0.9995 Gy, 4 pieces with 1.4974 Gy, 3 pieces with 2.0031 Gy and 4 pieces with 2.5009 Gy.

Figure 10 shows the two calibration curves:

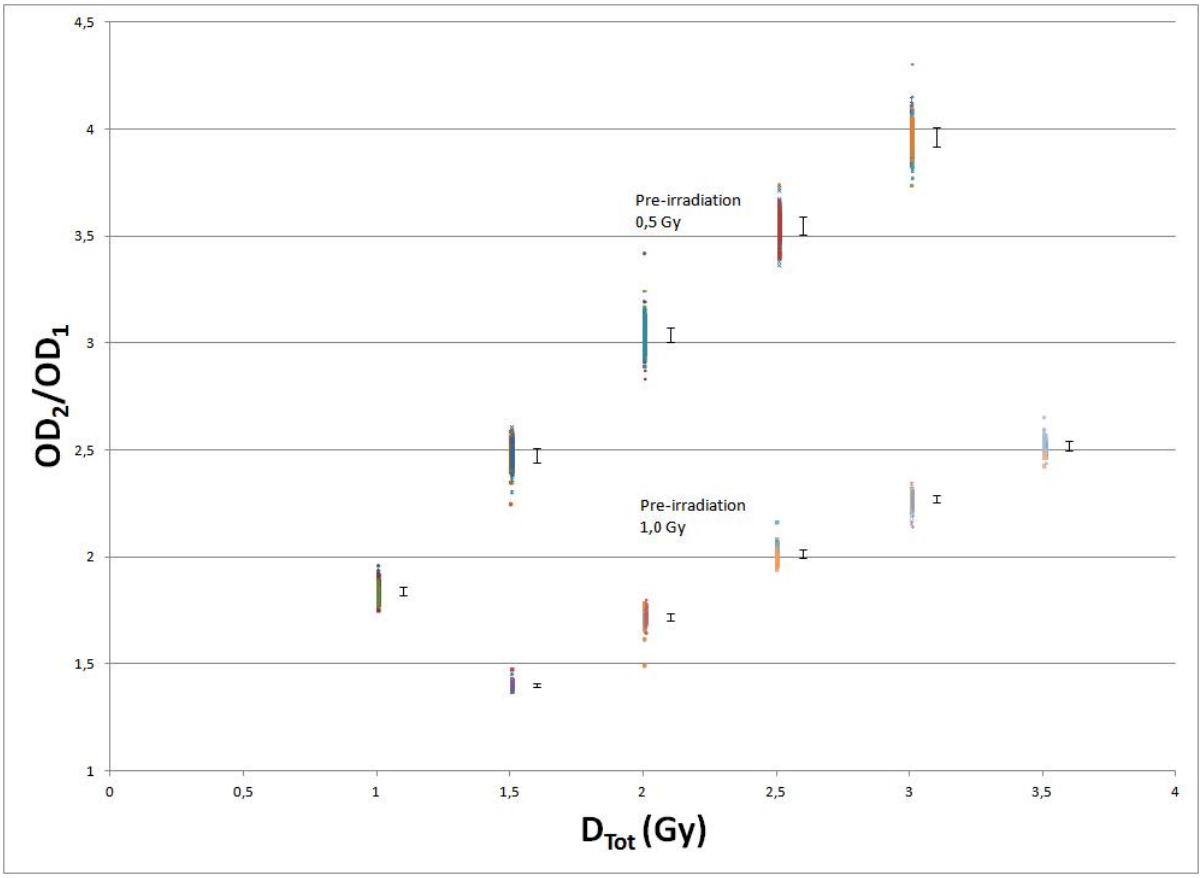


Figure 10 – Two calibrationcurves, first calibration curve with a pre-irradiation of 0.5 Gy and the second calibration curve with a pre-irradiation of 1.0 Gy

Each point in the pointcloud of all D_{tot} doses represents $\Delta OD_2/\Delta OD_1$ of each voxel of each film piece. The error bars of each pointcloud was moved to the right for a more clear view. The

standard deviation of one dose point was calculated over all the $R = \Delta OD_2/\Delta OD_1$ of all voxels of all film pieces at that dose point.

The calibration with 0.5 Gy pre-irradiation shows that the absolute standard deviation and the width of the point cloud at each dose is bigger than the calibration with 1.0 Gy. The values of the standard deviation of each pointcloud of all D_{tot} are shown in tables 5a and 5b:

Table 5 – Comparison of two pre-irradiations on radio chromic films. Table 5a shows the mean of all the OD values and its standard deviation of the pre-irradiation with 0.5 Gy and table 5b shows the mean of all the OD values and its relative standard deviation of the pre-irradiation with 1.0 Gy

(a) Pre-irradiation 0.5 Gy

D_{tot} (Gy)	Mean R	Rel. Std. Dev
1.0	1.840	0.012
1.5	2.475	0.013
2.0	3.037	0.012
2.5	3.547	0.012
3.0	3.964	0.011

(b) Pre-irradation 1.0 Gy

D_{tot} (Gy)	Mean R	Rel. Std. Dev
1.5	1.402	0.006
2.0	1.719	0.011
2.5	2.016	0.009
3.0	2.271	0.007
3.5	2.520	0.008

5.4 Total uncertainty Budget

Table 6 shows the estimated combined relative standard uncertainty on the irradiation on film in PMMA and water phantom and the scanning procedure. Equation 10 of section 3 determines the delivered dose on film in water. Two physical quantities, the conversion factor $C_{water,PMMA}$ and R and their uncertainty are partially determined by steps 1 and 2, as given in table 6.

The relative standard uncertainty of the conversion factor $C_{water,PMMA}$ film in PMMA and in water phantom is based on the deviation between the reference and calculated, R_{PMMA}/R_{water}. A uniform distribution is assumed with as difference between maximum and minimum value, the measured deviation of 0.4%. The relative standard uncertainty of $C_{water,PMMA}$ yields $\frac{0.4}{\sqrt{3}}\%$ (Relative standard ucnertainty no. 1 of step 1).

The relative standard uncertainty of the reproducibility of the scanner is included in the relative standard uncertainty of the reproducibility in repositioning films (Relative standard uncertainty no. 2 of step 2).

The relative standard uncertainty of the polarization effect given in the uncertainty budget, 0.52%, is the maximum value of all the unirradiated film pieces and orientation angles ϕ(see section 5.1.1) (Relative standard uncertainty no. 3 of step 2).

For the combined standard uncertainty in optical density, all the values of the sensitivity

coefficients are 1.0, for all the determined relative standard uncertainty quantities of steps 1 and 2[9]. However, the sensitivity coefficient for third order polynomial $g^{-1}(R)$ might differ from 1.0 and is yet to be determined.

Table 6 – Estimated combined relative standard uncertainty on the optical density of the irradiation on film in PMMA and water phantom and the scanning procedure

Step 1: Irradiating film in PMMA	*Relative Standard Uncertainty (%)*
Type of physical quantity or procedure	
1. Conversion dose to film in PMMA and water phantom	0.23
2. Start stop effect of Co-60 source and uncertainty in irradiation time	To be determined
3. Placement films on PMMA phantom	To be determined
Combined uncertainty in Step 1	*0.23*
Step 2: Scanning unirradiated, pre-irradiated and irradiated film pieces with the epson flat bed scanner	
Type of physical quantity or procedure	
1. Opening scanner door for new film piece	0.31
2. Placement of another film piece	0.7
3. Polarization effect, k_{pol}. Films that are rotated 10 ° as maximum	0.52
4. Wait time of 1 minute between placing film pieces	0.25
5. Scanner light nonuniformity	To be determined
Combined uncertainty in Step 2	*0.99*
Combined standard uncertainty in optical density (Steps 1+2)	**1.02**
Expanded combined standard uncertainty, k=2	**2.03 %**

6 Conclusions

If radio chromic films are placed with an orientation angle of $\phi = 90°$ on the flat bed scanner, the correction factor k_{pol} is 1.10 for unirradiated films and 1.06 for unirradiated films. When scanning films with the standard scanning procedure, a film that is placed on the scanner can have an orientation angle of ranging between 2 and 10 °. The relative standard deviation of k_{pol}, $u(k_{pol})$ at that range of orientation angles are ranged between 0.0005 and 0.0050 for unirradiated films and between 0.0003 and 0.0017 for irradiated films. $u(k_{pol})$ of the unirradiated film is greater than the irradiated film, due to the fact that the polarization effect of unirradiated films is bigger than irradiated films. A possible explanation might be that the polymer crystal orientation of irradiated films is less alligned in the direction of the incedent scanner light due to the polymerization process. The measured k_{pol} values do not contain solely the uncertainty of polarization effects. Other effects like the temperature due to cooling down of the scanner can contribute to the total determined uncertainty of the polarization effect measurements. This explains the wide variety in $u(k_{pol})$ of all the unirradiated and irradiated films at angles of ϕ ranging between 0 and 10°.

The four types of reproducibility (normal scanning, open/close door of scanner, repositioning and 1 minute wait) in the standard scanning procedure have an relative standard deviation, $rel.s(OD)$, (type A uncertainty) ranging between 0.0023 and 0.0027. The repositioning of a film have a rel. s ranging between 0.0072 and 0.0075. This implies that the placing of a new film, after the previous film has been scanned, has the biggest reproducibility uncertainty.

When films pieces were scanned at a resolution of 150 and 250 dpi, other than the standard 200 dpi, no changes in the standard deviation of scanning a film 20 times was noticed. This implies that scanning with a higher resolution is not more accurate than with a lower resolution. The average optical density values did show a difference between different resolutions.

The measured value of the ratio dose to film in PMMA phantom and water phantom, R_{PMMA}/R_{water} is 1.0020 with a relative standard deviation, $u(R_{PMMA}/R_{water})$, of 0.0007. The reference value of R_{PMMA}/R_{water} is 0.9979. The measured and calculated reference value of R_{PMMA}/R_{water} differ too much (deviation of -0.4%) when looked at $u(R_{PMMA}/R_{water})$ of the measured value. This can be explained by certain correction factors like k_{fl},k_{wall} and k_{cel} and parameters like the electron energy spectrum of the stopping power ratios of both water and PMMA, that have been simplified in the derivation process of the equations in the Rapport Radio Chromic Film Dosimetry [1]. The experiment results indicate that these simplifications might not be justified and can cause for a big deviation between the calculated and measured determined value of the ratio dose to film in PMMA phantom to water phantom.

The results water effect on films do not show a noticable effect to the optical density of films.

The values of the ratios of the average optical density of each film are within eachothers (control group and water group) standard deviation of the average optical density. No extra correction factor has to be introduced for the measurements of film in water.

The influence of different pre-irradiation values on uncertainty results show that pre-irradiating films in PMMA with 0.5 Gy have a bigger standard deviation in $\Delta OD_2/\Delta OD_1$ than when films are pre-irradiated with 1.0 Gy in PMMA.

7 Discussion and recommendations

The total uncertainty of the whole process of determining the dose distribution with RCF is partially completed. Some physical quantities that can play a role on the process of determining a dose distribution with RCF are yet to be determined. The difference in the measured value and reference value of R_{PMMA}/R_{Water} do not fall in each others relative standard deviation. Some effects (see section 5.2.1) that had been presumed simplified in the derivation process of the equations in the Rapport Radio Chromic Dosimetry might not be justified. More investigation on these effects is required.

When irradiating films, the start stop effect of rotating the Co-60 radio active source can give rise to an uncertainty in the deliverance of total dose to the film perpendicular to the beam. The effect of this new uncertainty in delivered dose on film, watercalorimeter or ionisation chamber has to be investigated, for it can give a new uncertainty to the determination of delivered dose.

When films are placed inside the PMMA phantom, the position of each film that is placed in consecutive order is not exactly the same. This small deviation in positioning the film in the PMMA phantom might have an influence on the delivered dose distribution. More investigation on this possible uncertainty is required.

When all physical quantities and its uncertainty of the whole process of determining the dose distribution with RCF are determined, only then is it possible to evaluate if RCFD might be a reliable method to determine an absolute 2D dose distribution.

Acknowledgements

Many thanks go out to my internship mentor/supervisor Jacco de Pooter for his continued support and guidance throughout the internship. I would also like to thank Leon de Prez for his time as vice-mentor of this internship. Both were willing to give their time to ensure I understood all aspects of this project. I would also like to thank Leila Joulaeizadeh for her ideas and suggestions that contributed to the project.

Special thanks to my mother and fater, for their everlasting support in the goal that I graduate from school.

8 Bibliography

References

[1] J. De Pooter *Radio Chromic Film Dosimetry* VSL

[2] Del Moral, F., Vázquez,J., Ferrero,J.,Willisch,P.,Ramírez,R.,Tejeiro,A., et al (2009) *From the limits of the classical model of sensitometric curves to a realistic model based on the percolation theory for GafChromic EBT Films* Med. Phys., 4015-4025.

[3] Zeidan, O., Stephenson, S., Meeks, L., Wagner, T., Willioughby, T., Kupelian, P., Langen, K (2006) *Characterization and use of EBT radiochromic film for IMRT dose verification* American Association of Physicists in Medicine, Med. Phys. 33, 2006

[4] Butson, M., Cheung, T., Yu, P., Alnawaf, H *Dose and absorption spectra response of EBT2 Gafchromic film to high energy x-rays* Australasian Physical & Engineering Sciences in Medicine Volume 32 Number 4, 2009

[5] Devic, S., Seuntjes, J., Sham, E., Podgorsak, E., Schmidtlein, C., Kirov, A., Soares, C. (2005) *Precise radiochromic film dosimetry using a flat-bed document scanner* American Association of Physicists in Medicine, Med. Phys. 32, 2005

[6] GafChromic *Self-Developing Film For Film Therapy Dosimetry* February 19, 2009

[7] Klassen, N.V., van der Zwan, L. *GafChromic MD-55: Investigated as a precision dosimeter* Med. Phys. 24, 1924-1934 (1997)

[8] Podgersak, E.B., *Radiation Oncology Physics: A Handbook for Teachers and Students*

[9] JCGM, *Evaluation of measurement data - Guide to the expression of uncertainty in measurement*

Appendix

Original internship assignment

Dubbele bestralingsprocedure radiochromatische film dosimetrie

Algemeen
VSL, Thijsseweg 11, 2629 AJ Delft
Technologie Ioniserende Straling (IO)
Stageduur: in overleg.
Contactpersoon VSL: Jacco de Pooter (jdpooter@vsl.nl 015-2691623)

Achtergrond
Radiotherapie speelt een belangrijke rol in de behandeling van kanker. Bij radiotherapie wordt een patint bestraald met ioniserende straling. Het doel is een zo hoog mogelijke stralingsdosis in de tumor en een zo laag mogelijke dosis in het gezonde weefsel. Om dit te bereiken wordt steeds complexere bestralingsapparatuur ontwikkeld. Nauwkeurig kunnen meten en berekenen van de stralingsdosis is van essentieel belang.

Een gevolg van de steeds complexere bestralingstechnieken is dat de absolute dosimetrie ook steeds complexer wordt. Bovendien is het niet alleen nodig om de dosis in een punt te bepalen (bijv. centraal in de tumor) maar wordt de complete 3D dosis verdeling steeds belangrijker. Op dit moment zijn er geen betrouwbare 3D dosimetrie technieken beschikbaar. Wel wordt radiochromatische film gebruikt om in 2 dimensies een relatieve dosis verdeling te bepalen.

De afgelopen jaren zijn er bij VSL procedures en opstellingen ontwikkeld voor radiochromatische film dosimetrie. Het doel van deze ontwikkelingen is om in 2D een absolute dosis verdeling te bepalen in een antropomorf fantoom met een goed bekende onzekerheid. Bij VSL wordt een zogenaamde dubbele bestralingstechniek gebruikt. Hierbij wordt een uniforme dosis toegediend aan een film om per pixel/voxel de response te bepalen. Vervolgens wordt de te meten dosis toegediend.

Inhoud stage
Voor de bepaling van het onzekerheidsbudget dienen een aantal onderwerpen uitgezocht en verbeterd te worden:

1. Bepalen onzekerheden scanprocedure:
    - Reproduceerbaarheid
    - Dosisafhankelijke correctie voor scanner non-uniformiteit
    - Afhankelijkheden van resolutie

- Onzekerheid in gradienten
- Scantemperatuur afhankelijkheid

2. Conversie PMMA naar waterfantoom
    - Validatie indirecte methode door metingen met film in water en in PMMA
    - Bepalen veldgrootte afhankelijkheid in water en in PMMA

Op basis van bovenstaande kan een definitief onzekerheidsbudget worden opgesteld, wat gevalideerd kan worden.

Functie eisen

Voor deze stage dient de kandidaat in het bezit te zijn van een niveau 5A stralingsveiligheidsdiploma. Eventueel kan dit aan het begin of voorafgaand aan de stage behaald worden. Verder is ervaring met Matlab en een nauwkeurige werkhouding een pre.