IMPROVING THE ENERGY RESPONSE OF EXTERNAL BEAM THERAPY (EBT) GAFCHROMIC DOSIMETRY FILMS AT LOW ENERGIES (≤100 keV)

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ABSTRACT

Many studies have been conducted to investigate the energy dependence of External Beam Therapy (EBT) GAFCHROMIC™ dosimetry films and showed that the different film models are water equivalent down to about 100 keV and their response is energy independent down to about 100 keV. The purpose of our study is to investigate the energy dependence of commercially available films to understand the physics behind the energy variation of the films response as well as the intrinsic energy dependence and to develop a new prototype with more uniform energy response at low energies (≤100 keV).

The study is comprised of two components. The first component is evaluating the energy dependence of three different commercial GAFCHROMIC™ dosimetry film models that represent the three different film configurations, EBT, EBT2 and EBT3 that have been manufactured up to date. The energy dependence evaluation can be further divided into two parts. The first part is experimentally evaluating the energy dependence of the response by irradiating the films to a fixed dose of 2Gy to water at different beam qualities (ranging from 50kVp to ^{60}Co) and then measuring the corresponding response of the film, i.e. net optical density change, using a flat bed document scanner. The second part of the energy dependence evaluation is using the DOSRZnrc Monte Carlo code, which is one of the user codes of the EGSnrcMP (Electron-Gamma-Shower) Monte Carlo code, to calculate the corresponding absorbed dose to water energy dependence of the films, i.e. the ratio of dose to water to dose to the active volume of the film, using the experimental beams spectra, which were calculated using SpekCalc, an x-ray spectrum generating software, by matching the measured HVL, tube potential and added filtration of the experimental beams.

The first component of our study would help us 1) understand the physics behind the energy variation of the film response, 2) evaluate the intrinsic energy dependence of the film, i.e. dose to film sensitive layer per unit film response as a function of beam quality, using the measured energy response and the corresponding absorbed dose to water energy dependence, 3) guide us to what can be done to improve the energy dependence at low energies.

The second component of the study is adjusting the film sensitive layer composition with the guidance of Monte Carlo simulations of the absorbed dose to water energy dependence of the film to reduce the energy dependence of the film response at low energies, and making new film prototypes based on the new possible elemental compositions, then experimentally evaluating their energy response.

Improving the energy dependence of the EBT GAFCHROMIC™ dosimetry film at low energies will make it more suitable for high quality clinical dosimetry. It would be very convenient for clinical dosimetry to have one film dosimetry calibration curve that works at kilovoltage and megavoltage beam qualities. This would allow us to create the film dosimetry calibration curve at, for example, ^{60}Co and then use it for film dosimetry at kilovoltage and other megavoltage beam qualities. On the other hand, since the x-ray spectrum changes in quality and quantity with depth as it penetrates into patient tissue, it is very important that the response of the detector as a function of beam quality be as flat as possible to minimize the uncertainty and error in dose determination. Thus, improving the energy dependence at low energy will result in improving the accuracy of film dosimetry.

FRENCH ABSTRACT

Plusieurs études ont été réalisées pour étudier la dépendance énergétique des films dosimétriques GAFChromic® et ont montré que les modèles de film différents sont équivalents d'eau à environ 100 keV et leur réponse est indépendante de l'énergie à environ 100 keV. L'objectif de notre étude est d'étudier la dépendance énergétique des film commerciaux pour étudier la physique derrière la variation d'énergie ainsi que la dépendance énergétique intrinsèque de développer un nouveau prototype avec une réponse uniforme énergétique aux basses énergies ($3.0 \leq$ 100 keV). L'étude se compose de deux éléments. Le premier est l'évaluation de la réponse énergétique de trois différents films dosimétriques GAFChromic® (EBT, EBT2 et EBT3), qui ont été fabriqués à jour, qui est effectuée par l`irradiation des films à une dose fixe de 2 Gy à l'eau à différentes qualités de rayonnement et mesurer la réponse correspondante au film, c'est à dire la variation nette de la densité optique, à l'aide d'un scanner à plat de documents. Puis, en utilisant le code Monte Carlo, DOSRZnrc, qui est l'un des codes d'utilisateur du code EGSnrcMP (Electron-Gamma-Shower) pour calculer la dose absorbée a l`eau correspondant à la dépendance énergétique des films. Le deuxième élément est le réglage de la composition de la couche sensible des films à ainsi réduire la dépendance énergétique de la réponse du film à basse énergie avec l'aide des simulations de Monte Carlo. En utilisant ce procédé la réalisation de prototypes de nouveaux films basé sur l'éventuelle nouvelle compositions élémentaires ont été tester expérimentalement pour la dépendance énergétique.

L'amélioration de la dépendance énergétique aux basses énergies va rendre les films dosimétriques plus adapté pour la dosimétrie de haute qualité. Puisque le spectre de rayons X changes la qualité et la quantité avec la profondeur en pénétrant dans les tissus du patient, il est très important que la réponse d`un détecteur en fonction de la qualité du faisceau être le plus plat possible pour minimiser l'incertitude et l`erreur dans la détermination de la dose . Donc, améliorer la dépendance énergétique aux basses énergies donnera lieu à l'amélioration de la précision de la dosimétrie du film. Il serait très pratique pour la dosimétrie d'avoir une

courbe de calibration pour les films qui fonctionne dans une large gamme d'énergies. Donc par exemple, vous pourriez d'établir la courbe de calibration au faisceau de Cobalte-60 et l'utiliser pour la dosimétrie au energies de kilovoltage ainsi que d'autres faisceaux de haute energies.

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Hamed A. Bekerat

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Improving the Energy Response of External Beam Therapy (EBT) GAFCHROMIC™ Dosimetry Films at Low Energies (≤100 keV)

Purpose: The purpose of this work is to investigate the energy dependence of different commercially available EBT radiochromic GAFCHROMIC™ dosimetry films, and to understand the physics behind the energy variation of the response at low energies as well as the intrinsic energy dependence. Based on these results we will try to develop a new radiochromic GAFCHROMIC film prototype with more uniform energy response at low energies (≤ 100 keV).

Method: We first investigate the energy dependence of three commercially available GAFCHROMICTM™ film models, namely EBT, EBT2 and EBT3. We irradiated each film model to a fixed dose of 2 Gy to water at different beam qualities (ranging form 50 kVp to ^{60}Co) and then we measured the corresponding response of the film, which is the net optical density, using a flatbed document scanner. On the other hand, we use the DOSRZnrc Monte Carlo user code to determine the absorbed dose to water energy dependence of the film using experimental beams spectra, which were calculated using an x-ray spectrum generating software, SpekCalc, for a given HVL, tube potential and added filtration of each of the experimental beams. In the second part of this study we adjust the film sensitive layer composition with the guidance of Monte Carlo simulations of the absorbed dose to water energy dependence of the film to reduce the energy dependence of the film response at low energies. Finally, based on our results we made suggestions to the film manufacturer to make new film prototypes based on the new possible sensitive layer compositions and experimentally evaluate their energy response.

Results: Commercially available EBT film model shows an under response at all energies below 100 keV; the under response is 39% ± 4% at about 20 keV. Both commercial EBT2 and EBT3 film models show an over response of about 16% ± 4% at about 40 keV and an under response of about 27% ± 4% at 20 keV. The energy response of commercially available film models at low energies show strong correlation with the corresponding

absorbed dose to water energy dependence curves. Commercial films show strong intrinsic energy dependence at low energies; the dose to the EBT2 and EBT3 films at 20 keV and ^{60}Co is the same and both films are water equivalent at the two energies, however, they show under response of 27% at 20 keV due to the strong intrinsic energy dependence. The response of the EBT2 and EBT3 films at low energies, excluding the intrinsic energy dependence, can be explained by examining the ratios of mass energy absorption coefficients of the elements incorporated into the film sensitive layer to water. Despite the strong intrinsic energy dependence, commercial EBT2 and EBT3 show over response at about 40 keV due to the incorporation of Bromine (Z=35) into the films sensitive layer. The energy dependence of the response of the EBT2 and EBT3 film models can be reduced by dropping Bromine or reducing its mass percent to eliminate the over response at 40 keV, and boosting the dose to the sensitive layer of the film relative to water at very low energies to compensate for the intrinsic energy dependence by increasing the mass percent of lower atomic number elements such as Aluminum or Silicon. Dropping Bromine in recent commercial lots of EBT3 and increasing the mass percent of Chlorine to 4% resulted in a reduction in the energy dependence of the film response at low energies. The latest film model shows under response at all energies below 100 keV; it shows under response of 22% ± 4% at 20 keV and 6% ± 4% at about 40 keV. However, increasing the mass percent of Chlorine makes the film more hydroscopic which may affect the stability of the film's readout. On the other hand, the addition of 4% Chlorine didn't improve the energy response significantly at very low energies (~20 keV). Monte Carlo Simulations of the absorbed dose to water of the films reveal that a high percentage (6%-7%) of either Al or Si could be more efficient in boosting the dose to the sensitive layer relative to water at very low energies (20-30 keV) compared to 4% Cl. The EBT3 film prototype with 7.5% Si shows a significant reduction in the energy dependence of the film response at very low energies compared to the commercial EBT3 films with (0.8% Br, 1.1% Cl) or 4% Cl; it shows under response of 15% ± 5% at about 20keV to 2% ± 5% at about 40 keV. However, according to the manufacturer, the addition

of 7.5% Si affected the viscosity of the active solution which made it difficult to be used in commercial machine coating.

Conclusions: The energy dependence of the response of commercially available films at low energies (≤100keV) can be improved by adjusting the sensitive layer composition. Dropping Bromine and increasing the mass percent of Cl to 4% in recent commercial EBT3 films eliminated the over response of the films at 40 keV and resulted in a reduction in the energy dependence of the response. Incorporating 7.5% Si into the sensitive layer reduced the energy dependence of the film response significantly compared to commercial EBT2 and EBT3 films with (0.8% Br and 1.1% Cl) or 4%Cl.

I. Introduction

The External Beam Therapy (EBT) radiochromic GAFCHROMIC™ dosimetry films[1] were introduced by International Specialty Products (ISP, Wayne, NJ) now part of ASHLAND to be used in clinical radiation dosimetry. Before the introduction of radiochromic films and in particular EBT films, radiographic films, which were routinely used in clinical radiotherapy applications, offered many advantages such as obtaining a two dimensional high resolution dose distribution from a single exposure. However, they needed special chemical processing before being evaluated. They showed pronounced energy dependence at low energies because of their high atomic number composition,[2,3] which made them unsuitable for low energy dosimetry applications. Also, their response showed dependence on the direction of the irradiation field with respect to the film.[4]

Many of the difficulties associated with the use of radiographic films in clinical dosimetry were overcome with the introduction of the radiochromic EBT GAFCHROMIC™ dosimetry films. They are self developing, i.e. there is no need for special chemical processing after irradiation. The EBT films use radiation sensitive monomers, usually diacetylene monomers, organized into micro-crystals and embedded in a gelatin binder. Upon exposure to ionizing radiation, the radiation sensitive monomers undergo a solid state polymerization which results in the formation of a blue colored polymer, where the change in color is proportional to the radiation dose deposited within the sensitive component of the film.[5] The blue coloration of the film due to radiation exposure is an indication that a broadband visible light source is strongly attenuated in the red band of the spectrum. Hence, the change of the film optical density due to ionizing radiation exposure can be read and related to the dose deposited in the sensitive volume of the film.[6,7] They are near tissue equivalent[8], and their response is energy independent for energies above 100 keV.[9,10,11] Also, they are highly sensitive to ionizing radiation,[12] and relatively insensitive to room light. All these features make them very suitable for high quality clinical dosimetry.

One of the most important properties of a radiation detector to be suitable for use in accurate clinical dosimetry is its energy independence. In general, three quantities are used to describe the energy dependence of a radiation dosimeter.[8,13,14] The first quantity is the absorbed dose to the reference medium, i.e. water, sensitivity of the detector, $S_{AD,w}(D,\dot{D},Q,\theta,\phi)$, or less formally the overall energy dependence of the dosimeter or for simplicity the energy response of the detector. For films, this quantity is defined as the net optical density due to ionizing radiation exposure per unit dose to the reference medium at beam quality Q

$$S_{AD,w}(D,\dot{D},Q,\theta,\phi)=\frac{netOD_{\det}(D,\dot{D},Q,\theta,\phi)}{D_w(Q)} \tag{1}$$

In general, it depends on dose, D, dose rate, $\dot{D}$, beam quality, Q, and orientation of the film with respect to the incident radiation (θ,ϕ). This is a quantity that can be evaluated experimentally by irradiating the film piece to a given dose to the reference medium and then measuring the corresponding response of the film, i.e. net optical density. The second quantity, is the absorbed dose to water energy dependence of the film or extrinsic energy dependence of the film, $f(Q)$. It is defined as the dose to the reference medium per unit dose to the film sensitive volume at beam quality Q

$$f(Q)=\frac{D_w(Q)}{D_{film}(Q)} \tag{2}$$

The third quantity of interest is the intrinsic energy dependence of the film, $K_{bq}(Q)$, defined as the dose to sensitive volume of the film per unit film response, i.e. net optical density, at beam quality Q

$$K_{bq}(Q)=\frac{D_{film}(Q)}{netOD(Q)} \tag{3}$$

The intrinsic energy dependence is a measure of the efficiency of the incident ionizing radiation in polymerizing the radiation sensitive material in the film and inducing a color change.

If the dose, dose rate, and geometrical factors are held constant, then, equation 1 reduces to

$$S_{AD,w}(Q) = \frac{netOD(Q)}{D_w(Q)} = \frac{1}{K_{bq}(Q).f(Q)} \tag{4}$$

which relates the absorbed dose to water sensitivity of the detector at beam quality Q to the absorbed dose to water and intrinsic energy dependence of the film.

Currently available Monte Carlo Codes for the transport of ionizing radiation in an absorbing medium can only be used to calculate the absorbed dose to water energy dependence of the film, f(Q). However, the intrinsic energy dependence of a particular film model can be evaluated using equation 4 by experimentally evaluating the energy response of the film, $S_{AD,w}(Q)$, and using Monte Carlo simulations to evaluate the absorbed dose to water of the film, f(Q).

Numerous experimental studies have been conducted to investigate the energy response of the original EBT film model. Chiu-Tsao *et al.*[15] investigated the energy response of an EBT film model using four beam qualities (6 MV photon beams, Ir-192 (370 keV), I-125 (28 keV), and Pd-103 (21 keV)); the film was scanned using red (665 nm) and green (520 nm) light sources in a Charge-Coupled Device (CCD) based densitometer and reported that the EBT film response is nearly energy independent within the measurement uncertainty. Butson *et al.*[9] investigated the energy response of an EBT film model using UV-visible spectro-photometer and reported that the energy response variations didn't exceed 10% in the effective energy range from 28 keV to 5.5 MeV. Rink *et al.*[10] investigated the energy response by using a real-time optical dosimeter and measuring the net optical density immediately at the end of irradiation period over the energy range from 75 kVp (3 mmAl HVL) to 18 MV and reported energy response variation within 3%. Richter *et al.*[11]

investigated the energy response of the EBT film model using a flatbed scanner and 12 beam qualities, 8 of which are in the orthovoltage range and varied from 10 kVp (0.04 mmAl) to 200 kVp (3.14mm Cu). Their results show strong energy dependence at low energies; the film shows under response of about 50% at 10 keV effective energy for a dose of 2 Gy to the reference medium. Ebert *et al.*[16] studied the suitability of the EBT film for dosimetry of very-low energy X-rays and reported a significant energy dependence within the measurement uncertainty for a 50 kVp beam. Lindsay *et al.*[17] investigated the energy dependence of different EBT film lots that were manufactured before 2006 and in 2007 at two orthovoltage beam qualities (150kVp, 3.2 mmAl; and 220 kVp, 1.7 mmCu HVL) and related the energy dependence to the film's chemical composition and date of production. They reported variations in the energy dependence between lots manufactured before 2006 and lots manufactured in 2007 due to variations in the chemical composition.

The overall energy dependence of the EBT2 film model was experimentally investigated by many authors with various results. Butson *et al.*[18] investigated the energy dependence of an EBT2 dosimetry film model in the energy range from 25.2 keV effective energy (50 kVp) to 2.2 MeV effective energy (10 MV), and reported an energy dependence of 6.5%. Arjomandy *et al.*[19] reported a variation in the energy dependence of the EBT2 film within ± 9 % over the energy range of 75 kVp to 18 MV. Lindsay *et al.*[17] investigated the energy dependence of three EBT2 film models at one orthovoltage beam quality (105 kVp, 3.5 mmAl) and also investigated the chemical composition of the films and reported that the energy response varied from 0.75 to 1.2 depending on the concentration of Br, Cl and K in the film sensitive layer.

On the other hand, Sutherland and Rogers[8] investigated the absorbed dose to water energy dependence of a commercial EBT film model and two commercial EBT2 film models that varied in the composition of the sensitive layer using Monte Carlo simulation techniques. The results of their study reveal that 1) the EBT and EBT2 film models are water equivalent down to about 100 keV; 2)for the EBT film model, the absorbed dose to water energy dependence of the film at low energies is affected by the compositions of the

surface and polyester layers; 3) the dose to the sensitive layer of the EBT2 film model at low energies is due to electrons that were created mainly within the relatively thick 25μm sensitive layer and hence there is an agreement between the ratio of the mass energy absorption coefficients of water to film sensitive layer and the corresponding absorbed dose to water energy dependence curve at low energies.

Despite the fact that different studies experimentally evaluating energy response of different film models varied in their findings at low energies, they all agree that the response of different film models is energy independent down to about 100 keV. Also, Sutherland and Rogers[8] study of the absorbed dose to water of the EBT and EBT2 film models showed that the films are water equivalent down to about 100 keV. Sutherland and Rogers compared the result of their study of the absorbed dose to water of an EBT film model and the results of three independent different studies of the relative energy response of the EBT film model (Butson *et al*.[9], Rink *et al*. [10], Richter *et al*.[11]) and reported that the results of the three studies disagree with their results. They cited two reasons for the disagreement: 1) Intrinsic energy dependence in the energy response of the films which cannot be accounted for using the current Monte Carlo code, 2) the studies were conducted for different EBT film lots that possibly varied in their composition as reported by Lindsay *et al*[17].

To overcome the shortcomings of previous studies, we investigate the energy response and the absorbed dose to water energy dependence of the same film models. In particular, we investigate the energy dependence of three commercially available GAFCHROMIC™ dosimetry film models, EBT, EBT2 and EBT3 which represent the three different configurations of the film that have been produced up to date. The investigation is conducted, by first, experimentally evaluating the energy response, $S_{AD,w}(Q)$, of each film model. Then, using Monte Carlo simulations to evaluate the corresponding absorbed dose to water energy dependence, $f(Q)$. $S_{AD,w}(Q)$ evaluation was performed by irradiating each film model to a fixed dose of 2 Gy to water at different beam qualities (ranged from 50kVp to ^{60}Co) and then measuring the corresponding response of the films, i.e. the net optical density, using a flat bed document scanner. We then used the

DOSRZnrc[20] Monte Carlo, which is one of the user codes of the EGSnrcMP[21] Monte Carlo code, to investigate the corresponding absorbed dose to water energy dependence using experimental beams spectra, which were calculated using SpekCalc[22], an x-ray generating software, by matching the measured HVL, inherit filtration and tube potential of the experimental beams. The advantage of our work over previous studies is that it will allow us to 1) understand the physics behind the energy variation of the response; 2) evaluate the intrinsic energy dependence of the film using equation 4; 3) guide us to what is needed to be done to develop a new prototype with more uniform energy response at low energies (≤ 100 keV).

It would be very convenient for clinical dosimetry to have a dosimeter with a response that is energy independent over a wide range of x-ray energies that are used in the clinic. This would allow us to create the film dosimetry calibration curve at, for example, ^{60}Co and then use it for film dosimetry at orthovoltage beam qualities. On the other hand, in radiotherapy we often deal with x-ray spectrum that changes in quality and quantity with depth due to attenuation and scattering as it penetrates into patient tissues. Hence, it is very important that the response of the detector as a function of beam quality is as flat as possible to minimize the uncertainty and errors in dose determination. Thus, improving the energy dependence of the response of the film at low energies will eventually result in improving the accuracy of film dosimetry.

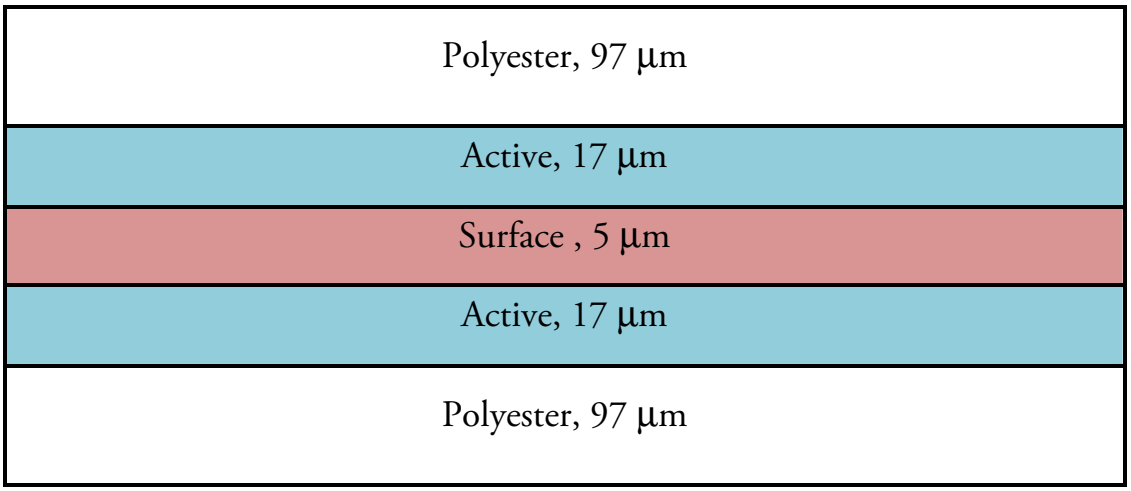
II. MATERIALS AND METHODS

In the following sections we discuss the experimental setup and techniques used for reference dose delivery and measuring the corresponding response of the film, i.e. net optical density, as well as the Monte Carlo technique used in evaluating the extrinsic energy dependence of the films.

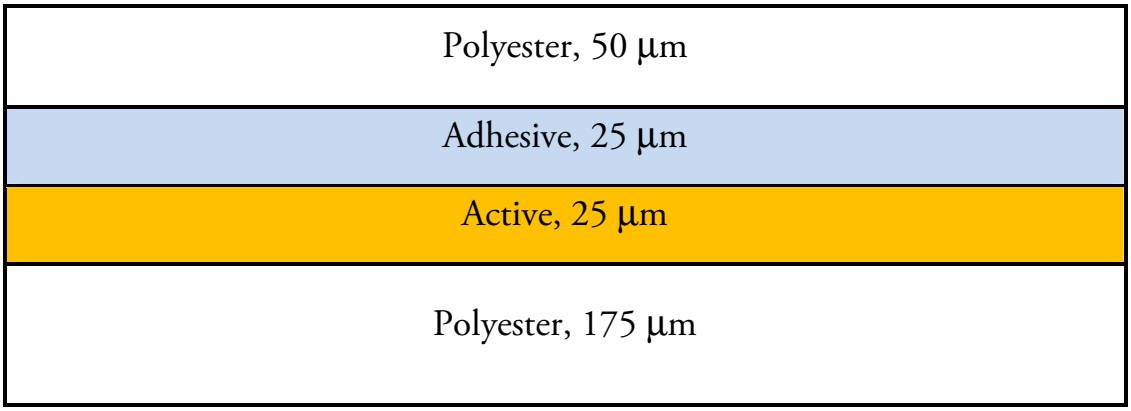
A. Films Material

The first step in our investigation is to evaluate experimentally the energy response of three commercial EBT GAFCHROMIC™ dosimetry film lots: EBT- 48022-07I, EBT2-A08161006 and EBT3-A07251102. The lots represent the three different EBT film geometries that have been produced up date by International Specialty Products (ISP, Wayne, NJ) now part of ASHLAND. Figure 1 shows the configuration of the films, while table 1 shows the mass percent of each element incorporated into the different layers of the films and the effective atomic number of each layer, which was calculated using the formula from McCullough and Holmes[23].

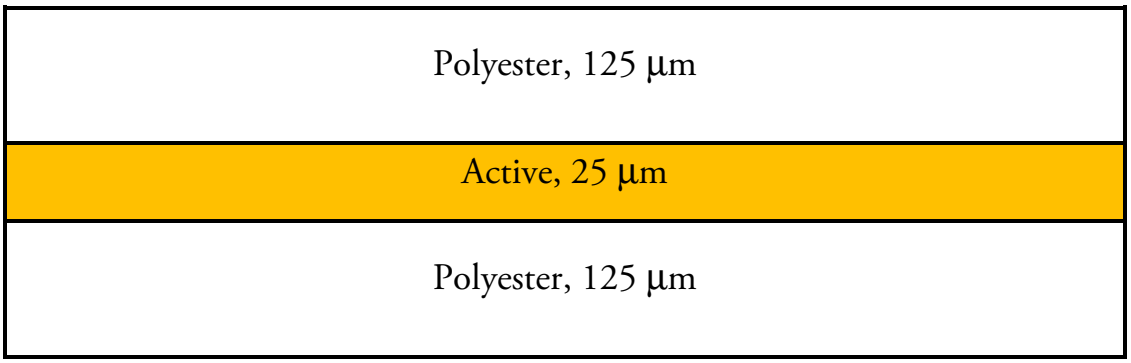
The original EBT film model which is no longer produced is symmetric and comprised of 5 layers; two relatively thin 17 micron active layers separated by a 5 micron surface layer and all sandwiched between two 97 micron polyester layers. Compared to the EBT, 1) the EBT2 is asymmetric; 2) there is only one relatively thick 25 micron active layer instead of two; 3) a new adhesive layer was added and the surface layer was eliminated; 4) a yellow active dye was incorporated into the active layer of the EBT2 film to be used to correct for variations in the film response due to variations in the film active layer thickness. In going from EBT2 to EBT3, the configuration of the film was changed; EBT3 is symmetric and has one 25 micron active layer sandwiched between two 125 micron polyester layers. Also, the manufacturer decided to incorporate silica particles into the polyester layers to prevent the formation of Newton rings.



(a) EBT- 48022-07I.



(b) EBT2-A08161006.



(c) EBT3- A07251102.

Fig.1. Different Configurations of EBT GAFCHROMIC™ Dosimetry Films that have produced by the manufacturer up to date (Film lot numbers used in our investigation are also shown)

Table 1. Composition of EBT- 48022-07I, EBT2- A08161006 and EBT3- A07251102 Film layers in Mass Percent

		H	Li	C	N	O	Na	S	Cl	Br	Z_{eff}	Dens. (g/cm)
EBT	active	9.4	0.8	57.6	1 3..2	16.4	-	-	2.6		6.98	1.1
	surface	8.6	0.4	42.0	21.6	21.3	-	-	6.1		7.99	1.2
EBT2	active	9.7	0.9	58.4	0.1	28.4	0.4	0.20	1.1	0.8	9.38	1.2
	adhesive	9.0	-	66.0	-	25.0	-	-	-	-	6.26	1.2
	top coat	8.8	1.0	47.2	-	38.2	-	-	4.9	-	7.82	1.2
EBT3	active	9.7	0.9	58.4	0.1	28.4	0.4	0.20	1.1	0.8	9.38	1.2
	polyester	4.0	-	63.0	-	33.0	-	-	-	-	6.64	1.35

B. Reference Dose Delivery

In this section, techniques and experimental setups used for reference dose delivery are discussed. Table 2 lists beam qualities we used for experimentally evaluating the energy dependence of the film response due to exposure to ionizing radiation. For each of the orthovoltage beam qualities, the table lists the tube potential in kVp, mean energy in keV, and half value layer (HVL) in mm Al or mm Cu and the corresponding effective energy in keV. A Gulmay orthovoltage x-ray unit and a Theratron 780 cobalt unit are used to perform irradiations at orthovoltage and ^{60}Co beam qualities, respectively. While the film irradiations at ^{192}Ir are performed using a Nucletron-Elekta High Dose Rate (HDR) brachytherapy remote afterloader unit.

The experimental evaluation of the energy dependence of any GAFCHROMIC™ film model is performed by irradiating film pieces to a fixed dose of 2 Gy to a small mass of water in air at orthovoltage beam qualities and 2 Gy to water in a solid water phantom at

Table 2. Beam qualities used to evaluate films energy response.

Beam Quality		Machine	Applicator	E_{eff} (keV)	N_k cG/nC	E_{mean} (keV)	Chamber	Dosimetry Protocol
Nominal energy	HVL (mm)							
50 kVp	0.16 Al	Gulmay	5 cm Circ.	12.74	105.9	21.1	Parallel Plate	TG-61
50 kVp	0.33 Al	Gulmay	10 cm Square	15.15	105.2	23.7	Parallel Plate	TG-61
70 kVp	1.33 Al	Gulmay	5 cm Circ.	23.47	13.197	35.4	Thimble	TG-61
80 kVp	2.18 Al	Gulmay	5 cm Circ.	29.5	12.64	41.1	Thimble	TG-61
120 kVp	4.19 Al	Gulmay	5 cm Circ.	41.8	12.46	57.0	Thimble	TG-61
180 kVp	3.00 Cu	Gulmay	5 cm Circ.	64.0	12.36	74.0	Thimble	TG-61
Ir-192	2.5 Pb	Nucletron -Elekta HDR				398	HDR Well	TG-43
Co	11.0 Pb	T-780				125 0	Thimble	TG-51

^{192}Ir and ^{60}Co, and then measuring the corresponding response of the film. Three pieces of the same film were used at each beam quality and were irradiated to the prescribed dose, and one film piece was kept un-irradiated and used as a control piece to correct for changes in optical density due environmental conditions such exposure to light, temperature, humidity, etc. Accurate evaluation of the energy dependence requires accurate determination of the dose delivered to water and therefore reference dosimetry was performed before film irradiation at each beam quality to determine the number of MUs needed to deliver 2 Gy to a small mass of water in air following the recommendation of the AAPM TG-61 protocol at orthovoltage irradiation and the time required to deliver 2 Gy to water following the recommendations of TG-51 at ^{60}Co irradiations and TG-43 at ^{192}Ir.[24, 25, 26]

1. Reference Dosimetry at Orthovoltage Beam Qualities

According to the TG-61 protocol, reference dosimetry at orthovoltage beam qualities involves two steps: First, the ionization chambers to be used in reference dosimetry need to be calibrated in terms of exposure or air-kerma in air at beam qualities that are very close to the user beams in terms of HVL and tube potential; the calibration must be traceable to national standards, i.e., from NRC in Canada or NIST in the USA. Second, measuring the dose in the user beam using the calibrated ion chamber, which only requires determining the HVL of the beam in an attenuator such as Al or Cu as the beam quality specifier.[21]

Two types of ionization chambers were used in our experiments to perform reference dosimetry at orthovoltage beam qualities. A parallel plate chamber PTW model R23342 with a Keithley model 6517A electrometer is used at the two tube potentials at 50 kVp and a farmer type thimble chamber NE model 2577C with a Keithley model 6517A electrometer is used at tube potentials ≥ 70 kVp. The chambers and electrometers were calibrated together in terms of air kerma in air by the National Research Council of Canada (NRCC).

1.1. Chamber Calibration

For chamber calibration by the standards lab, the TG-61 recommends that beam qualities be determined in terms of HVL in mm Al or mm Cu and tube potential (kVp). To minimize the uncertainty in determining the calibration coefficient for the user beam qualities and keep it within the recommended limit, i.e. less than or equal 2%, the TG-61 protocol recommends the following:

1. For accurate HVL determination, the protocol recommends among other things using small volume chambers for proper coverage of the sensitive volume of the detector; the volume of the R23342 parallel plate chamber is 0.02 cm^3 and the NE 2577C chamber is 0.2 cm^3.
2. The protocol requires the calibration at the standards lab to be performed at beam qualities that are very close to the beam qualities used in the clinic in terms of HVL

and tube potential, and at more than one beam quality to insure that the beam qualities used in the clinic are properly covered.

3. The detector response must have very limited beam quality dependence (within 5%) in the energy range of interest between 40 and 300 kVp.

The HVL measurements at each beam quality followed the recommendations of the AAPM TG-61 protocol. Figure 2 shows a diagram of the experimental setup used for HVL measurement, while the pictures in Fig. 3a and 3b demonstrate the clinical setup used for measuring the HVL. It involves the determination of the thickness of some standard material such as Al or Cu (added Copper or Aluminum in Fig. 2 that is required to reduce the beam intensity to half its original value. A thick sheet of lead (limiting diaphragm) is used to reduce the beam diameter to less than 4 cm and attenuate the primary beam to ≤ 0.1%, thus achieving the condition of narrow beam geometry. The chamber was placed at least 50 cm from the attenuator and about 50 cm from the ground to minimize radiation scatter into the detector. A piece of GAFCHROMIC™ film is used to insure the alignment of the source, diaphragm and the detector as demonstrated by Fig. 3a. The HVL is measured by placing a series of attenuators, Aluminum or Copper depending on the beam energy, just few centimeters from the lead attenuator as demonstrated by Fig. 3b and measuring air kerma with the variation of the attenuators thickness. For HVL measurements we used the NE 2577C ion chamber.

The chambers were sent to the National Research Council of Canada (NRCC) with the corresponding electrometers for calibration. Tables 3a and 3b show the calibration factors for the parallel and thimble chambers respectively, while, Fig. 4a and 4b shows the energy dependence of the parallel plate chamber as provided by the manufacturer and the calibration curve as provided by NRC, respectively. Fig. 5 shows the calibration curve for the thimble chamber as provided by NRC. The curves demonstrate graphically why a parallel plate chamber is needed at very low energies. As required by the TG-61 dosimetry protocol, to minimize the uncertainty in determining the calibration factor and keep it within the recommended limit (≤ 2%), the detector response must have a limited beam quality

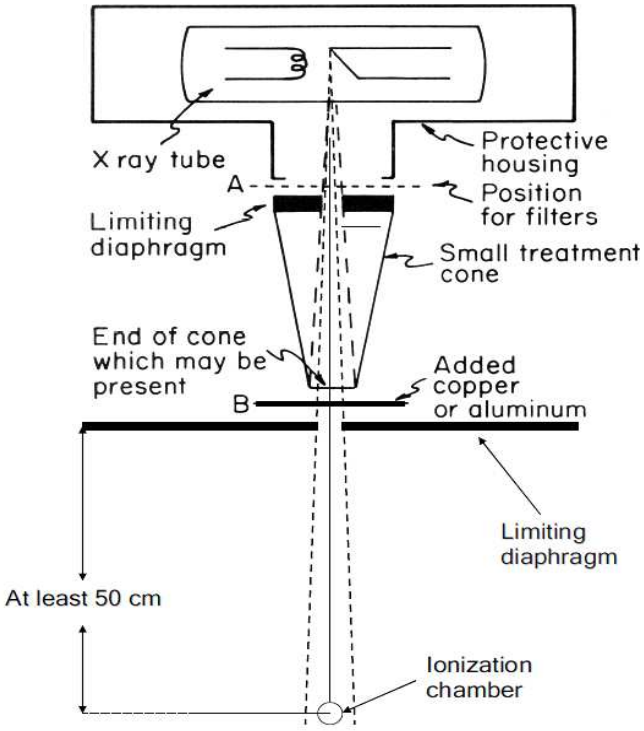


Fig.2. A diagram of the experimental setup used for HVL determination.

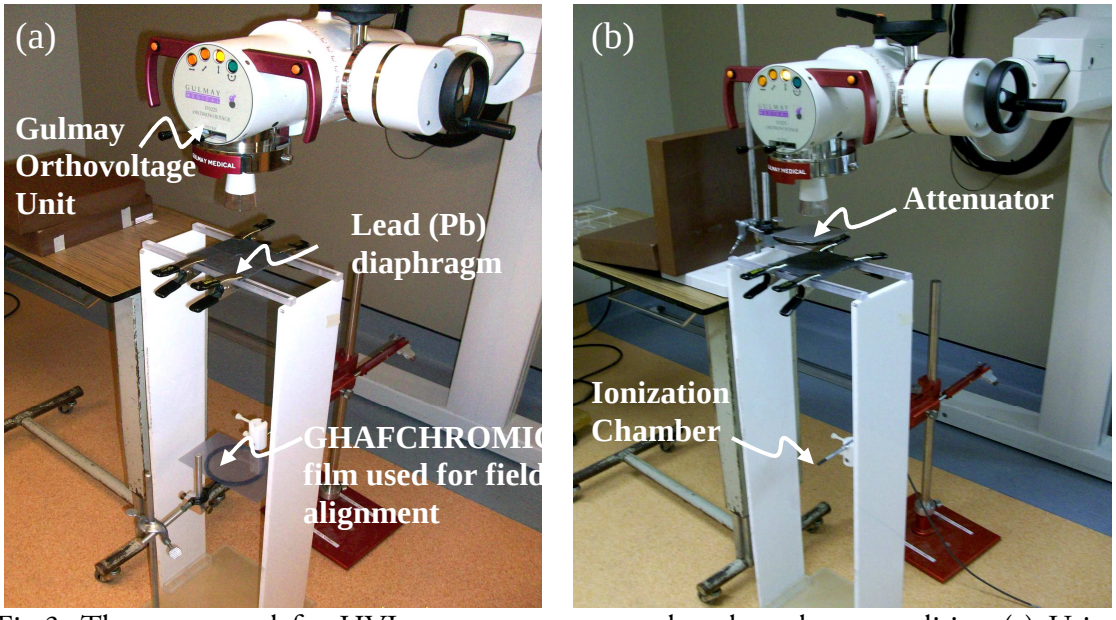


Fig.3. The setup used for HVL measurement at orthovoltage beam qualities. (a) Using a GAFCHROMIC™ film to insure proper alignment. (b) Measuring the HVL using the thimble chamber.

Table 3.a Beam specification and corresponding calibration coefficients for the parallel plate chamber R23342 (the calibrations were performed by NRCC).

Tube Potential (kVp)	Filtration (mm) Inherent Be(mm)	added Al (mm)	HLV mm		N_k cGy/nC	Nx R/nC	Uncertainty Conf. Level:95% K=2	E_{eff} kev	$\left(\frac{\mu}{\rho}\right)_{h\nu,z}$ cm^2/g
50	1	0.19	0.17	Al	105.9	120.8	1%	14.24	9.442
50	1	0.34	0.32	Al	105.2	120.0	1%	27.16	1.411

Table 3.b Beam specification and corresponding calibration coefficients for the thimble chamber NE2577C (the calibrations were performed by NRCC).

Tube Potential (kVp)	Filtration (mm) Inherent	added		HLV (mm)		N_k	Nx	Uncert. Conf.	E_{eff}	$\left(\frac{\mu}{\rho}\right)_{h\nu,z}$
	Be mm	Al mm	Cu mm			cGy/nC	R/nC	Level:95% K=2	keV	cm^2/g
50	1	0.25		0.272	Al	15.21	17.36	1%	14.24	9.442
80	3	1.29		1.820	Al	12.78	14.58	1%	27.16	1.411
120	3	1.54		3.030	Al	12.57	14.34	1%	33.22	0.848
180	3	1.00	0.05	0.350	Cu	12.34	14.08	1%	52.9	2.210
220	3	1.00	0.50	1.100	Cu	12.39	14.13	1%	83.28	0.703
250	3	1.00	1.28	2.220	Cu	12.52	14.28	1%	114.56	0.348

dependence within 5% in the energy range of interest. Fig. 4a and 4b show that the variation in the response of the parallel plate chamber in the energy range from 12 keV to 32 keV is less than 1%, while the thimble chamber response shows a variation of about 23% between 10 and 50 keV, which makes the parallel plate chamber more suitable for reference dosimetry at very low energies.

1.2. Performing Reference Dosimetry and Irradiations at Orthovoltage Beam Qualities

At orthovoltage beam qualities, the energy dependence of the film was evaluated by irradiating the films to 2 Gy to a small of water in air at each beam quality and measuring the corresponding response of the film. Therefore, it was necessary to perform reference dosimetry at each beam quality to determine the number of Monitor Units (MUs) needed to deliver the prescribed dose.

Using of ionization chambers in reference dosimetry within the user beams, after being calibrated at NRCC, according to the TG-61 protocol requires only HVL as the beam quality specifier to determine the corresponding calibration factor. Thus, HVL was measured for each beam quality used in the experiment following the procedure described in subsection 1.1. The measured HVL values were used to determine N_k for each beam quality according to the following steps:

1. For each beam quality, the mass-attenuation coefficient, $(\mu/\rho)_{h\nu,z}$, in Al or Cu is determined using the following equation

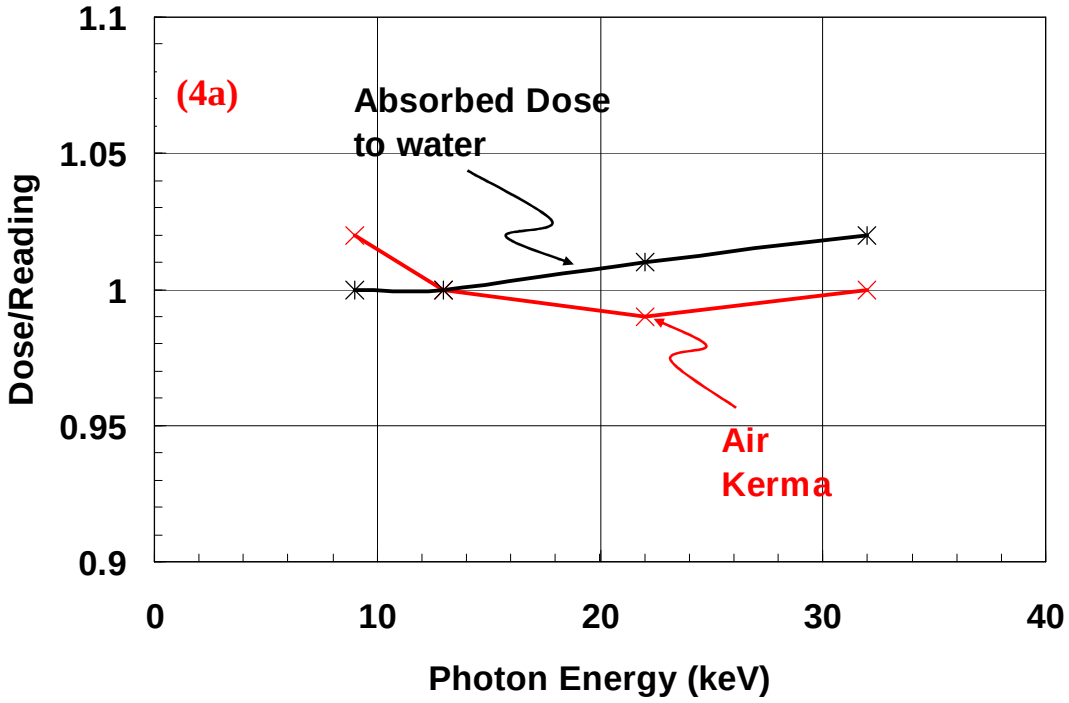
$$\left(\frac{\mu}{\rho}\right)_{h\nu,z} = \frac{1}{\rho}\frac{\ln 2}{HVL} \qquad [\text{cm}^2.\text{g}^{-1}], \tag{5}$$

where μ is the linear attenuation coefficient of the beam quality in Al or Cu in units of [cm], ρ is the mass density of the attenuator material in units of [g.cm^{-3}].

Using the National Institute of Standards and Technology (NIST)* data base for the mass-attenuation coefficients of Al and Cu, the effective energy (E_{eff}) for each beam quality is determined by interpolating between the mass attenuation coefficients.

3. The calibration factors for the experimental beams were determined by interpolating between the effective energies in the calibration beams.

* http://www.nist.gov/pml/data/xraycoef/index.cfm/



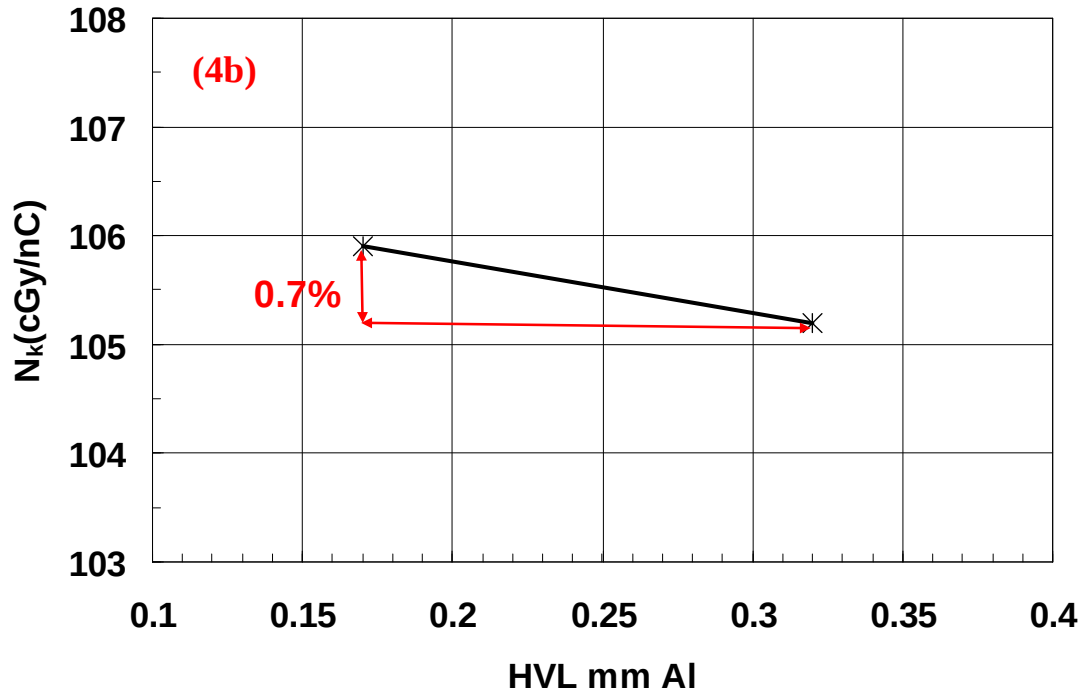


Fig.4. The energy response and calibration curves of the parallel plate PTW R23342 ionization chamber. (a) Energy dependence of the parallel plate PTW R23342 as provided by the manufacturer. (b) The calibration curve of the parallel plate PTW R23342 chamber as provided by NRC

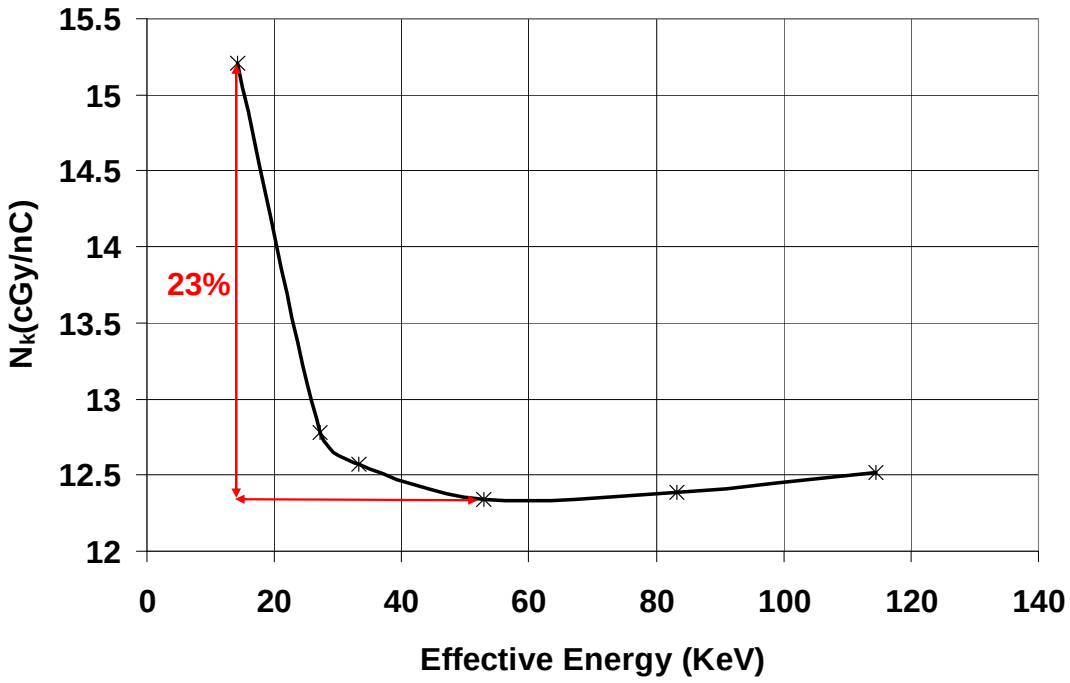


Fig.5. The calibration curve of the thimble chamber NE2577C

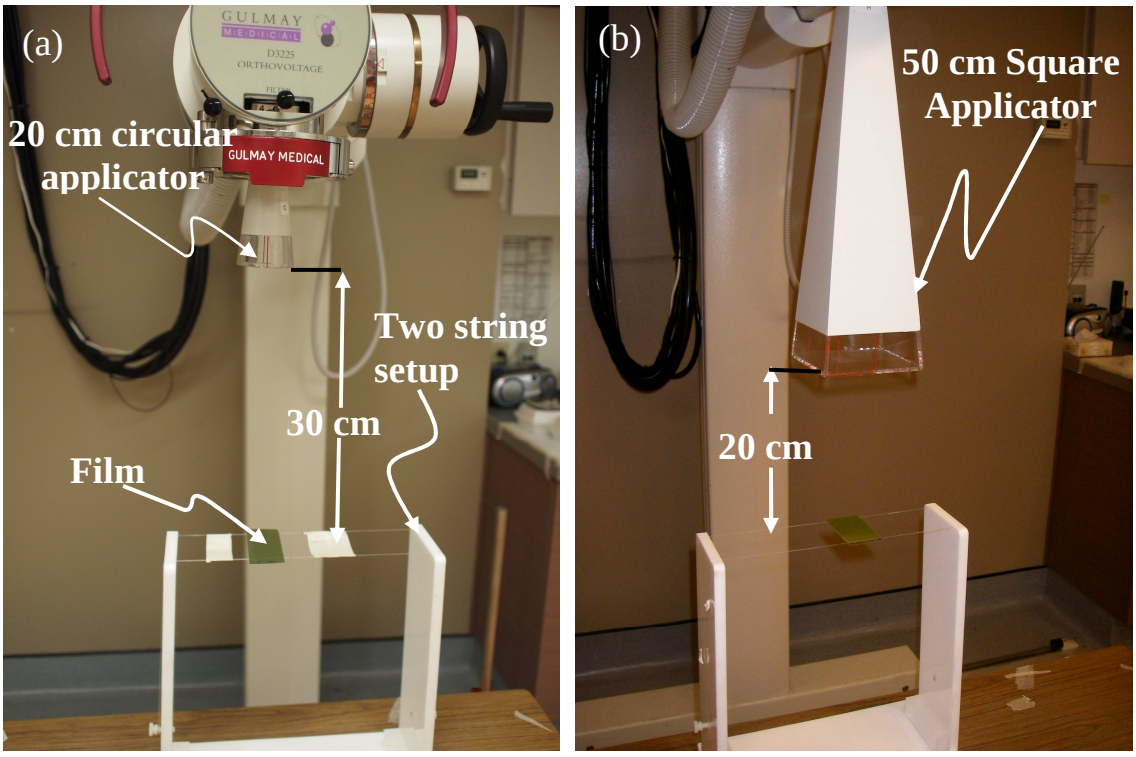


Fig.6. The experimental setup used to irradiate the films at orthovoltage beam qualities.
(a) Circular cone applicator. (b) Square cone applicator

The measured HVL and corresponding N_k values of the beam qualities used in the experiment are given in Table 1.

The experimental setup used to irradiate films at orthovoltage beam qualities is shown in Fig. 6a and 6b. Two types of applicators are used, a circular cone that is 5 cm in diameter and 20 cm source to cone end distance and a square cone with 10 cm side length and 50 cm source to cone end distance. A two string setup is used with the film placed at 30 cm from the circular cone end and 20 cm from the square cone end.

Reference dosimetry at each beam quality was performed free in air by placing the chamber at the position of the film with the center of the chamber placed along the central axis of the radiation field, and taking into account that the reference point for the parallel plate and thimble chamber is at the center of the chamber for orthovoltage beam qualities. The absorbed dose to a small mass of water per monitor unit (MU) is given by[21]

$$\dot{D}'_w = \dot{M} N_k P_{stem,air} \left[\left(\frac{\bar{\mu}_{en}}{\rho} \right)^w_{air} \right]_{air} \qquad [\text{cGy.MUs}^{-1}], \qquad (6)$$

where $\dot{M}$ is the free in air chamber reading per MUs corrected for temperature, pressure, ion recombination, polarity effect with the center of the chamber cavity is placed at the measurement point. N_k is the air kerma calibration factor, $P_{stem,air}$ is the chamber stem correction factor which accounts for the change in photon scatter in the chamber stem between the calibration and measurement mainly due to changes in the field size, $\left[(\bar{\mu}_{en}/\rho)^w_{air}\right]_{air}$ is the ratio of the mass-energy absorption coefficient water to air in air averaged over the incident photon spectrum and given by Table IV in TG-61. Then, the number of MUs to give a fixed dose of D'_w to a small mass of water in air is given by

$$MUs = \frac{D'_w}{\dot{D}'_w} \qquad (7)$$

2. Reference Dosimetry and Film Irradiation at ^{60}Co

At ^{60}Co, film pieces were irradiated to 2 Gy to water within a solid water phantom using a Theratron T-780 Cobalt teletherapy machine following recommendations of the AAPM TG-51 dosimetry protocol for high energy photon and electron beams. Figure 7a shows a schematic diagram of the ^{60}Co irradiation, while Fig. 7b and 7c show pictures of the experimental setup used to irradiate the films at ^{60}Co. An SSD setup is used with a source to surface distance of 80 cm. The film is placed at a depth of 5 cm in the solid water phantom; the field size at the phantom surface is 30 × 30 cm^2. A 10 cm thick slab of Solid Water was placed bellow the film in order to provide sufficient backscatter material.

Reference dosimetry was performed to find the time required to give 2 Gy to water in the solid water phantom. According to the TG-51 protocol, the absorbed dose to water per unit time at the point of measurement in absence of the ion chamber is given by

$$\dot{D}_W^{^{60}Co} = \dot{M} N_{D,w}^{^{60}Co} \qquad \text{[cGy/s]}, \tag{8}$$

where $\dot{M}$ is the electrometer reading per unit time in [nC/s] which has been corrected for ion recombination, polarity and electrometer calibration effects and corrected to standard environmental conditions of temperature and pressure and $N_{D,w}^{^{60}Co}$ is the ^{60}Co absorbed dose to water calibration factor of the ionization chamber in [cGy/nC]. The time required to give a fixed dose to water, $D_w^{^{60}Co}$, at the point of measurement without the shutter correction time (τ_s), which accounts for any possible end effects as the source moves to its treatment position and returns to its safe position at the end of treatment, is given by

$$T = \frac{D_w^{^{60}Co}}{\dot{D}_W^{^{60}Co}} \tag{9}$$

Treatment time corrected for possible end effects is given by

$$T_c = T + \tau_s \tag{10}$$

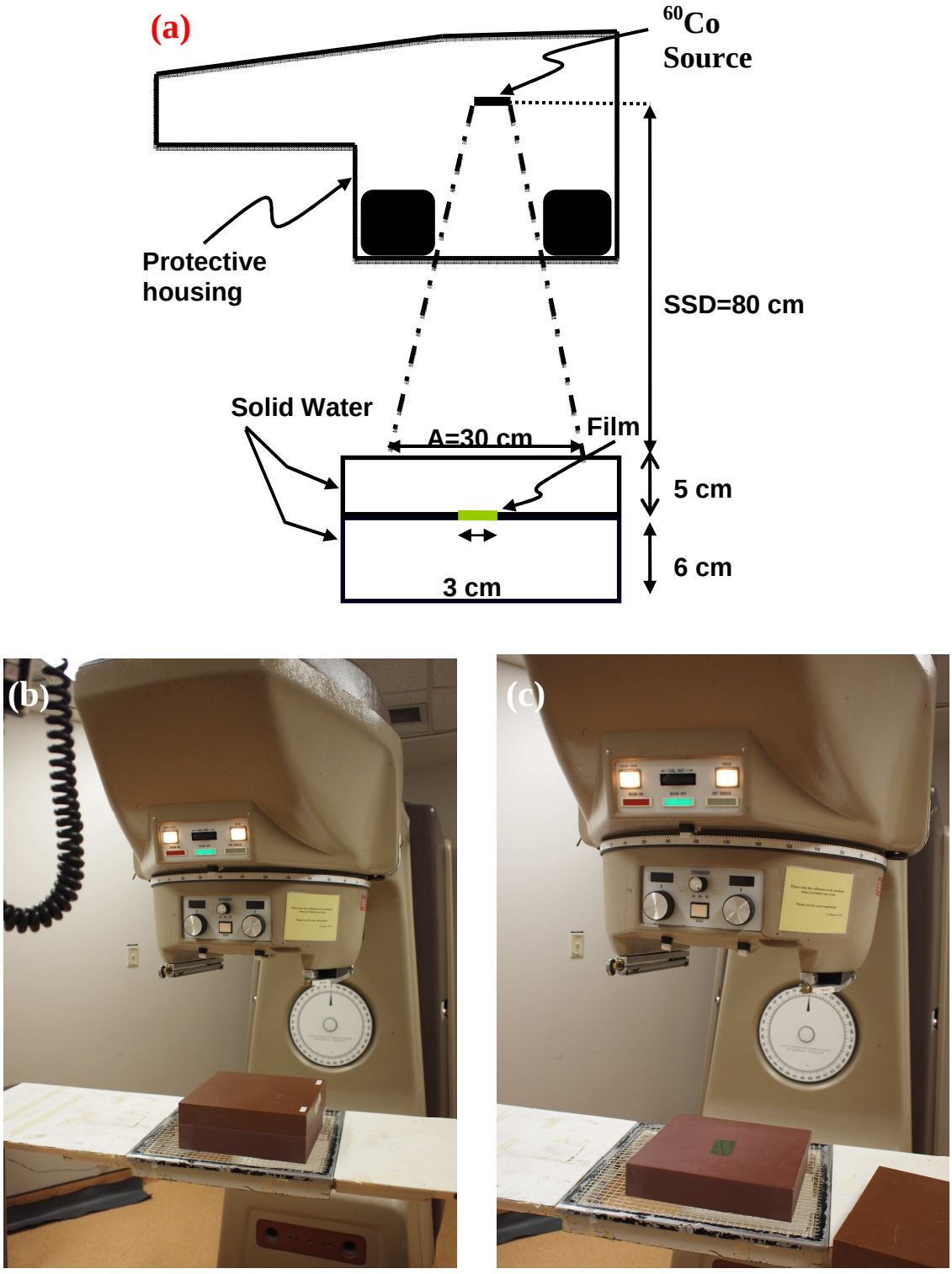


Fig.7. Film Irradiations at ^{60}Co using a Theratron 780 cobalt unit. (a) Schematic diagram of ^{60}Co irradiation. (b) Picture of film irradiation setup. (c) The film is placed at a depth of 5 cm in a solid water phantom.

for the cobalt unit used in our experiment, τ_s=0.02 min and was measured using the multiple start-stop method. [27]

3. Reference Dosimetry and Film Irradiation at ^{192}Ir

Film irradiations at ^{192}Ir were performed in a solid water phantom using the irradiation setup designed and procedures suggested by Aldelaijan *et al*.[28,29] Figures 8 and 9 show a diagram and photographic images of the phantom designed by Aldelaijan to establish the calibration curve of an ^{192}Ir source and used in our experiment to evaluate the energy dependence of the film response at ^{192}Ir. The ^{192}Ir source used in the experiment is encapsulated and characterized by an energy spectrum with effective energy of 370 keV. The source is delivered by a High Dose Rate (HDR) brachytherapy unit (V3 digital, Nucletron-Elekta, Veenedaal, the Netherlands).

The phantom comprised of 6 blocks of solid water with a source to source nominal distance of 6 cm, which was achieved by drilling straight pathways through two 1 cm solid water blocks with a diameter that is just wide enough to accommodate the catheters. The film is placed between 2 cm solid water blocks, and a region that defines the film bed was drawn on the lower 2 cm solid water block. A 5 cm solid water block placed on each side of the phantom to provide sufficient back scatter.

The irradiation setup, Fig. 9, utilized Anterior Posterior-Posterior Anterior (AP-PA) geometry to irradiate the film. As has been shown by Aldelaijan, the main advantage of this irradiation setup is to achieve a larger degree of dose homogeneity in the region of interest in the phantom, where the dose delivered by the remote afterloader is defined, which would minimize the uncertainty in the dose delivered due to 1) source or film positions inaccuracies, 2) short source to film distances. If only one source is used, the film has to be placed closer to the source to achieve a strong signal, which would result in a higher uncertainty in the dose delivered due to eventual positional error of the film piece with respect to the source.

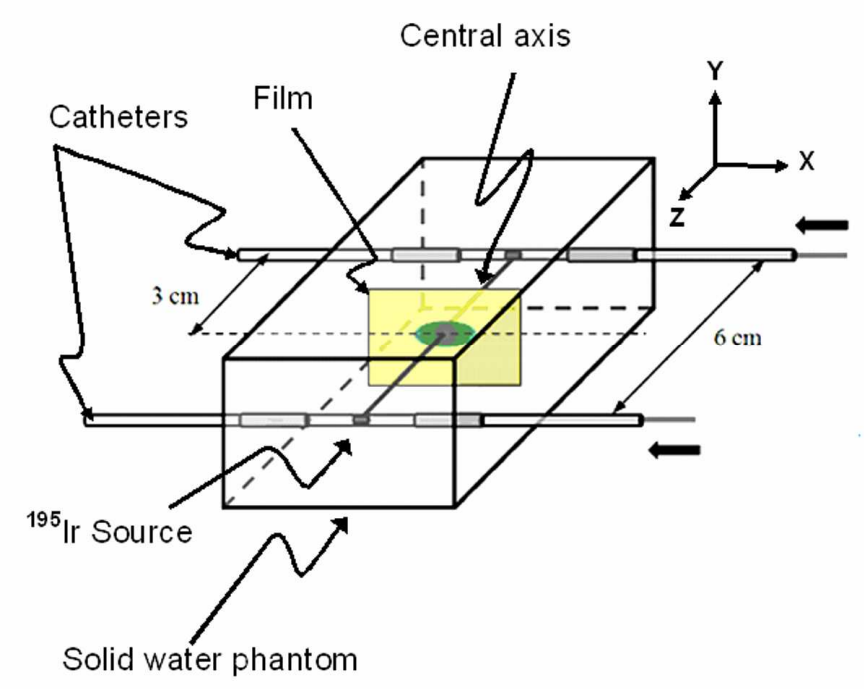


Fig.8. Schematic diagram of the solid water phantom used to irradiate the films at ^{192}Ir (Aldelaijan[24])

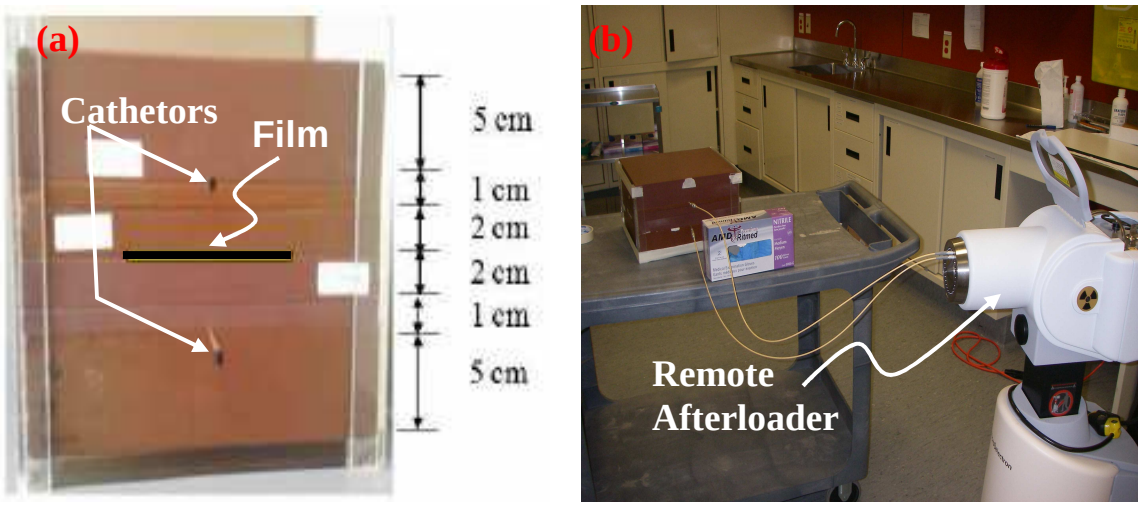


Fig.9. Film irradiation at ^{192}Ir. (a) Solid water phantom. (b) Film irradiation using Nucletron-Elekta remote afterloader.

The time needed to deliver a certain dose to water at the position of the film using the setup described above was investigated by Aldelaijan *et al*[28,29]for different source to film distances and ± 0.5% dose confidence region (homogeneity) using Oncetra treatment planning system (Nucletron-Elekta, Veenedaal, Netherland). They showed that for a source to film distance of 3 cm, a reasonable dose delivery time is achieved with approximately ± 0.5% dose confidence region of about 4×4×2 mm^3 in size.

For the purpose of film response energy dependence evaluation at ^{192}Ir: 1) the time needed to deliver 2 Gy to water at the position of the film using the film irradiation setup described above was determined using the Oncetra treatment planning system following the recommendations of the TG-43 dosimetry protocol[26]. 2) Film irradiation positional accuracy has a large impact on the accuracy of brachytherapy sources dosimetry, therefore, to ensure proper position and alignment of the sources and the film in the solid water phantom, we followed the stringent criteria and procedures suggested by Aldelaijan to insure positional accuracy.

C. Film Net Optical Density (netOD) Evaluation

In the following section, the methods used to scan and measure the film response, i.e. net optical density (*netOD*), due to exposure to ionizing radiation are discussed. The film scanning protocol has an impact on the accuracy and precision of the measured response of the film.[30]Therefore, it was necessary to adopt a certain scanning protocol and maintain the same film scanning procedures for all the film models tested in our work.

Following the procedure suggested by Devic *et al* [30] an Epson Expression 10000XL flatbed document scanner is used to scan all the film pieces used in our work; the technical details of the scanner can be found in the manufacturer website[‡]. It scans opaque or transparent samples with a color depth of 24 or 48 bits in the red-green-blue (RGB) color mode. The scanner uses a white florescent lamp behind a diffuser as a light source and a

[‡] http://www.epson.com

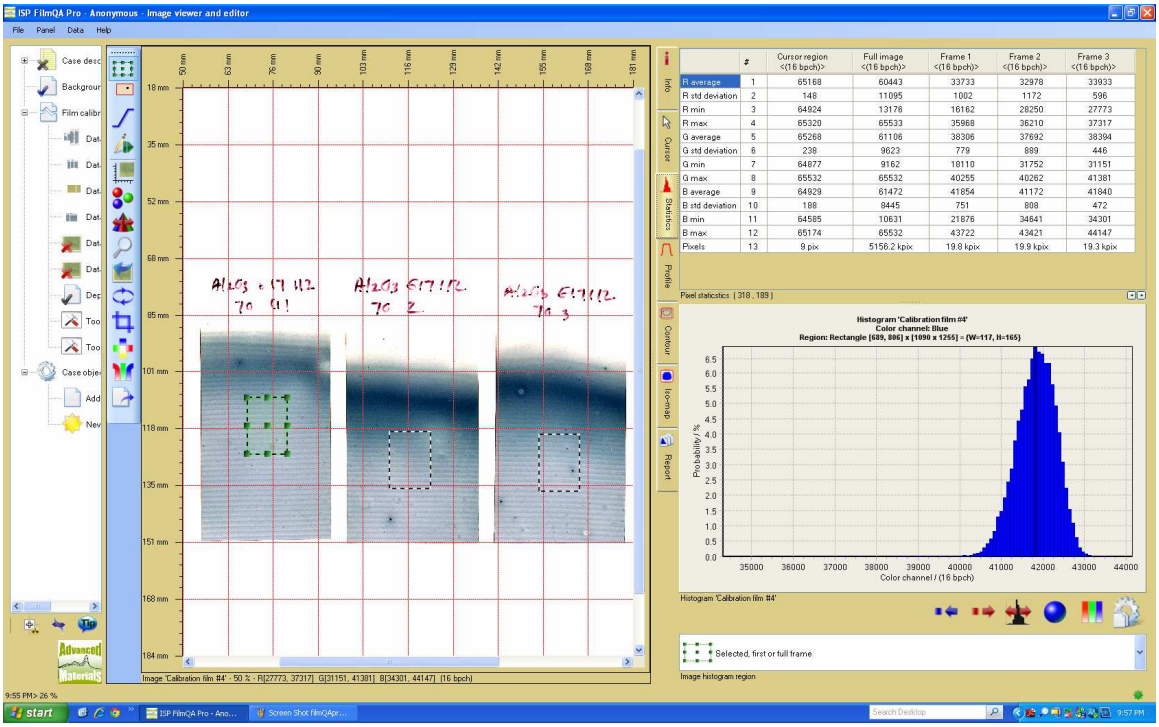


Fig.10. A screen shot of FilmQA Pro2011 shows the three films pieces that were irradiated at the same beam quality after irradiation. The histogram shows the pixel value distribution in the red channel over the ROI of film piece 1. The table shows the average pixel value and standard deviation in the three channels evaluated over the ROI of each film piece.

Charge Coupled Device (CCD) for light detection with three optical filters that split the incident light spectrum into three measurable wavelength bands corresponding to the red, blue and green colors. In our study, the film pieces were scanned in transmission mode using the Epson scanning software EPSON SCAN 3.01A. The scanning was performed with the maximum optical density range with all image enhancement features were turned off. The film pieces were scanned at 254 dpi which corresponds to 0.1 mm/pixel in the 48 bit RGB color mode (16 bit per channel), i.e. the maximum measured intensity in any channel corresponds to 2^{16}-1 (65535).

For film scanning, the three film pieces of the same film model that are irradiated at the same beam quality are aligned next to each other at the center of the scanning bed and scanned together before and after exposure to ionizing radiation and subsequently saved in Tagged Image File (TIF) format. To quantify the change in optical density due to the effects

of scanning light, visible light, temperature, humidity and other effects other than radiation we used the control film piece. The control film piece was handled in the same way as the irradiated film pieces, and was scanned at the same time with the film pieces that were irradiated before and after irradiation. Thus, for each film model, the scanning procedure resulted in two TIF images of the control piece before and after irradiation, and two TIF images of the three film pieces that are irradiated at each beam quality before and after irradiation. To avoid errors associated with the orientation of the film relative to the scanner, we preserved the orientation of the cut film pieces relative to the large uncut film sheet when aligned on the scanner. [31]

For film net optical density (*netOD*) evaluation, we used the response of the film in the red channel because it shows the highest sensitivity at the delivered dose of 2 Gy to water.[27,28]For pixel value readout in the red channel, we used the film manufacturer software FimQA Pro2011[§]. The software has the capability to extract the red, green and blue components of a GAFCHROMIC™ film image that was scanned in the RGB mode.

Figure 10 shows a snapshot of FilmQA Pro2011 that shows three film pieces of the same prototype that were irradiated at the same beam quality (the three pieces are numbered and identified by the beam quality and film prototype lot number and scanned together before and after irradiation). The first step in determining the response of each film piece is to determine a Region Of Interest (ROI) around the center of the film piece that coincides with the center of the radiation field. The ROIs are determined by the triangles in the snapshot and of typical dimensions of 15 mm wide × 20 mm length. Once the ROI is determined, FilmQA Pro2011 has the capability of determining the average pixel value and the standard deviation over the ROI in the red, green, and blue channels, display histograms showing the pixel value statistics over the ROI, and display cross profiles of the pixel value in the three channels.

For each one of the three film pieces that are irradiated at the same beam quality, the net optical density is calculated using the following equation

[§] www.filmqapro.com

$$netOD(D_w, Q) = \log_{10}\left(\frac{\overline{PV}_{bef}}{\overline{PV}_{aft}}\right) - \log_{10}\left(\frac{\overline{PV}^{C}_{bef}}{\overline{PV}^{C}_{aft}}\right) \tag{11}$$

Where $\overline{PV}_{bef}$ and $\overline{PV}_{aft}$ are the average pixel value in the red channel evaluated over the ROI of the irradiated film piece before and after irradiation, respectively; $\overline{PV}^{C}_{bef}$ and $\overline{PV}^{C}_{af}$ are the average pixel value in the red channel over the ROI of the control piece before and after film irradiation.

Also, a blue channel correction is applied to correct for variations in the response of each film piece due to nonuniformities in the thickness of the sensitive layer of the film.[26] The correction was performed by, first, calculating a blue channel correction (BCC) using the following formula

$$BCC = \frac{\sum_{i}^{N} \overline{PV}^{Bc}_{bef}}{N} \tag{12}$$

$\overline{PV}^{Bc}_{bef}$ is the average pixel value in the blue channel calculated over the ROI of each film piece of the same film model before irradiation and N is the total number of film pieces. Then, calculating the corrected netOD, $(netOD)_{corr}$, for each film piece using the following formula

$$(netOD)_{corr} = \frac{\overline{PV}^{Bc}_{bef}}{BCC} \cdot netOD \tag{13}$$

The uncertainty in the pixel value is evaluated using an error propagation formula that ignores cross correlation:

$$\sigma_y^2 = \sum_i \left(\frac{\partial y}{\partial x_i}\right)^2 \cdot \sigma^2_{x_i}. \tag{14}$$

Applying this formula on the expression of the *netOD*, the uncertainty in the *netOD* is given by

$$\sigma_{netOD} = \frac{1}{\ln 10}\left[\left(\frac{\sigma_{PV_{bef}}}{\overline{PV}_{bef}}\right)^2 + \left(\frac{\sigma_{PV_{aft}}}{\overline{PV}_{aft}}\right)^2 + \left(\frac{\sigma_{PV^c_{bef}}}{\overline{PV}^c_{bef}}\right)^2 + \left(\frac{\sigma_{PV^c_{aft}}}{\overline{PV}^c_{aft}}\right)^2\right]^{1/2} \quad (15)$$

The statistical uncertainty in equation 15 includes uncertainties due to film active layer nonuniformity, scanner inhomogeneity, and inhomogeneity in the irradiation field.

The net optical density at each beam quality is calculated as a weighted average of the net optical density of the three film pieces that were irradiated at the same beam quality

$$\Delta netOD(Q, D_w) = \frac{\sum_{i=1}^{3} \Delta netOD^i_{corr} / (\sigma^i_{netOD_{corr}})^2}{\sum_{i=1}^{3} 1/(\sigma^i_{netOD_{corr}})^2} \quad (16)$$

and the standard deviation is given by

$$\sigma_{netOD_{corr}} = \frac{1}{\sum_{i=1}^{3} 1/(\sigma^i_{netOD_{corr}})^2} \quad (17)$$

D. Investigating the film Extrinsic Energy Dependence, *f*(Q)

The absorbed dose to water or extrinsic energy dependence of the film, *f*(Q), investigation was performed using DOSRZnrc, which is one of the user codes of the EGSnrcMP (Electron-Gamma-Shower) Monte Carlo code.[21,21]The code simulates the transport of an electron or photon beam in a finite, right cylindrical geometry, and the energy deposited within various user defined regions is scored and analyzed statistically following the simulation. The transport of photons or electrons can be simulated in any element, compound or mixture. The code is used to calculate *f*(Q), i.e. the ratio of *dose to water* to *dose to the active volume of the film* using the experimental spectra, which for kVp beams were calculated using SpekCalc, an x-ray spectrum generating software, by matching the HVL, tube potential and added filtration of the experimental beams.[22] For the Monte Carlo

simulations conducted in our study, the setup and procedure are very similar to those used by Sutherland and Rogers[8] and our results were validated against their results.

To perform the simulations using DOSRZnrc, the user is required to setup two files: the material specific data file (.pegs4dat) and input file (.egsinp). The material specific data file used in all EGSnrc user codes is generated using the data preparation package, PEGS4. In order to generate the material specific pegs4 data file, PEGS4 uses another two files, a density file (.density) and inputs file (.pegs4inp) for each material to be used in the simulation, i.e. air, water, solid water, material used in the different layers of the film. The density file contains: 1) the density effect corrections and the mean ionization excitation potential, I(eV), of the material, which were obtained for the simulations performed in this study from the estar NIST data base[**], 2) the mass percent of the elements incorporated into each material. On the other hand, the input file (.pegs4inp) contains the electron threshold energies (AE and UE), which were set to .511 and 20.0 MeV, respectively, and photon threshold energies (AP and UP), which were set to 0.001 and 20.0 MeV, respectively, and the atomic numbers and mass percent of the elements incorporated into the material. Also, the following set of control parameters (EPSTFL, IRAYL, IAPRIM) were set to 1 in the input file (.egsinp), EPSTFL to use the density effect correction data and the mean ionization excitation potential from the provided density file, IRAYL to append the Rayleigh coherent scattering data to the PEGS data file, and IAPRIM to rescale the unrestricted radiative stopping powers to ensure that the data calculated by PEGS4 were identical to those calculated by Berger and Seltzer and included in ICRU Report 37; it is recommended that this option is turned on at low energies, because it makes a significant difference to the bremsstrahlung cross sections at those energies.[32,33,34]

The DOSRZnrc input file is divided into blocks of input parameters with values to be assigned by the user. Each block of parameters starts and ends with a control delimiter variable (:start control variable: and :end control variable:), which is a descriptive variable of

[**] http://www.nist.gov/pml/data/xraycoef/index.cfm/

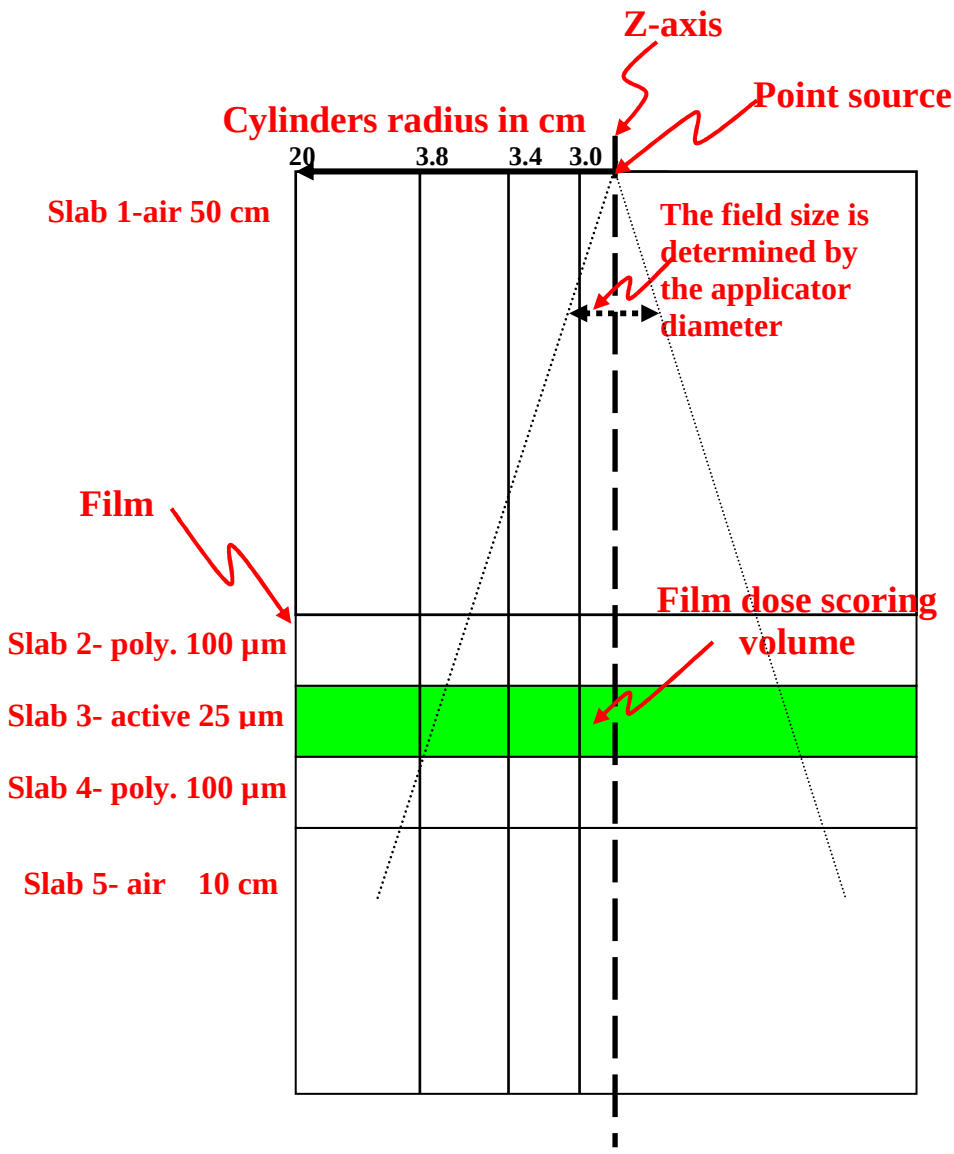


Fig.11. Geometry and grid used as input to DOSRZnrc to calculate the absorbed dose to water energy dependence of an EBT3 film geometry at orthovoltage beam qualities.

the code input parameters within that block. The important control delimiter variables are: input/output control, Monte Carlo inputs, geometrical inputs, source inputs, MC transport parameter, variance reduction and plot control. In the following, we discuss briefly the values of the different parameters within each delimiter block used in our simulations.

For the Monte Carlo inputs control, quantities of interest are calculated by averaging over a given set of MC particles, *N*, referred to as histories or showers, which is determined

by the user. As such, the Monte Carlo estimate of quantities of interest is subject to statistical uncertainty which decreases as $N^{-1/2}$. For the simulations performed in our work, we set the number of histories such that the statistical uncertainty in the dose to water or dose to film sensitive layer is ≤ 0.1%

For the input geometrical grid, the cylindrical geometry and grid used in the simulations are shown in Fig.11. The geometrical grid consists of slabs perpendicular to the z-axis determined by the z-coordinate and cylinders determined by the radius r. For in film simulations, the film is assumed to comprise the entire volume of the cylindrical geometry except for the first and last slabs which are air; the radius of the film active layer scoring volume is 3 cm. For in water simulations, the film material was replaced with water.

For the source inputs, a point source was assumed along the Z-axis and the field size on the front face of the first slab was determined based on the applicator diameter used at each orthovoltage beam qualities. The code also requires as an input, the corresponding spectrum for the point source, which was calculated using SpekCalc[34] by matching the measured HVL, tube potential and added filtration at each beam quality.

For the Monte Carlo (MC) transport parameters, ECUT (electron transport cutoff) and PCUT (photon transport cutoff) were set to 521 and 1 keV, respectively, and the following processes were switched on: Rayleigh scattering, photoelectron angular sampling, bound Compton scattering, radiative Compton corrections, electron impact ionization, spin effects and atomic relaxations. For the photon cross data, the default data from Storm and Israel have been used.[33]

The geometry of the simulations at ^{60}Co is very similar to that at orthovoltage beam qualities except that the film was placed between two solid water blocks. The simulations at ^{192}Ir for the EBT2 commercial film used in this study were performed by Sarfehina *et al.*[35]

E. Uncertainties Associated with Net Optical Density Determination and Absorbed Dose to Water Determination

The uncertainty in netOD determination is due to three sources

1. Statistical uncertainties associated with film active layer nonuniformity, scanner inhomogeneity, and inhomogeneity in the irradiation field, these uncertainties are included in equation 14.
2. Uncertainties associated with dose delivery such as uncertainties in the determination of the ionization chamber calibration coefficient and electrometer which have been taken out from the instruments calibration certificate, and uncertainties in different correction coefficients used in the equation to determine the dose to the reference medium from the chamber measurement.
3. Due to the structure of EBT films, photon attenuation in the polyester over laminate can have a significant impact on the response of the film at very low energies, which adds to the uncertainty in the netOD evaluation. The effect of photon attenuation on the response is discussed in section III.D, but was not taken into account in the energy response evaluation.

Monte Carlo calculations of the dose to water or film sensitive layer per unit incident photon fluence are performed by averaging over a given set of MC histories or showers and subject to statistical uncertainty which decrease as $N^{-1/2}$. For the simulations performed in our work, we set the number of histories such as the statistical uncertainty in the quantities of interest is ≤ 0.1%.

There are uncertainties associated with performing the irradiations in solid-water instead of water at ^{192}Ir and ^{60}Co. Due to the fact that the density of Solid water ≅ 1.035 the density of water, the dose at the depth of 5 cm in solid water will be slightly lower than 2Gy. However, the difference in the dose is much less than 1% and therefore no correction for the number of MUs or time to give 2Gy to water at the depth of 5 cm in solid water was used. At Ir-192, Aldelajin et al[28] used Monte Carlo simulation techniques to calculate a dose correction factor to convert the dose to water into dose to Solid Water™ and reported a correction factor $(D_{SW}/D_W)^{^{192}Ir}$ of 0.9808 ± 0.14%. Considering that ^{60}Co energy is much higher than ^{192}Ir, the correction will be even smaller at ^{60}Co.

III. RESULTS AND DISCUSSION

A. Experimental Evaluation of the Relative Energy Response, $S^{rel}_{AD,w}(Q)$, and Absorbed Dose to Water Energy Dependence, $f(Q)$, of Commercial EBT, EBT2 and EBT3

Figure 12 shows the results of the experimental evaluation of the relative energy response, $S^{rel}_{AD,w}(Q)$, i.e. the net optical density in the red channel due to ionizing radiation exposure at beam quality Q normalized to 1 at the response of ^{60}Co, of the three commercial EBT GAFCHROMIC™ dosimetry films, EBT-48022-07I, EBT2-A08161006 and EBT3-A07251102 (the solid curves)

$$S^{rel}_{AD,w}(Q) = \frac{netOD(Q, D_f)}{netOD(^{60}Co, D_f)} \tag{18}$$

$S^{rel}_{AD,w}(Q)$ is plotted as a function of beam mean energy. The figure reveals the following: 1)at energies < 100 keV, despite the fact that the EBT2 and EBT3 films differ in their geometries, the responses of the two films are similar and significantly different from the response of the EBT model. Both EBT2 and EBT3 film models show an over response of about 16% ± 4% at about 40 keV and an under response of about 27% ± 4% at 20 keV. While, the EBT shows an under response at all energies below 100 keV; it shows under response of about 39% ± 4% at about 20 keV.

The results of the corresponding Monte Carlo simulations of the inverse of the extrinsic energy dependence or inverse of the absorbed dose to water energy dependence, f^{-1}(Q), for the three lots are shown in Fig.12 (the dashed curves). The results reveal the following:

1. At low energies, f^{-1}(Q) of the EBT2 and EBT3 agree with each other, which confirms that for the EBT2 and EBT3 film geometries, the dose to the film sensitive layer at low energies is governed by the composition of the relatively thick 25 micron sensitive layer.[8]
2. At energies < 100 keV, there is a strong correlation between $S^{rel}_{AD,w}(Q)$ and the corresponding f^{-1}(Q) of the films. For the EBT2 and EBT3, the maximum response

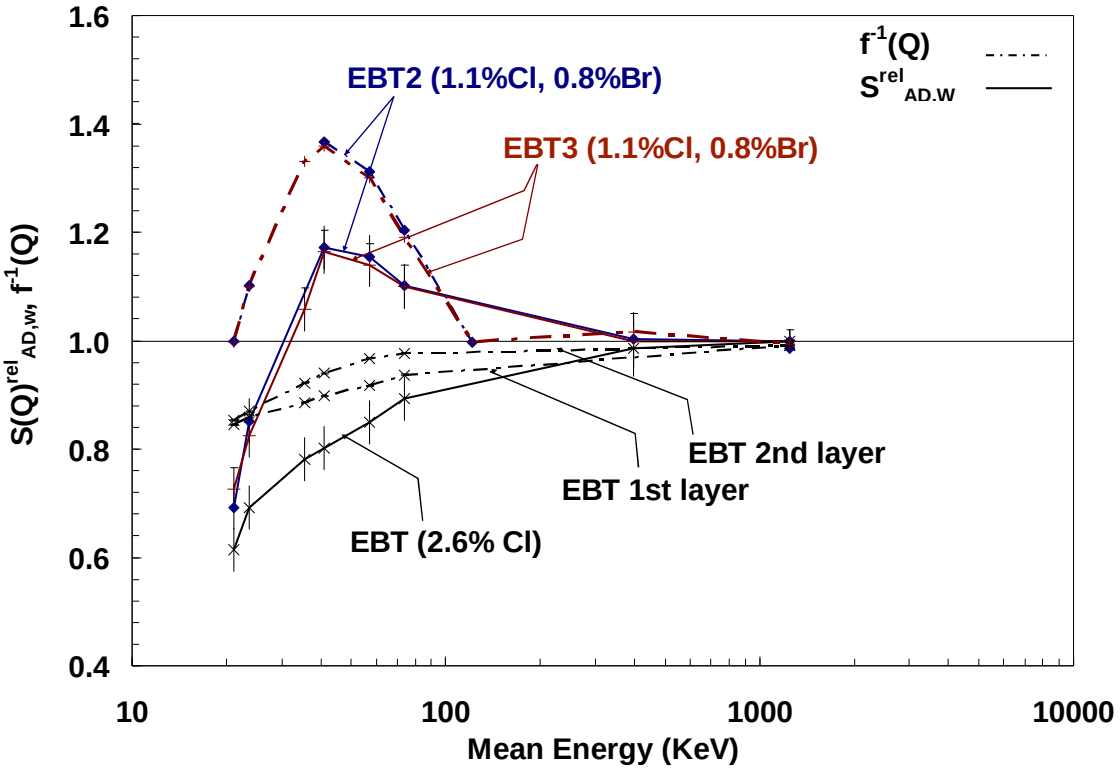


Fig.12. Relative response $S(Q)^{rel}_{AD,w}$ in the red channel and extrinsic energy dependence $f^{-1}(Q)$ of EBT-48022-07I, EBT2-A08161006, EBT3- A07251102 dosimetry film models.

of both films at about 40 keV coincides with the maximum dose to the film sensitive layer relative to water. For EBT, both $S^{rel}_{AD,w}(Q)$ and $f^{-1}(Q)$ decrease as the energy decreases.

3. For the EBT film model, the dose to the second sensitive layer relative to water is higher than that to the first sensitive layer in the energy range between ~30 and ~60 keV. However, the difference diminishes at about 20 keV and as expected at high energies. At very low energies ~ 20 keV, the majority of the electrons depositing their energy within the sensitive layer are created within that layer by the incident photon fluence spectrum and only a small fraction coming from the polyester or surface layer, which resulted in almost the same dose to the sensitive layer relative to water in both sensitive layers. At slightly higher energies, the

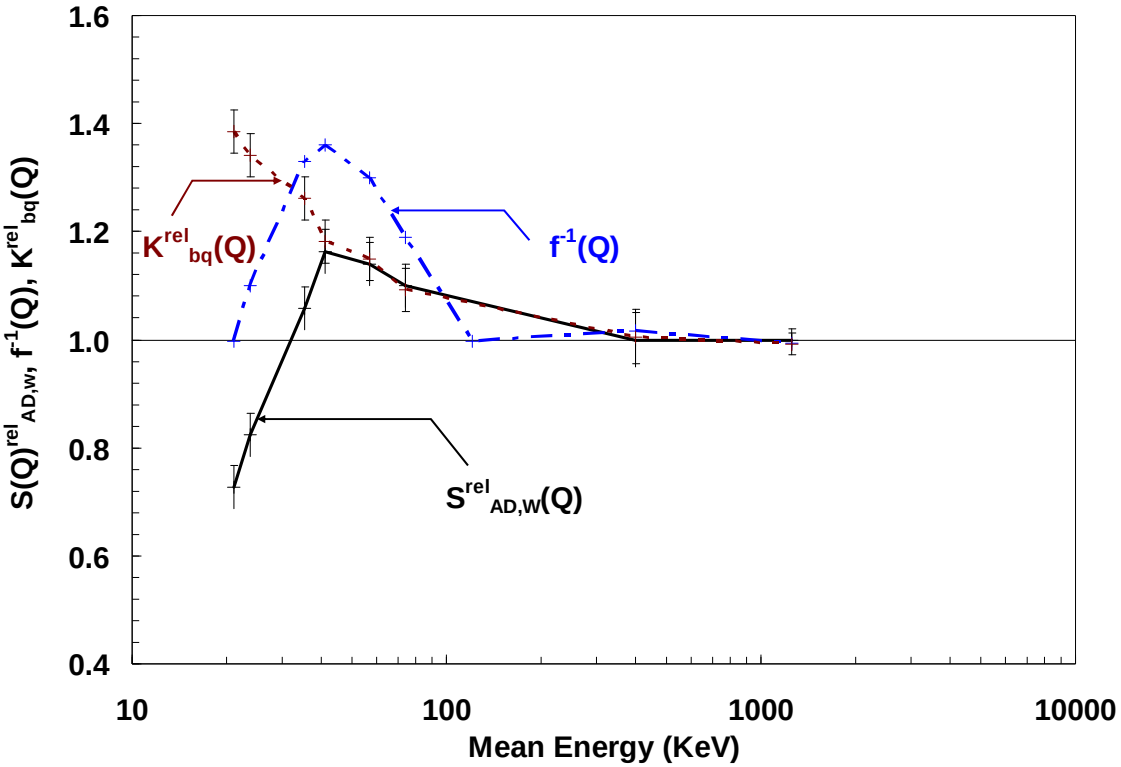


Fig. 13. The relative energy response, inverse of absorbed dose to water and relative intrinsic energy dependence of the commercial EBT3-A07251102 film model.

contribution to the dose to the second sensitive layer due to electrons created in the relatively higher atomic number surface layer increases, which resulted in a higher dose to the second sensitive layer relative to water compared to the first sensitive layer. At ^{60}Co, the majority of the dose to the sensitive layers is due to electrons created in the solid water phantom above the film resulting in almost the same dose being deposited in the two sensitive layers.

4. The intrinsic energy dependence of the film, $K_{bq}(Q)$, i.e. the dose to film sensitive layer per unit film response or net optical density in the red channel at beam quality Q, is clearly evident for the three films. In Fig.12, $f^{1}(Q)$ of the EBT2 or EBT3 film show that the dose to the active layer of the film at about 20 keV is almost equal to the dose at ^{60}Co and the EBT2 and EBT3 films are water equivalent at both energies. However, the films response at 20 keV is almost 27%

lower than that at ^{60}Co implying that the beam at about 20 keV is less effective in inducing a color change or polymerizing the active layer than at ^{60}Co. In general, if there is no intrinsic energy dependence, then , $S(\mathrm{Q})^{rel}_{AD,w}$, and the inverse of the relative absorbed dose to water, $f_{rel}^{-1}(Q)$, would be equal. Figure 13 shows the intrinsic energy dependence of the commercial EBT3 film model normalized at the intrinsic energy dependence at ^{60}Co and clearly shows that the intrinsic energy dependence increases as the energy decrease.

5. Both EBT2 and EBT3 show an over response at 40 keV despite the strong intrinsic energy dependence at that energy due to the high dose to the sensitive layer at about 40keV.

Comparing our results for f^1(Q) of the commercial EBT-48022-07I film model to the results of Sutherland and Rogers[8], despite the fact that the sensitive layer composition of the EBT film models used in both studies are almost the same, f(Q) of the EBT film model investigated in their results show a minimum at about 40 keV, where the dose to film is almost 10% higher than the dose to water. While for the EBT film model investigated in our study, the dose to film at about 40 keV is about 10% lower than the dose to water (note that Fig.12 shows f^1(Q) not f(Q)). As Sutherland and Rogers pointed out, the absorbed dose to water of the EBT film is affected by the geometries and compositions of the surface and polyester layers. The geometry of the EBT film model as opposed to the EBT2 and EBT3 is characterized by two relatively thin 17 micron sensitive layers separated by a thin 5 micron surface layer, Fig. 1. Due to this geometry, the contribution to the dose to the sensitive layer due to electrons from the surface layer can be significant depending on the energy of the incident photon fluence and composition of the surface layer. The surface layer of the EBT film model used in their study contained 16.8% Cl and its Z_{eff}=9.9, while in our study, the surface layer contained 6.10% Cl and its Z_{eff}=7.99, which resulted in their case in a larger enhancement of the photoelectric cross section of the surface layer relative to water (Z_{eff} water=7.42) around 40 keV and thus a higher dose being deposited in the second sensitive

layer of the EBT film relative to water due to electrons entering the sensitive layer from the surface layer.

Sutherland and Rogers compared the results of their study of the absorbed dose to water of the EBT film model and the results of three studies of the relative energy response of the EBT film model (Butson *et al.*[9], Rink *et al.* [10], Richter *et al.*[11]) and reported that the results of the three studies disagree with their results. They cited two reasons for the disagreement: 1) Intrinsic energy dependence in the energy response of the films which cannot be accounted for using the current Monte Carlo code, 2) the studies were conducted for different EBT film lots that possibly varied in their composition as reported by Lindsay *et al*[17]. On the other hand, the advantage our study has over previous studies is that the Monte Carlo simulations of $f(Q)$ were conducted for the same film lots used to experimentally evaluate $S(Q)_{AD,w}^{rel}$. Except for the intrinsic energy dependence which cannot be accounted for using the current DOSRZnrc Monte Carlo code, our study shows a strong correlation between the experimental evaluation of $S(Q)_{AD,w}^{rel}$ and the corresponding Monte Carlo simulations of $f^1(Q)$, and it allows for indirect evaluation of the intrinsic energy dependence, $k_{bq}(Q)$ using equation 4 as demonstrated by Fig. 13. Also, our results of the experimental evaluation of the energy response of the EBT film are in agreement with the results of Richter[11] and Ebert[16], which show significant energy dependence at low energies.

Butson *et al.* [18] investigated $S(Q)_{AD,w}^{rel}$ of a commercial EBT2 dosimetry film model in the energy range from 25.2 keV effective energy (50 kVp) to 2.2 MeV effective energy (10MV), and reported an energy dependence of 6.5% ± 1%. The shape of the energy response curve of the EBT2 film model investigated in their study is similar to the shape of the EBT2 film investigated in our study. It shows a peak between 30 and 40 keV, then drops below 1 at about 25 keV. However, the amplitude of the peak is lower than the amplitude of the peak in our study. The discrepancy could be due to differences in the composition of the sensitive layers of the films combined with the fact that they used a different experimental setup and different dosimetry protocol at low energies. Lindsay *et al.*[17] investigated the

energy dependence of three EBT2 film models at one orthovoltage beam quality (105 kVp, 3.5 mmAl) and reported that the energy response varied from 0.75 to 1.2 depending on the concentration of Br, Cl and K in its sensitive layer. This is in agreement with our results which show an over-response of about 1.2 around 40 keV (Fig. 12), the sensitive layer of the EBT-2 film model used in our study contained 0.8%Br, 1.1%Cl.

Many studies have argued that making the film water equivalent at low energies would reduce the energy dependence of the film. The absorbed dose to water energy dependence curve of the commercial EBT2 and EBT3 reveal that the film is water equivalent at about ^{60}Co and 20 keV, i.e. the absorbed dose to water is equal to 1 at both energies, however, the response of both films shows under response of about 27% at 20 keV. Thus, clearly shows that making the film water equivalent wouldn't solve the problem of energy dependence at low energies. On the other hand, the fact that the EBT2 and EBT3 films show over response at 40 keV despite the intrinsic energy dependence tells us that the intrinsic energy dependence in principle could be compensated for by careful adjustment of the film sensitive layer composition.

B. The Effect of Film Elemental Composition on the Absorbed Dose to Water Energy Dependence, $f^1(\mathrm{Q})$, and Film Response, $S(\mathrm{Q})^{rel}_{AD,w}$.

Sutherland and Rogers[8] investigated $f(\mathrm{Q})$ of two commercial EBT2 film lots that varied in the composition of the film active layer. Their study showed that in the energy range below 100 keV for both EBT2 film models, the shape of $f(\mathrm{Q})$ follows closely the corresponding ratio of the mass energy absorption coefficient curve, $(\mu_{en}/\rho)^{film\_Active}_{w}$. On the other hand, our study showed strong correlation between $f^1(\mathrm{Q})$ and the corresponding $S(\mathrm{Q})^{rel}_{AD,w}$. Thus for EBT2 and EBT3 film geometries, the variation in the energy response curve at energies below 100 keV, ignoring the intrinsic energy dependence, can be explained to first order by

examining the shape of the ratio of the mass energy absorption coefficients of the elements incorporated into the film active layer to water $(\mu_{en}/\rho)_w^Z\Big|_{h\nu}$.

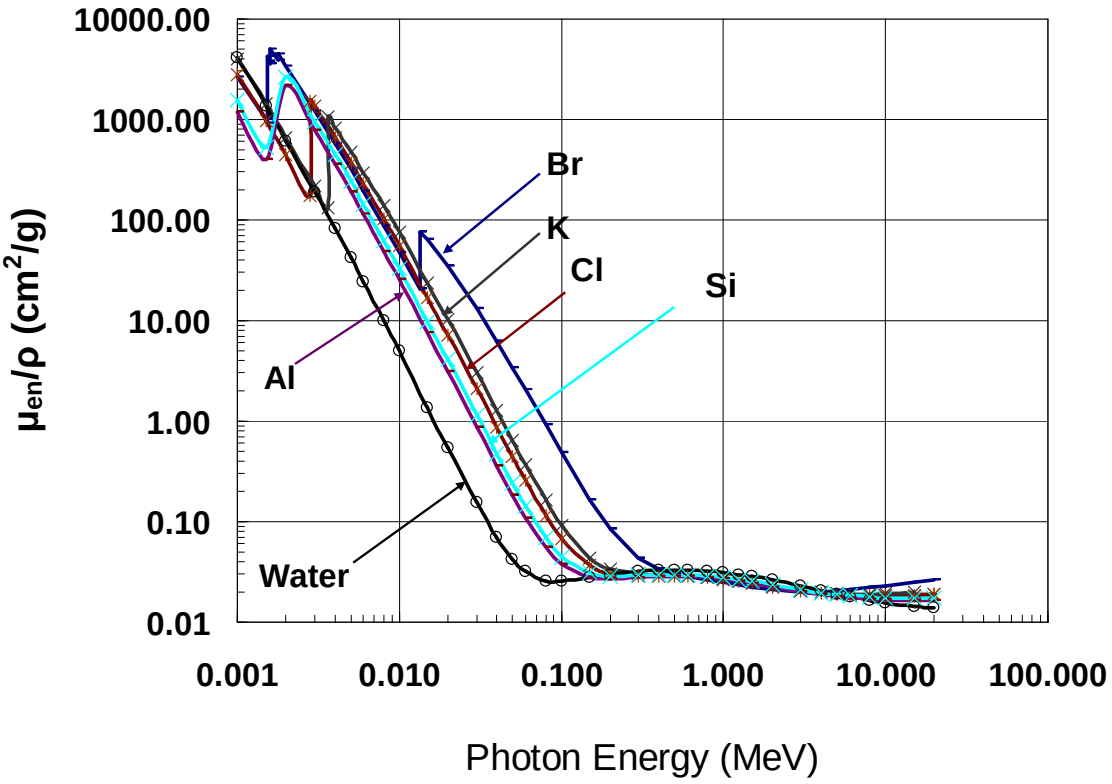


Fig .14. The mass energy absorption coefficients H2O, Na, Al, K, Cl and Br (NIST X-ray Attenuation Databases).

Table 1 lists the mass percent of the elements incorporated into the different layers of the three commercial films investigated in our study (Fig.12). Elements such as Al, Si, Cl, K and Br can be added or removed from the active layer. However, the addition or changing the mass percent of an element must be done with constraints (Dave Lewis at ASHLAND, private communication). To demonstrate the effect of the elemental composition on the absorbed dose to water and energy response of the films, Fig.14 and 15 show $(\mu_{en}/\rho)_z$ and $(\mu_{en}/\rho)_w^z$ of Aluminum (Al, Z=13), Chlorine (Cl, Z = 17), Potassium (K, Z = 19) and Bromine (Br, Z = 35). The following can be concluded from the figure:

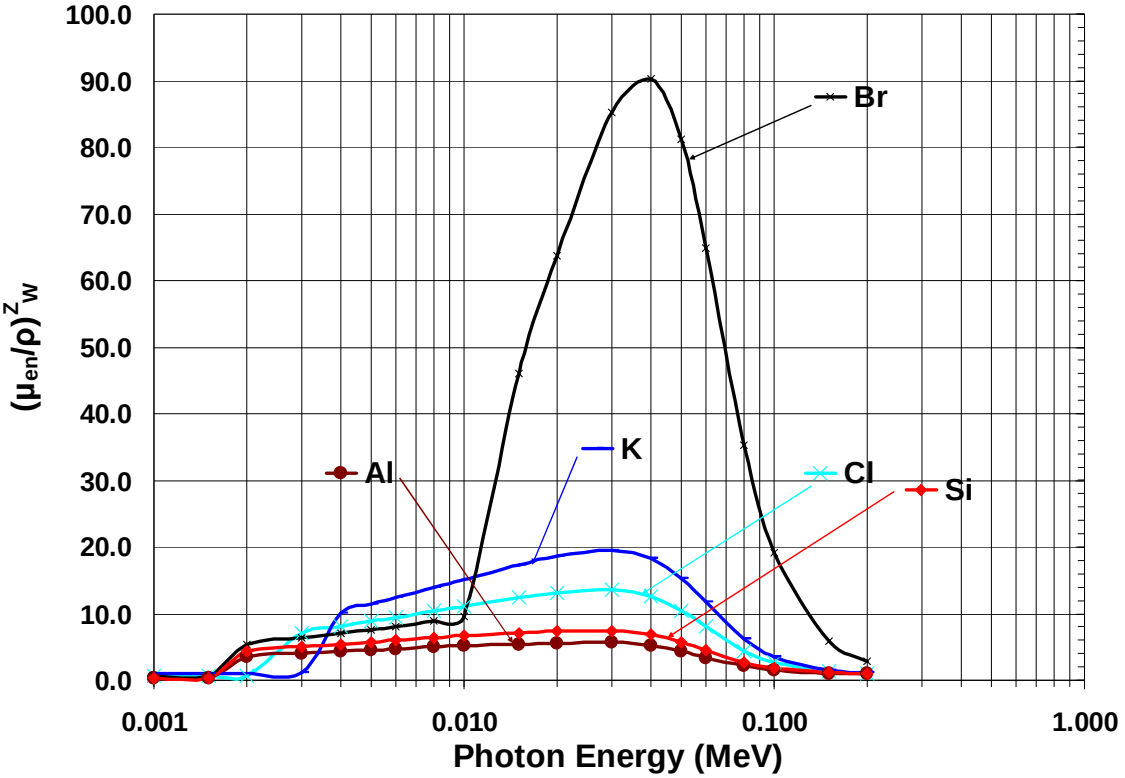


Fig.15. The ratio mass-energy absorption coefficients $(\mu_{en}/\rho)_w^z$ of Al, Cl, K and Br as a function of photon energy in MeV (NIST X-ray Attenuation Databases).

1. Bromine has a K absorption edge at 13.5 keV as a result $(\mu_{en}/\rho)_w^{Br}$ increases from about 10 at 10 keV to a maximum of 90 at 40 keV, then drops to about 20 at 100 keV. Thus, the inclusion of an element like Br in the sensitive layer even by a small amount will result in a much higher dose to the sensitive layer of the film relative to water at energies around 40 keV than energies around 10 or 100 keV.
2. The sharp drop in $(\mu_{en}/\rho)_w^z$ below 4 keV for Potassium and below 3 keV for Chlorine is due to the absorption edges in the vicinity of these energies. At energies above 4 keV, the increase in $(\mu_{en}/\rho)_w^{el}$ for K and Cl is not as sharp as that for Br. For K, it increases from 10 at 4 keV to a maximum of 20 at 30 keV, then drops to about 5 at 100 keV. For Cl, it increases from 8 at 3 keV to a maximum of 14 at 30 keV, then drops to about 5 at 100 keV.

3. $(\mu_{en}/\rho)_w^{Al}$ of Aluminum is almost flat and varies from about 3 to 5 in the energy range from 3 to 60 keV. Note that $(\mu_{en}/\rho)_w^{Si}$ of Silicon (Si, Z=14) exhibits a behavior similar to that of Al.

Based on the above results we can make the following conclusions

1. The high dose to the active layer relative to water at about 40 keV which resulted in a peak in the response curves of EBT2-A08161006, EBT3- A07251102 (Fig.12) is mainly due to the incorporation of Br (0.8%) into the active layer of the film, which resulted in a large enhancement of the photoelectric cross section of the film active layer relative to water and a larger dose to the film active layer at about 40 keV. This is in agreement with the results of Sutherland and Roregrs[8] for the EBT2-020609, which contained 1.7% Cl, 0.6% K, 1.3% Br and shows a very high dose to film sensitive layer relative to water at about 40 keV.
2. The addition of Chlorine or Potassium will boost the dose to the sensitive layer of the film relative to water in the energy range from 4 to 70 keV, which should improve the energy response of the film at those energies. However, the dose to the film active layer relative to water will reach a maximum at about 30 keV due to the peak in the ratio of the mass energy absorption coefficients at that energy; this will result in a higher response at 30 keV than at lower energies, which would results in a lower limit below which we won't be able to reduce the energy dependence. This conclusion is also in agreement with the results of Sutherland and Rogers for the EBT2- LOT031109 which contained 2.3% Cl, 1.3% K and shows a peak in the dose to film sensitive layer relative to water at about 30 keV.
3. The near flat mass-energy absorption coefficients ratio for elements such as Aluminum or Silicon in the energy range from 6 to 50 keV will result in a higher dose to the film active layer relative to water and almost the same dose being deposited in the active layer in that energy range. However, bringing the dose up to a level such that the intrinsic energy dependence is being adequately compensated for compared to

commercially available films may require a high percentage of Si or Al being incorporated into the active layer of the film.

C. Reducing the Energy Dependence of the Film Response at Low Energies by Adjusting the Composition of the Sensitive Layer

The above results demonstrated that the EBT2 and EBT3 GAFCHROMIC™ dosimetry films show strong intrinsic energy dependence at energies below 100 keV. If there is no intrinsic energy dependence, then making the film water equivalent at low energies by adjusting the sensitive layer composition at low would also make the response energy independent. However, because of the strong intrinsic energy dependence, we are left with two options to reduce the energy dependence of the film response at low energies

1. Improving the polymerization efficiency of the active layer of the film upon exposure to ionizing radiation at low energies.
2. Boosting the dose to the film active layer at very low energies where the film is showing under-response and lowering it at energies where the film shows over-response.

The first option involves chemistry to create a film with improved intrinsic energy dependence, i.e. the radiation polymerization efficiency is almost same at all beam qualities. This might involve increasing the density of the radiation sensitive centers in the active solution, which might be difficult to achieve. The second option involves adjusting the film active layer composition. In particular, the fact that both commercial EBT2 and EBT3 show an over-response at about 40 keV despite the strong intrinsic energy dependence at that energy make us conclude that the low response of the film at very low energies could be improved by boosting the dose to the film sensitive layer by adding or changing the mass percent of elements such as Al, Si, Cl and K; and the high response of the film at 40 keV can be reduced by lowering the mass percent of Br or dropping it from the active layer.

However, while it is possible to boost the dose or lower it by adjusting the composition of the film sensitive layer, the adjustment must be done with constraints to preserve physical properties of the film. On the other hand, the only way to know whether or

not the intrinsic energy dependence can be adequately compensated for by boosting the dose at very low energies is to make new prototypes with the recommended possible compositions, and then experimentally test them for energy dependence. In the following sections, we demonstrate the effect of adjusting the composition of the film sensitive layer on the absorbed dose to water and energy response of the film.

1. The Effect of Cl and Br on the Absorbed Dose to Water, f(Q), and Relative Energy Response, $S(Q)^{rel}_{AD,w}$, of the Film

In this section the effect of adding Cl or Br on the energy dependence of GAFCHROMIC™ films at low energies is demonstrated by examining the response of 4 prototypes that were made by the manufacturer of the film, ASHLAND, for that purpose. Fig. 16 is the same as Fig.12 but shows the results of investigating the energy response and Monte Carlo simulations of the absorbed dose to water of the four EBT2 film prototypes and, for comparison, the results of commercial EBT2 are included. The prototypes varied in the mass percent of Cl or Br: 1) contains no Br or Cl (a control film), 2) contains 4% Cl but no Br, 3) contains 0.1% Br but no Cl, and 4) contains 4% Cl and 0.06% Br. The figure reveals the following:

1. The intrinsic energy dependence is clearly evident. Although the doses to the active layers of the prototypes with 4% Cl and with (4% Cl, 0.06% Br) at about 20 keV are slightly higher than the dose at ^{60}Co, the response is about 20% lower than that at ^{60}Co. However, the response of these prototypes at 20 keV is slightly higher than that of commercial EBT2 which contains 1.1% Cl and 0.8% Br.
2. Comparing the EBT2 prototype with 4% Cl to the control film and commercial EBT2 demonstrates that the addition of 4% Cl resulted in a higher dose to the film active layer relative to water at lower energies, which resulted in an improvement in the energy response at those energies. However, the increase in the dose at low energies was not sufficient to adequately compensate for the

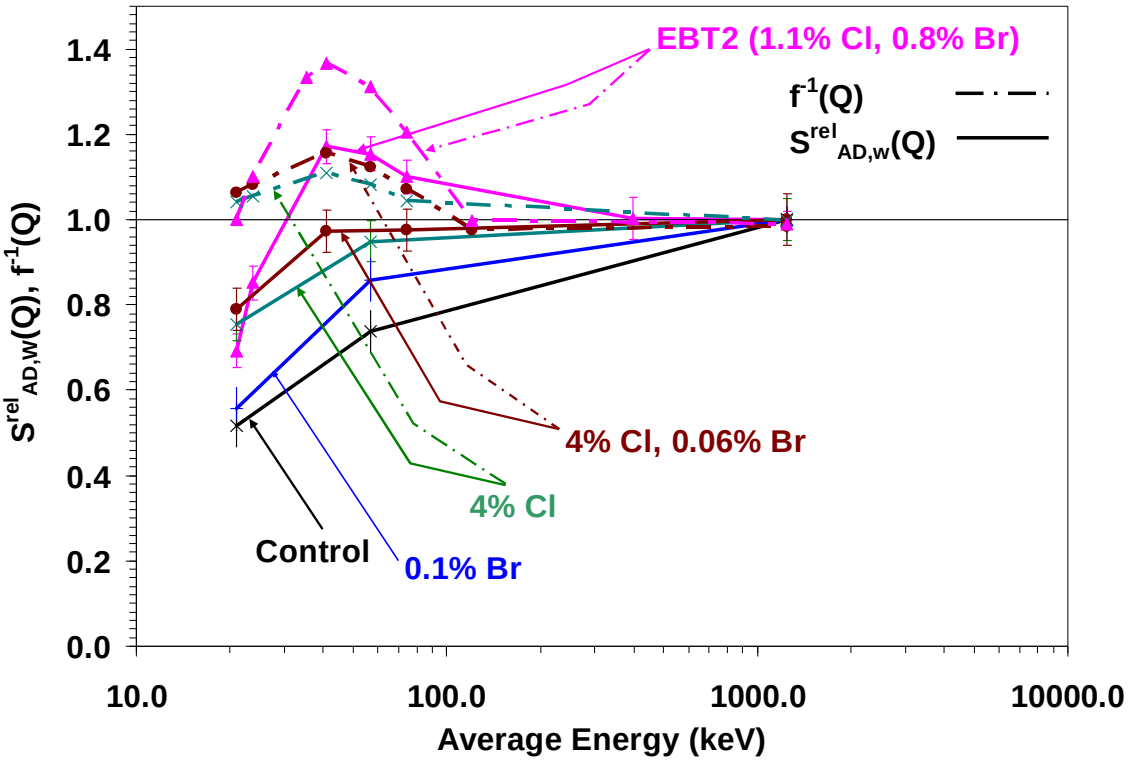


Fig.16. Energy response and absorbed dose to water of 4 prototypes that varied in the mass percent of Chlorine or Bromine

intrinsic energy dependence as evident from the under response of the prototypes with 4% Cl.

3. The effect of dropping or reducing the mass percent of Bromine on the response of the film is clearly evident in Fig.16.
   - Compared to commercial EBT2, the two prototypes with 4% Cl no longer show an over response at about 40 keV, despite the high mass percent of Cl.
   - The response of the prototype with 0.1% Br demonstrate that the reduction of the mass percent of Br from 0.8% in commercial EBT2 to 0.1% removed the over-response of the film around 40 keV and also reduced the energy dependence around that energy.

2. The Effect of Increasing the Mass Percent of Cl and Reducing the Mass Percent or Dropping Bromine on the Energy Response of the Film

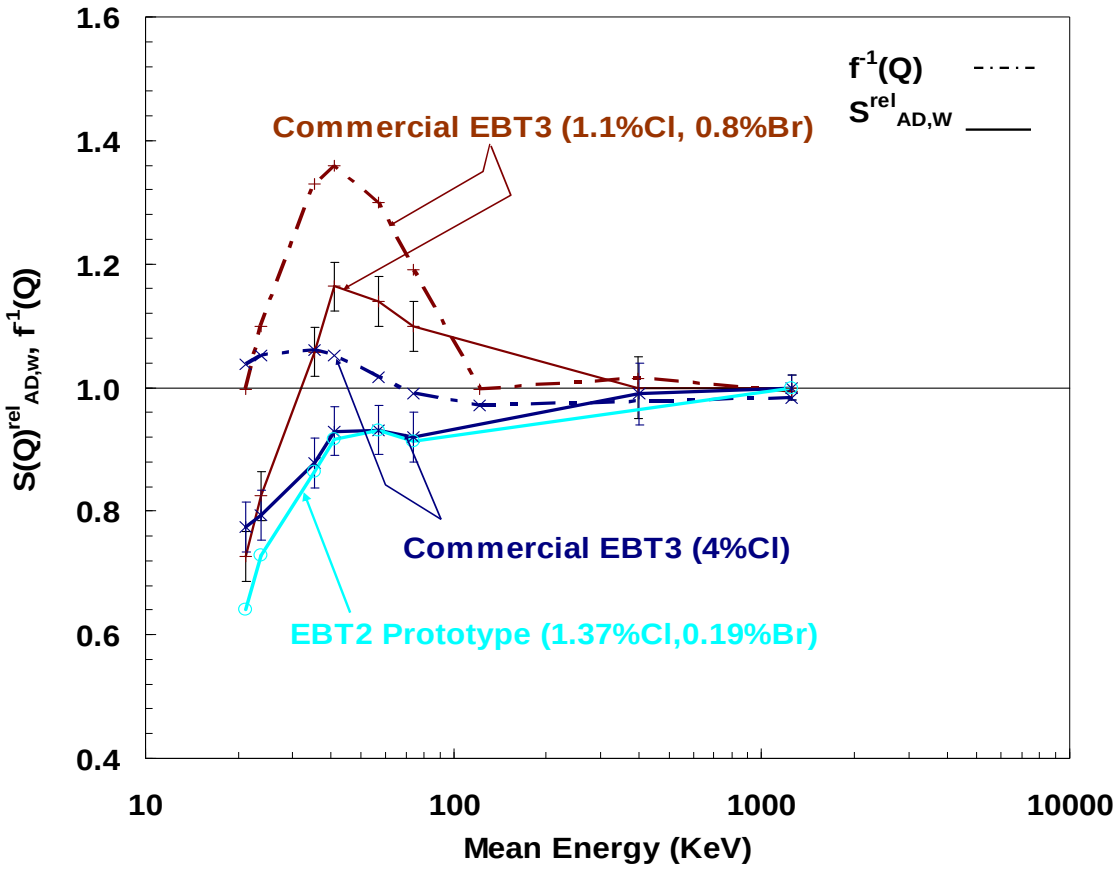


Fig. 17. The energy response of commercial EBT3- A03051204 with 4%Cl and no Br.

Based on our conclusions, the manufacturer decided to drop Bromine and increase the mass percent of Chlorine to 4% in recent commercial EBT3 lots. Fig. 17 shows the energy response and absorbed dose to water of a commercial EBT3-A03051204 which contains 4% Cl and no Bromine. The addition of 4% Cl and dropping Br eliminated the over response at 40 keV and in general reduced the energy dependence of the response compared to commercial EBT3 with 0.8%Br and 1.1%Cl. The new film shows under response at all energies below 100 keV; it shows under response of 22% at 20 keV and 6% at about 40 keV. However, the addition of 4% Cl, wasn't very effective in improving the energy response at

20 keV. Also, according to the manufacturer, the addition of more Chlorine made the sensitive layer of the film more hydroscopic which may affect the sensitivity and response of the film.

Also, the figure shows the energy response of an EBT2 prototype is which the mass percent of Bromine was reduced to 0.19% and the mass percent of Cl was increased to 1.38%. Its response again confirms that the reduction of the mass percent of Br eliminated the over response at 40 keV. On the other hand, the combination (1.38%Cl, 0.19%Br) is less effective in boosting the dose at about 20keV than (1.1%Cl, 0.8%Br) or 4%Cl. These results demonstrate the need of adding a high percentage of lower atomic number elements such as Si or Al in order to boost the dose at very low energies.

3. The Effect of Adding Si or Al in addition to Cl and K on the Energy Dependence of the Film

In this section we demonstrate the effect of adding lower atomic number elements such as Al or Si in addition to Cl and K. Fig. 18 shows the absorbed dose to water of 4 hypothetical EBT3 films that contains: 1) 7.5% Si with no Cl or K; 2) 4%Al, 2.5%Cl and 1.17%K; 3) 4%Si, 2.5%Cl and 1.17%K; 4) 7.3%Si, 2%Cl. Note that the mass percent of Chlorine to Potassium must be 3 to 1 (Dave Lewis, personal communication).

1. Since Potassium is slightly higher atomic number than Chlorine, a small amount of Potassium will be more efficient in boosting the dose at about 30 keV than Cl (See figure 14). Thus, we can make the film less hydroscopic by combining Cl with K.
2. The figure reveals that the addition of Aluminum or Silicon would result in a more uniform dose to the sensitive layer in the energy range from 20 keV to 30 keV, which makes these two elements more suitable for improving the energy dependence at low energies than Cl.

Fig. 19 shows the energy response of a prototype that was made by the manufacturer to test the effect of Si on the film response. It shows a reduction in the energy dependence

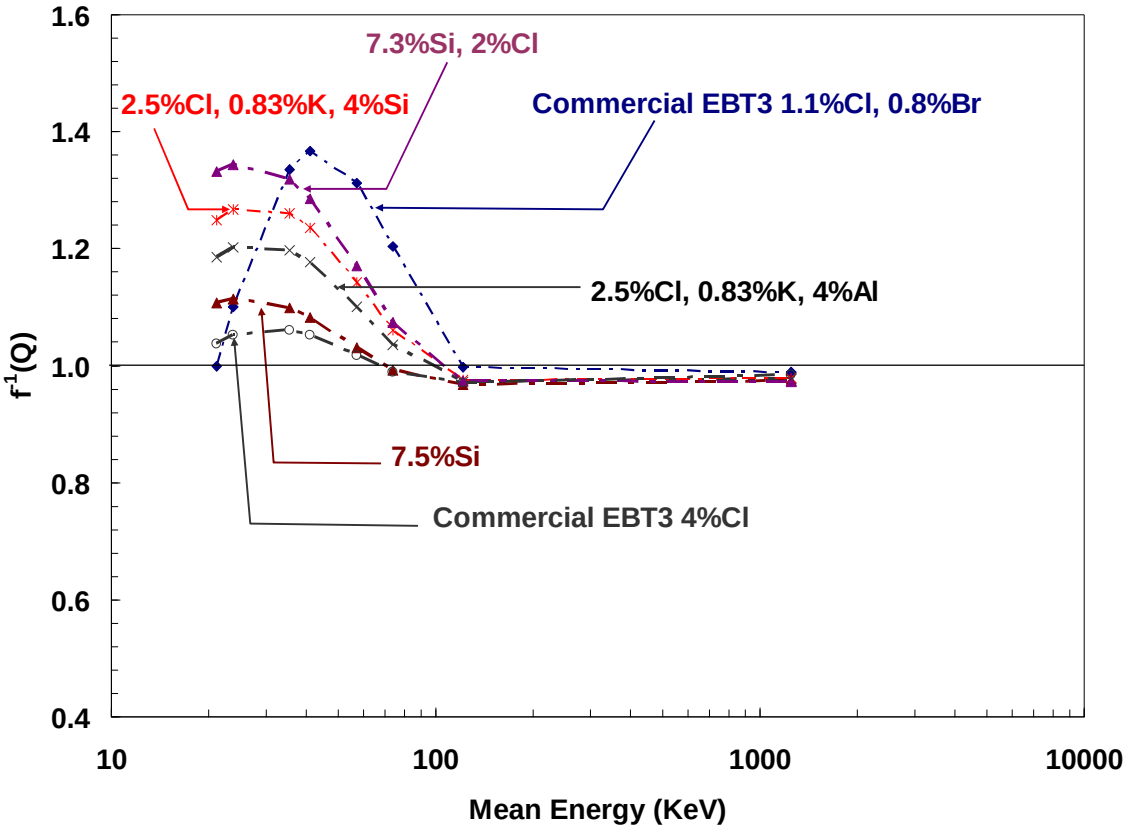


Fig. 18. The effect of adding Al or Si in addition to Cl and K on the absorbed dose to water energy dependence of the film.

compared to commercial EBT3 with 4% Cl; the prototype shows under response of 15% ± 5% at about 20 keV to 2% ± 5% at about 40 keV. Unfortunately, according to the manufacturer, the active solution with 7.5% Si turned out to be chemically unstable and tends to separate later which affected the viscosity of the solution and the ability to being used later in commercial machine coating. For this reason, the manufacturer is trying now to incorporate Aluminum instead of Silicon into the sensitive layer of the film. However, while improving the response at about 20 keV is possible by dropping Bromine or even Chlorine and increasing the mass percent of Al as much as possible to boost the dose to the sensitive layer at very low energies, the film response will always peak at about 40 keV. Thus, the reduction in the energy dependence of the response at low energies by adjusting the film sensitive layer composition is an interplay between increased intrinsic energy

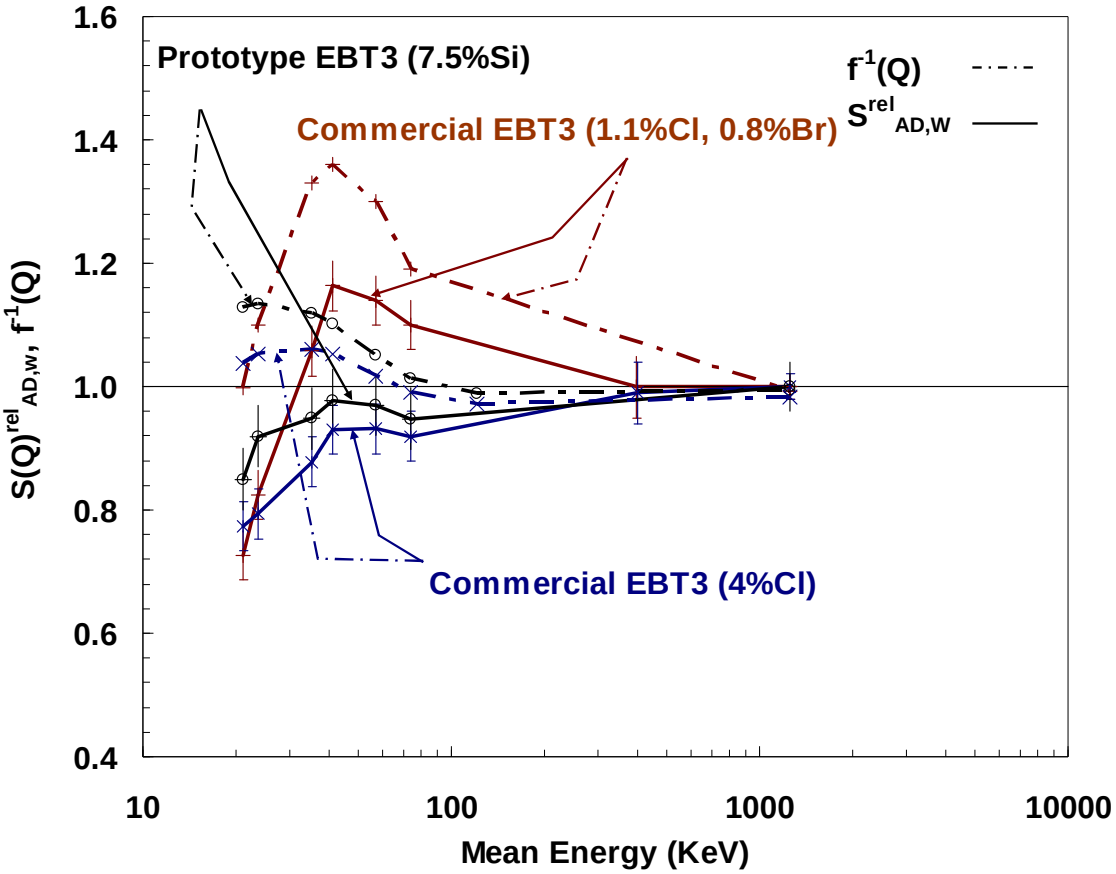


Fig. 19. The energy response of an EBT3 prototype with 7.5% Si and no Cl or Br.

dependence as the energy decreases and the over response of the film at about 40 keV as we try to compensate for the strong intrinsic energy dependence at very low energies by increasing the mass percent of Al.

D. The effect of the Thickness of the Polyester Layer on the Response of the Film at low energies

Photon attenuation in the polyester over laminate layer on the top of the sensitive layer can have an impact on the response of the film at very low energies. The effect of the thickness of the polyester over laminate layer on the response of the film at low energies is investigated by experimentally evaluating the response of three film prototypes that have the same active layer composition but varied in the thickness of the polyester over-laminate: 1) naked film,

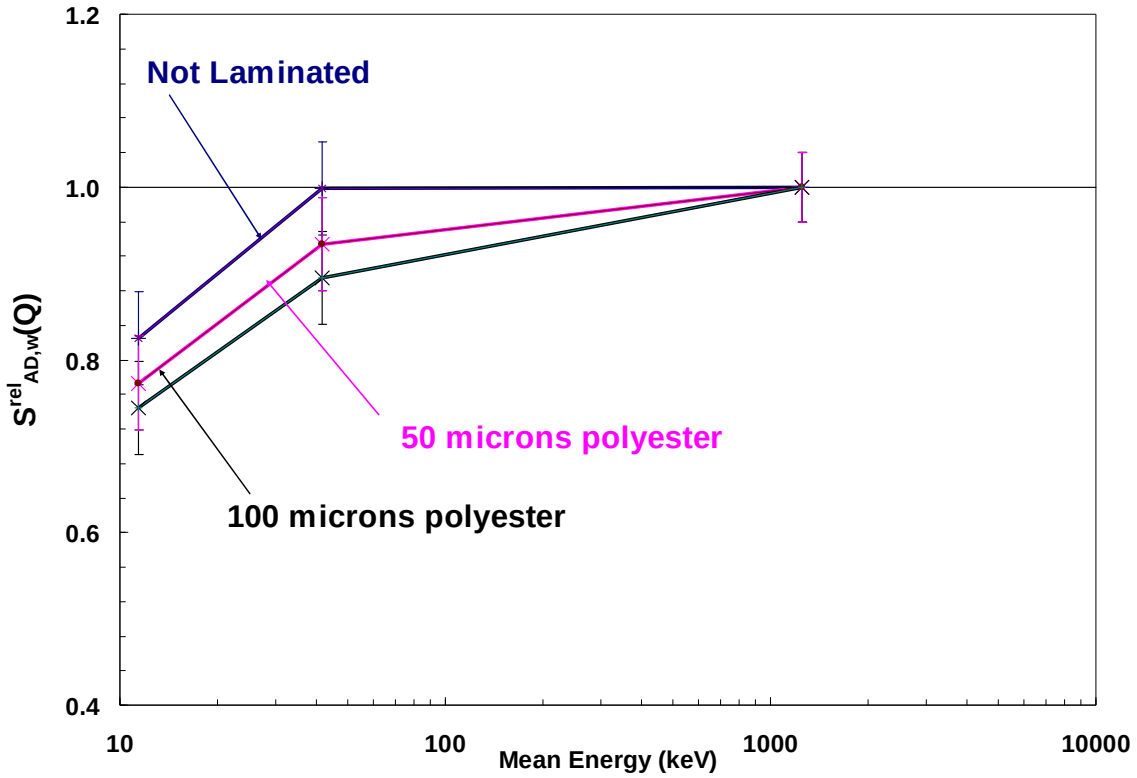


Fig. 20. The effect of the thickness of the polyester over laminate on the relative response of the film.

2) 50 μm polyester over laminate, 3) 100 μm polyester over laminate. The relative response of the films is shown in Fig. 20; the response of the films at different beam qualities where normalized to 1 at the response of ^{60}Co. These films were only tested at three beam qualities (50kVp, 0.16 mmAl HVL; 120kVp, 4.19 mmAl HVL; ^{60}Co) due to the small size of the film sheets received from the manufacturer. At 50 kVp and 120 kVp, the films were irradiated in air at 30 cm from the end of the 20 cm circular cone applicator.

The response curves show that the polyester thickness has an impact on the response of the film at low energies. At 50 kVp (0.16 mmAl) , which is a very soft beam, the response of the100 micron polyester over laminate is 9% lower than the naked film and 2% lower of the 50 micron over laminate film. At that energy, the dose to the naked film is due mainly to electrons that were created in the relatively thick 25 micron sensitive layer by the incident photon fluence spectrum and a small fraction is due to contamination electrons from the

applicator and air. On the other hand, the over laminated films are thick enough to stop most of contamination electrons at 50 kVp, and most of the dose is due to electrons that were created within the sensitive layer and only a small fraction is due to electrons that were created in the polyester and deposit part of their energy in the sensitive layer. Thus, the difference in the response of the two over laminated films at 50 kVp is due to increased photon attenuation with polyester thickness. At 120 kVp (4.19mm Al), the response of the film with 50 micron polyester over laminate is 2% higher than the film with 100 micron . At this energy, it is not expected that photon attenuation to play a role in the difference in the response of the laminated films; and the difference is mainly due to contamination electrons that manage to reach the sensitive layer of the film with 50 micron in a higher percentage than the film with 100 micron polyester over laminate. However, the effect of photon attenuation on the response at very low energies was not corrected for in our study.

IV. Conclusions

Many studies have investigated the energy dependence of External Beam Therapy (EBT) GAFCHROMIC™ dosimetry films and show that the different EBT film models are water equivalent down to about 100 keV and their response is energy independent down to about 100 keV. The purpose of our study was to develop a new prototype with a more uniform energy response at low energies (≤ 100 keV). Our study was comprised of two components. The first one was experimentally evaluating the energy response, $S(Q)^{rel}_{AD,w}$, of three commercial EBT GAFCHROMIC™ dosimetry films that represents the three different film configurations that have been manufactured up to date, and then investigating the corresponding absorbed dose to water energy dependence of the films, f (Q), using Monte Carlo Simulation techniques and the experimental spectra. The first component helped us understand the physics behind the energy variation as well as the intrinsic energy dependence at low energies. The second component was to adjust the film sensitive layer composition to reduce the energy dependence of the film response at low energies with guidance of Monte Carlo simulations of f(Q) of the film and making new film prototypes based on the new

possible elemental compositions, then experimentally testing the new prototypes for energy dependence of the response. The following can be concluded from our study

1. Both commercial EBT2 and EBT3 film models show an over response of about 16% ± 4% at about 40 keV and an under response of about 27% ± 4% at 20 keV. While, the EBT film model shows an under response at all energies below 100 keV, which increases as the beam energy decreases; the under response is 39% ± 4% at about 20 keV
2. $S(\mathrm{Q})^{rel}_{AD,w}$ of commercially available film models at low energies show strong correlation with the corresponding $f^{1}(\mathrm{Q})$. For both EBT2 and EBT3, the maximum response of both films at about 40 keV correlates with the maximum dose to the film sensitive layer relative to water. For the EBT film model, the dose to film is lower than the dose to water and the film shows under response at all energies < 100 keV; both the absorbed dose to water and energy response curves decrease as the energy decreases.
3. While the intrinsic energy dependence of the film cannot be calculated directly using available Monte Carlo codes, it can be estimated from our evaluation of the relative response and the corresponding relative absorbed dose to water of the film at each beam quality. Our study reveals that commercial films show strong intrinsic energy dependence at low energies, i.e. for the same dose to the reference medium, the efficiency of film polymerization or the ability of the beam to induce a color change decreases as the energy of the radiation beam decreases. If there is no intrinsic energy dependence, then the relative energy response of the film, $S^{rel}_{AD,w}(Q)$, and the corresponding inverse of the relative absorbed dose to water energy dependence, $(f^{rel}(Q))^{-1} = f(^{60}Co)/f(Q)$), would agree with each other; and making the film response energy independent at low energies, it would be sufficient to make the film water equivalent.

4. The response of the film at low energies, excluding the intrinsic energy dependence, can be explained by examining the ratio of mass energy absorption coefficients of the elements incorporated into the film sensitive layer to water. In particular, the over response of the EBT2 and EBT3 models investigated our study at 40 keV is due to the incorporation of Bromine (Z=35) into the films sensitive layer which boosted the photoelectric effect in the sensitive layer relative to water and resulted in a much higher dose to the sensitive layer and a higher response at that energy.
5. There are two options to improve the energy response at low energies
    a. Improving the polymerization efficiency of the films at very low energies, which might be difficult to achieve.
    b. Careful adjustment of the sensitive layer composition to boost the dose to the sensitive layer of the film to compensate for the intrinsic energy dependence. In particular, the fact that Both EBT2 and EBT3 films show over response around 40 keV due to the incorporation of Bromine into the sensitive layer despite the strong intrinsic energy dependence make us believe that this approach might actually help in reducing the energy dependence of the response at low energies.
6. The absorbed dose to water energy dependence studies of hypothetical films with no Bromine and higher percentage of Chlorine show that the high dose to commercial EBT2 and EBT3 at about 40 keV can be reduced significantly by dropping Bromine and increasing the mass percent of Chlorine up to 4%. On the other hand increasing the mass percent of Chlorine to 4% would result in a higher dose at about 20 keV compared to commercial EBT2 and EBT3 with 0.8%Br.
7. Based on our results, the manufacturer dropped Bromine in recent lots of EBT3 and increased the mass percent of Chlorine to 4%, which, generally, resulted in a reduction in the overall energy dependence of the film of at low energies. The new film shows under response at all energies below 100 keV; It shows under response

of 22% ± 4% at 20 keV and 6% ± 4% at about 40 keV. However, increasing the mass percent of Chlorine makes the film more hydroscopic which may affect the sensitivity and the response of the film. On the other hand, the addition of 4% Chlorine didn't improve the energy dependence significantly at very low energies.

8. Monte Carlo simulations of the absorbed dose to water of the films reveal that incorporating a high percentage (6-7%) of lower atomic number elements such Al or Si into the film sensitive layer would increase the dose to the sensitive layer of the film relative to water at very low energies compared to the film with 4%Cl.
9. The EBT3 film prototype with 7.5% Si shows a significant reduction in the energy dependence of the film at very low energies compared to the film with 4% Cl; it shows under response of 15% ± 5% at about 20keV to 2% ± 5% at about 40 keV However, according to the manufacturer, the addition of Si affected the viscosity of the active solution which made it difficult to be used in commercial machine coating.

Based on the above results, the manufacturer is now trying to increase the mass percent of Aluminum and simultaneously bringing down the mass percent of Cl to lower levels, i.e. 1 to 2%.

These results show that reducing the energy dependence of the film response at very low energies ~20 keV is possible by dropping Bromine or even Chlorine from the sensitive layer of the film and increasing the mass percent of elements such as Al as much as possible to boost the dose to the sensitive layer at very low energies, while preserving other properties of the film. However, this technique is limited by the fact that improving the response at about 20 keV by boosting the dose at that energy will always result in a peak in the response at about 40 keV. Thus, reducing the energy dependence of the film response by adjusting the film sensitive layer composition is an interdisplay between increased intrinsic energy dependence as the energy decreases and the over response of the film at about 40 keV as we

try to compensate for the strong intrinsic energy dependence at very low energies by increasing the mass percent of Al.

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