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An investigation of backscatter factors for kilovoltage x-rays: a comparison between Monte Carlo simulations and Gafchromic EBT film measurements

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Abstract

Backscatter factors are important parameters in the determination of dose for kilovoltage x-ray beams. However, backscatter factors are difficult to measure experimentally, and tabulated values are based largely on Monte Carlo calculations. In this study we have determined new backscatter factors by both experimental and Monte Carlo methods, and compared them with existing backscatter factors published in the AAPM TG-61 protocol. The purpose of this study is twofold: (1) to evaluate the overall effectiveness of using Gafchromic EBT film for backscatter factor measurements and (2) to determine whether existing Monte Carlo-calculated backscatter factors need to be updated. We measured backscatter factors using Gafchromic EBT film for three field sizes (2, 4 and 6 cm diameter cones) and three kilovoltage beam qualities, including 280 kVp for which similar measurements have not previously been reported. We also present new Monte Carlo-calculated backscatter factors obtained using the EGSnrc/BEAMnrc code system to simulate the Pantak kilovoltage x-ray unit used in our measurements. The results were compared with backscatter factors tabulated in the AAPM TG-61 protocol for kilovoltage x-ray dosimetry. The largest difference between our measured and calculated backscatter factors and the AAPM TG-61 values was found to be 2.5%. This agreement is remarkably good, considering that the AAPM TG-61 values consist of a combination of experimental and Monte Carlo calculations obtained over 20 years ago using different measurement techniques, as well as older Monte Carlo code and cross-section data. Furthermore, our Monte Carlo-calculated backscatter factors agree within 1% with the AAPM TG-61 values for all beam qualities and field sizes. Our Gafchromic film measurements had slightly larger differences with the AAPM TG-61 backscatter factors, up to approximately 2% for the 6 cm diameter cone at a beam quality of 50 kVp. The largest difference in backscatter factors, of 2.5%, was found between Monte Carlo-calculated and Gafchromic film-measured data for the 100 kVp x-ray beam with the 4 cm diameter cone. The differences in backscatter factors between the three data sets (measurements, calculations and published values) are all within the uncertainties from our Gafchromic film measurements and Monte Carlo calculations. Our results demonstrate the suitability of using Gafchromic EBT film to measure equipment-specific backscatter factors for kilovoltage x-ray beams over the entire energy range and also confirm that backscatter factors published in kilovoltage dosimetry protocols still remain valid.

1. Introduction

Kilovoltage x-rays are widely used to treat superficial cancers and it is therefore of crucial importance to determine absorbed dose on or near the surface of the patient as accurately as possible. At these energies, the dose at the surface consists of both primary and scatter components, as radiation can be scattered back toward the phantom surface via various interactions including Rayleigh scattering, Compton scattering, the photoelectric effect as well as fluorescent and characteristic radiation (Williams and Thwaites 2000). Backscatter factors (BSFs) are an important measure of the scattered radiation contribution to the absorbed dose at the surface of the phantom and are used in the in-air calibration method for reference dosimetry (Ma *et al* 2001, Aukett *et al* 2005). The BSF is defined by the following equation (Mayles 2007):

$$\mathrm{BSF} = \frac{D_{\mathrm{sur,fs}}}{D_{\mathrm{air,fs}}} \tag{1}$$

where $D_{\mathrm{sur,fs}}$ is dose at the surface of a phantom for a given field size, and $D_{\mathrm{air},fs}$ is dose in air with the phantom absent for the same field size. The BSFs depend on a number of factors including beam quality, field size and source-to-surface distance (SSD), and it varies depending on the thickness of the underlying phantom and shielding material (Klevenhagen 1989, Hill *et al* 2007, Chica *et al* 2008, Healy *et al* 2008).

At kilovoltage x-ray energies, BSFs have been usually determined by Monte Carlo calculations (Grosswendt 1984, Knight 1992, Knight and Nahum 1994, Ma and Seuntjens 1999, Shimizu *et al* 2001). The BSFs published in the IPEMB and AAPM dosimetry protocols for kilovoltage x-ray beams are based on Monte Carlo calculations by Grosswendt (1984) with further calculations by Knight and Nahum (1994) and Ma and Seuntjens (1999) as well as experimental measurements by Klevenhagen (1989). These BSFs are tabulated for a wide range of field sizes, source-to-surface distances (SSD) and beam energies ranging from 40 to 300 kVp (Grosswendt 1984, Ma *et al* 2001). In a more recent study, Chica *et al* (2008) used the PENELOPE Monte Carlo code to calculate BSFs for x-ray energies up to 150 kV and showed that the uncertainty in determining the BSF from the half-value layer (HVL) only is not negligible. This was further confirmed in the calculations by Rosenschöld *et al* (2008) who calculated BSFs for 120 and 200 kVp beams using EGSnrc/BEAMnrc and found differences of up to 3% compared to BSFs listed in the AAPM TG61 protocol. In their analysis, they suggested that using generic BSFs tended to increase the uncertainties in absorbed dose determination for the higher energy kilovoltage x-ray beams.

The direct measurement of BSFs is a difficult task to perform clinically due to the influence of the detector within the x-ray beam. For ionization chamber measurements, consideration needs to be made of the energy dependence of chamber response and size, which perturbs the x-ray beam in the kilovoltage range (Ma and Seuntjens 1999, Williams and Thwaites 2000, Mayles 2007). For these reasons, experimentally determined BSFs have been limited to date and performed using specially designed 3 mm thick parallel-plate ionization chambers or thin thermoluminescent dosimeters (TLDs). These detectors have also been used to verify the Monte Carlo-calculated BSFs published in kilovoltage dosimetry protocols (Klevenhagen 1989, Harrison *et al* 1990, Coudin and Marinello 1998). The *British Journal of Radiology* (BJR) Suppl. 25 also tabulates measured BSFs, but only for closed-ended cones and for medium energy x-rays (BJR 1996, Ma *et al* 2001, Aukett *et al* 2005).

There has been growing interest in Gafchromic™ EBT film (hereafter called EBT film) for the dosimetry of x-ray beams. The favorable characteristics of EBT film include good spatial resolution, high sensitivity over a broad dose range (0.01–8 Gy), self-development and simplicity of use (Martisikova *et al* 2008). EBT film has a thickness of approximately 0.2 mm, which is ten times thinner than the parallel-plate ionization chamber that Klevenhagen used for his BSF measurements (Klevenhagen 1989, Fiandra *et al* 2006, Butson *et al* 2007). The response of EBT film has been assessed in a number of studies and found to be almost energy independent (to within 3%) in the megavoltage and kilovoltage energy range (Chiu-Tsao *et al* 2005, Butson *et al* 2006, Rink *et al* 2007). EBT film was also used for percentage depth dose (PDD) measurements for 50 and 100 kV x-rays by Fletcher and Mills (2008) and showed agreement with Monte Carlo-calculated PDD curves to within ±8% over the full range of data (Fletcher and Mills 2008). BSFs for beams in the range from 50 kVp to 150 kVp have been measured with EBT film in a recent study by Butson *et al* (2007), who reported very good agreement (within 2%) with IPEMB published data for the Gulmay x-ray unit.

In this paper, we report BSFs for a range of kilovoltage x-ray beam qualities calculated using Monte Carlo methods and measured with Gafchromic EBT film. We have determined BSFs for a 280 kVp beam for which there are very limited experimental values published in the literature. The Monte Carlo calculations included a full simulation of the x-ray tube and the individual cones. The accuracy of the phase space files used in the Monte Carlo calculations was verified by comparing the calculated and measured HVLs and PDDs. The measured and calculated BSFs were compared with corresponding values in the AAPM TG-61 protocol. The clinical significance of using generic tabulated BSFs as well as the clinical implications of the discrepancies in BSFs determined by different methods is discussed.

2. Method and materials

2.1. Backscatter factor measurement

All measurements were performed using a Pantak Therapax DXT 300 kilovoltage x-ray therapy unit with a tube potential varying from 50 to 280 kVp. The x-ray tube has a tungsten target angled at 30° and the beryllium window is 5 mm thick. Table 1 lists the measured HVL and filtration of available x-ray beams in the unit. For the rest of this paper, each particular x-ray beam will be referred to its peak potential (kVp).

In this work, we studied three x-ray beam energies: 50 kVp, 100 kVp and 280 kVp with three different cone sizes of diameter 2, 4 and 6 cm. These three cones are open ended in design with an SSD of 30 cm. Determination of beam quality was performed by measuring the HVL using a PTW 30013 Farmer-type ionization chamber (PTW Freiburg, Freiburg, Germany) using the method recommended by the IPEMB dosimetry protocol (Klevenhagen *et al* 1996). The beam attenuators were either aluminum or copper sheets of purity better than 99.9% and with thicknesses specified by the manufacturer to an accuracy of ±5%.

Table 1. Beam qualities with inherit filtrations generated from the Pantak Therapax DXT 300 x-ray unit.

Filter	Peak potential (kVp)	Tube current (mA)	Inherent filtration	Half value layer (HVL)
1	50	30	1.65 mm Al	1.5 mm Al
2	75	30	1.65 mm Al	2.5 mm Al
3	100	22	3.10 mm Al	3.8 mm Al
4	125	20	0.1 mm Cu + 2.5 mm Al	6.7 mm Al
5	180	16.1	0.35 mm Cu + 1.5 mm Al	0.85 mm Cu
8	280	9.5	0.8 mm Sn + 0.25 mm Cu + 1.5 mm Al	3.4 mm Cu

Percentage depth doses (PDDs) were measured for each combination of x-ray beam energy and cone. The Advanced Markus ionization chamber (PTW Freiburg, Freiburg, Germany) was used to acquire PDDs in a PTW MP3 water tank (Hill *et al* 2009). A 1 cm gap was kept between the end of the cone and the water surface to prevent a collision of the chamber holder with the cone. The dose was measured at 1 mm intervals from the surface to 50 mm depth, and 5 mm intervals from 50 mm to 150 mm along the central axis. The chamber was fitted with a 1 mm buildup cap to ensure that it is waterproof. The effective point of measurement of the chamber was assumed to be at the inner surface of the front window, which meant that for the surface dose measurement, the buildup cap was sitting slightly above the water surface.

BSFs were measured using Gafchromic EBT film (International Specialty Products, NJ) which consists of two active layers (approximately 17 μm) of radiosensitive polymer laminating a surface layer (approximately 3 μm) (Fiandra *et al* 2006). The active layers are coated with transparent polyester (approximately 97 μm). When the active component of EBT film is exposed to ionizing radiation, it turns blue, with peak absorption at a wavelength of 636 nm.

Two sets of EBT measurements were undertaken in accordance with the definition of the BSF: in-air and on the surface of a RMI-457 solid water phantom (RMI Gammex, Middleton, WI). For the in-air measurements, there was no scattering material at least 1 m distance from the end of the cone to prevent unwanted scattered radiation interacting with the film. The EBT films were attached to the end of the cone using cling wrap, which also acted to remove very low energy secondary electrons generated from the wall of the cone (Grosswendt 1984, Rosenschöld *et al* 2008). Measurements were performed in full scatter conditions at the surface of the phantom, with underlying thickness of 10 cm, as recommended by the IPEMB dosimetry protocol (Klevenhagen *et al* 1996). The slabs of solid water were selected for the phantom material as it has been found to be appropriate for dosimetry of low energy x-ray beams (Reniers *et al* 2004, Hill *et al* 2005, 2008). Cling wrap was again used to cover the cone and also to secure the film in one during the irradiation.

The EBT film was calibrated by delivering a range of doses ranging from 1 to 2.2 Gy with the reference cone (6 cm diameter) on the surface of the solid water under full scatter conditions for each of the three x-ray beams. The resultant calibration curves give the optical density (OD) as a function of beam quality. The absorbed doses were determined following the IPEMB protocol and addendum (Klevenhagen *et al* 1996, Aukett *et al* 2005). The mean optical density versus absorbed dose calibration curves were plotted for 50, 100 and 280 kVp x-rays and are displayed in figure 1. A third-order polynomial fit was applied to each of the calibration curves using the Sigmaplot software package version 11 (Systat Software Inc., San Jose, USA).

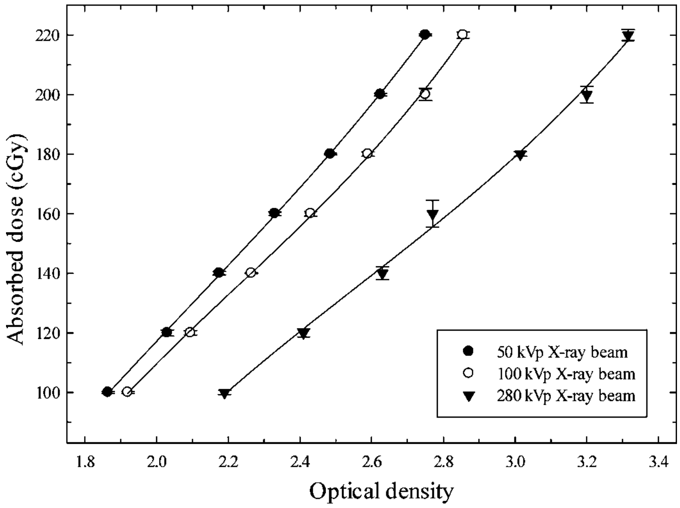

Figure 1. Gafchromic EBT film calibration curves for the x-ray beams used in this study. Error bars are indicated for each of the measurements.

For the BSF measurements, we used small square samples of the EBT film (1×1 cm^2). Each sample of the EBT film was irradiated with 200 Monitor Units (calibrated to give 2.0 Gy for the reference cone) while placed underneath the particular cone for either the in-air or in-phantom irradiation. The absorbed dose for the films with and without the backscatter material was calculated using the calibration curve for that x-ray beam energy. BSFs for each beam quality with three different cone sizes were then determined using equation (1).

The irradiated films were given several days to allow complete development of the film (Soares 2007). A densitometer (X-rite model 361T) with 2 mm aperture was used to measure the optical density of the irradiated films. For each particular EBT film sample, the mean and standard deviation of the optical density reading were determined from at least three readings using the highest optical density resolution available on the densitometer. Slightly different locations were chosen for the film readings in order to measure film inhomogeneity.

The uncertainties in all of our experiments including HVL, PDD and BSF measurements were determined using the ISO methodology as assessed in the IAEA TRS-398 dosimetry protocol (ISO 1995, Andreo *et al* 2000). The uncertainty in the HVL measurement consists of reproducibility of the x-ray unit, repeatability of HVL measurements, measurement equipment drift, thickness of the attenuator, long-term x-ray tube stability, temperature and pressure variation during the measurements. The factors contributing to the uncertainty in BSF measurements include the reproducibility of the optical density measurement, dose output reproducibility of the x-ray unit (type A) as well as uncertainties in the best-fit EBT film calibration curve, the position of the film at the end of the cone and the small SSD variation between the cones (type B).

2.2. Monte Carlo methods

2.2.1. X-ray tube simulations. The kilovoltage x-ray unit was modeled using the BEAMnrc user code (V4-r2-2-5, National Research Council of Canada, Ottawa, Canada) that is built on the EGSnrc Monte Carlo code system. The EGSnrc/BEAMnrc Monte Carlo package is commonly used to solve radiation dosimetry problems and is valid over therapeutic x-ray energy ranges (Kawrakow 2000, Rogers 2006). The EGSnrc system is able to model the low-energy photon and electron interaction processes that are relevant to this study. A number of previous studies have used the EGSnrc code to simulate kilovoltage x-ray beams including modeling of the x-ray tubes and treatment cone (Seuntjens and Verhaegen 1996, Verhaegen *et al* 1999, Ma and Seuntjens 1999, Verhaegen 2002, Reniers *et al* 2004, Mainegra-Hing and Kawrakow 2006, Hill *et al* 2007, Bazalova and Verhaegen 2007, Knoos *et al* 2007, Ali and Rogers 2008, Rosenschöld *et al* 2008).

The Monte Carlo model of the kilovoltage unit comprised six parts: the x-ray tube, beryllium window of the tube, the monitoring ionization chamber, treatment filters, the cone and a thin slab of air of 0.2 cm thickness at the end of the cone. The three cones were modeled as accurately as possible according to the component specifications provided by the manufacturer and verified by inspection of the cones. The details of the filters were taken as given in table 1. For each x-ray beam, the calculation parameters were used in the calculations for each cone with the only changes being in the geometry of the cone.

For each of the BEAMnrc simulations, we collected phase space (PHSP) data in the thin air slab at the end of the cone. A large number of incident particles (at least 1×10^9) and directional bremsstrahlung splitting (DBS), a photon splitting technique in BEAMnrc, were used to reduce the statistical errors for the first PHSP file. A splitting number of 1000 was used, which is recommended in the BEAMnrc user manual (Rogers *et al* 2005). The following EGSnrc input parameters that affect dose at low photon energies were turned on at all times: bound Compton scattering, photoelectron angular sampling, Rayleigh scattering, atomic relaxations and electron impact ionization (Mainegra-Hing and Kawrakow 2006). The global energy cutoffs for electrons (ECUT) and for photons (PCUT) were set to 0.521 and 0.001 MeV, respectively.

2.2.2. Verification of the phase space file data. The Monte Carlo simulations were verified by comparing the calculated and measured HVLs and PDDs. The HVL simulations were performed in BEAMnrc using the PHSP files for the 2 cm cone as the beam source. The 2 cm diameter cone was used to achieve the required narrow beam geometry. A total of 2×10^9 incident particles were used and all the EGSnrc calculation options were kept the same as in the x-ray tube simulations.

Two sets of simulations were made: one with an aluminum (Al) or copper (Cu) sheet with a thickness corresponding to the measured HVL value for that beam quality and the other without the metal sheet. The distance between the cone (30 cm FSD) and the beam attenuator was 20 cm. The thickness of the attenuator was selected to be the thickness according to the experimental results. The dose was scored in a small cylindrical volume of air with dimensions 1 cm in radius by 1 cm in height at a distance 70 cm from the source. The ratio of the scored dose with and without the attenuator was calculated and compared with the experimental HVL calculations. The BEAMnrc model of each x-ray beam was then modified by adjusting the primary electron energy striking the tungsten target until the difference between the Monte Carlo-calculated and measured HVL was less than 3% consistent with previous studies (Ubrich *et al* 2008).

PDDs in a large water phantom were calculated for each of the x-ray beams using the DOSRZnrc user code (V4-r2-2-3) and compared with the experimental data. The water phantom consisted of slabs of 2 mm thickness near the surface and then increased thickness at depth, with a large thickness underneath to provide full scatter conditions. The dose was scored in voxels with dimensions of 5 mm radius and 2 mm thickness located on the central axis of the phantom. A 1 cm air gap between the cone and the water phantom was also simulated for consistency with the experimental setup. The relative doses were normalized to the dose at a depth of 1 cm. A total of 1×10^9 histories were used with the PHSP files.

2.2.3. Backscatter factor calculations. BSFs were calculated in the DOSRZnrc user code using the calculated PHSP files for each x-ray beam energy and cone. The dose was scored in a water volume with a thickness corresponding to the thickness of EBT film (0.234 mm). In previous studies, up to 8% differences in MC-calculated absorbed dose have been found when the thickness and shape of the scoring volume varied (Rosenschöld *et al* 2008, Ubrich *et al* 2008). The cling wrap, which has a thickness of approximately 10 μm, was included in the geometry for the calculations and simulated as polyethylene. For the dose calculations under full scatter conditions, a 10 cm thick water phantom was placed beneath the small water volume as recommended in the IPEMB protocol (1996).

To reduce the statistical errors in such a small area, the variance reduction techniques DBS and Russian roulette were turned on and a large number of particle histories (up to 1.6×10^{10}) were used. The calculation parameters and options within DOSRZnrc were kept the same as those used for the PDD calculations. Two sets of simulations were made: one for the dose calculation without the backscatter material and the other with the backscatter material. Calculated BSFs for 50, 100 and 280 kV x-ray beams with 2, 4 and 6 cm circular cones were compared with the experimental data and the data from the AAPM TG-61 dosimetry protocol (Ma *et al* 2001). BSFs from AAPM TG-61 were interpolated to obtain the appropriate values for the given beam quality and field size based on the measured HVL.

3. Results and discussion

3.1. Verification of Monte Carlo-calculated phase space files

Figure 2 shows the primary photon spectra from the Monte Carlo-calculated PHSP files and derived using the BEAMDP program. In this work, the statistical uncertainty in the Monte Carlo HVL calculations was less than 0.5%. Each x-ray beam was fine-tuned by a small adjustment of up to 2% of the incident electron energy in order to achieve a difference in the measured and calculated HVLs of less than 3%. This is an improvement over some previous Monte Carlo-calculated kilovoltage x-ray beams that have reported discrepancies of up to 10% between measured and Monte Carlo-calculated HVL values (Omrane *et al* 2003, Ubrich *et al* 2008, Rosenschöld *et al* 2008). The comparison of measured and Monte Carlo-calculated HVLs is presented in tables 2 and 3. The uncertainty in the HVL determination was found to be approximately directly proportional to the uncertainty in the attenuator thickness, which was up to ±5%. The initial agreement found between Monte Carlo-determined HVLs and measured HVLs was poorest for the 280 kVp beam. To improve the agreement for this beam, the thickness of Cu in Monte Carlo simulation was varied, and the best agreement was found when the attenuator thickness was increased by 5%.

Figure 3 shows the comparison of the measured and calculated PDDs for the 50, 100 and 280 kVp x-ray beams. The statistical uncertainty in depth dose calculations using the DOSRZnrc user code is less than 0.8%. The uncertainties in the measured PDDs on the Pantak x-ray unit have been found to be less than 2.0% (Hill *et al* 2009). The agreement between measured and calculated PDDs was in general better than 1% for all beam energies and field sizes, with the largest difference of 1.9% occurring for the 100 kVp x-ray beam and 4 cm diameter cone. This level of agreement is comparable to previous studies that have reported differences of up to 5% between measured and Monte Carlo-calculated PDDs (Omrane *et al* 2003, Knoos *et al* 2007, Rosenschöld *et al* 2008).

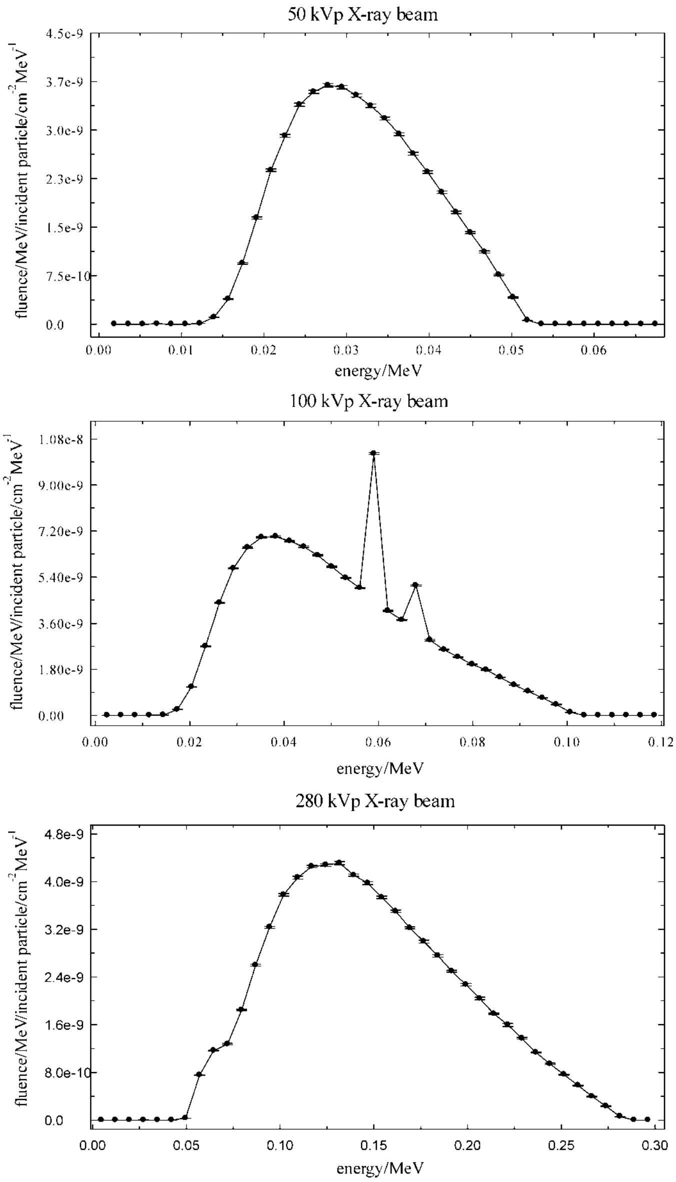

Figure 2. X-ray beam spectra of 50, 100, 280 kVp Monte Carlo-modeled x-ray beams using BEAMnrc. Phase-space files were scored at the end of the cone.

3.2. Backscatter factor determination

Table 4 shows the uncertainty budget for the measured BSFs and gives a total uncertainty of 2.5%. The statistical uncertainty in the Monte Carlo-calculated BSFs was determined to be less than 1%. Figure 4 shows a comparison of the BSFs from our EBT film measurements, our Monte Carlo calculations and interpolation of the published data from the AAPM TG-61 report. The BSFs in figure 4 are for 50, 100 and 280 kVp x-ray beams and for field sizes of the 2, 4 and 6 cm diameter circles.

Table 2. Results from HVL calculations using the DOSRZnrc user code in BEAMnrc. The dose is scored in air when the attenuator is removed. The measured attenuator thickness was used for the calculations.

Cone (cm)	Energy	Beam attenuation ratio	Statistical uncertainty (%)
2.00	51 kVp	0.489	0.4%
	102 kVp	0.487	0.4%
	285 kVp	0.485	0.5%

Table 3. Results from HVL measurements using an ionization chamber. The percentage difference between calculated and measured values is also shown.

Cone	Energy	Thickness of the attenuator	With Al/Cu	Without Al/Cu	Ratio	Diff. between MC and measured data
2.00 cm	50 kVp	1.5 mm Al	0.679	1.36	0.499	2.0%
	100 kVp	3.8 mm Al	0.872	1.74	0.501	2.9%
	280 kVp	3.4 mm Cu	0.629	1.26	0.499	2.8%

Table 4. Dosimetric uncertainties associated with the experimentally measured backscatter factors using EBT film.

Component	Std uncertainty (%)
OD measurement over pixels	2.0
Pantak x-ray unit reproducibility	0.5
EBT film best-fit calibration curve	1.0
Position of film at the end of the cone	0.6
FSD variation between cones	0.6
Film homogeneity	0.5
Long term x-ray tube stability	0.3
Total	2.5

The measured BSFs are in good agreement, to within 2%, with the AAPM TG-61-published BSFs which is within the calculated uncertainty of 2.5% for the EBT film measurements. In particular, the differences in BSFs for the 280 kVp x-ray beam are less than 0.3% for the 4 and 6 cm cones and 1.1% for the 2 cm cone. For the two lower energy x-ray beams, the difference in BSFs was up to 2% for the 6 cm cone and less than 0.5% for the two smaller cones. Our results are comparable to the BSFs obtained by Butson *et al* (2007) measured using EBT film. They achieved an agreement of 2% between measured BSFs and values tabulated in the IPEMB dosimetry protocol, which are based on the calculations by Grosswendt (1984) (Aukett *et al* 2005). However, their study used x-ray beams with energy only up to 150 kVp and so did not consider medium energy kilovoltage beams. We note that our calibration curve (figure 1) suggests some degree of energy dependence in the EBT film and this may have contributed to some of our BSF measurement uncertainties. Variations in energy dependence characteristics between batches of EBT film have also been reported elsewhere in the literature (Fletcher *et al* 2008, Rink *et al* 2009), which also indicates the

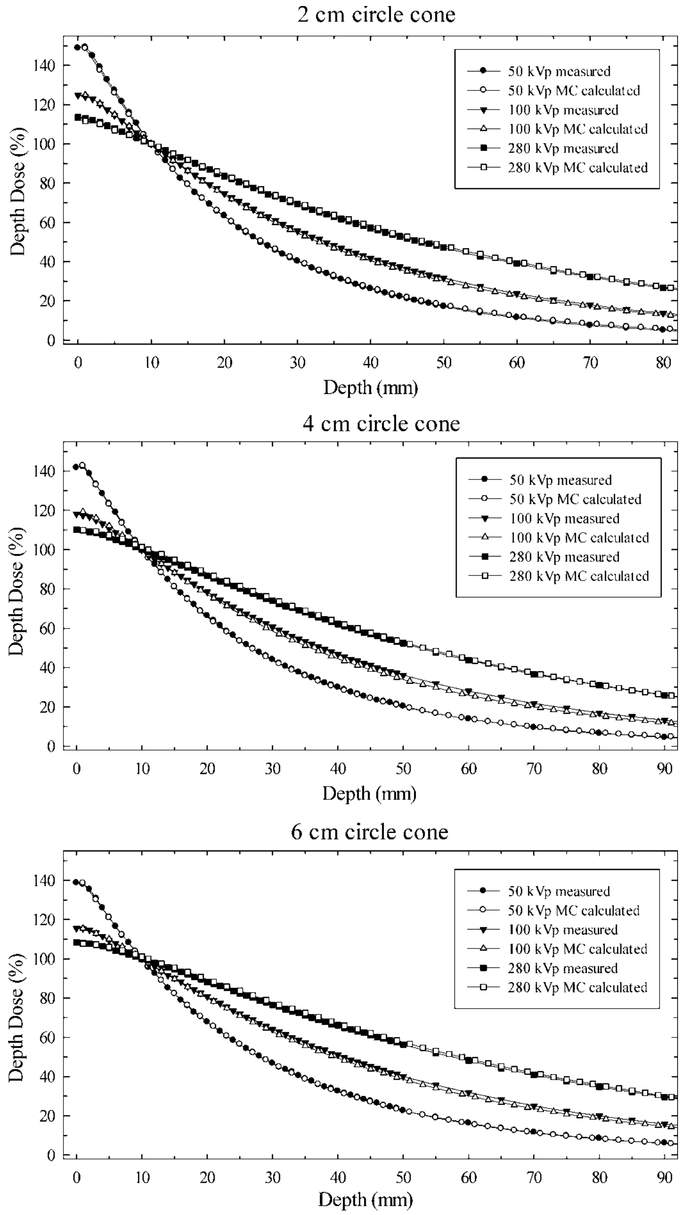

Figure 3. The comparison of measured and Monte Carlo-calculated percentage depth dose data for 50, 100 and 280 kVp x-ray beams for cone sizes used in this study of 2, 4 and 6 cm in diameter.

importance of individual calibration curves for each film batch and not relying on generic curves.

Our Monte Carlo-calculated BSFs are also in good agreement to within 1% with BSFs calculated from the AAPM TG-61 protocol for all the beam energies and field sizes studied. The statistical uncertainties in the Monte Carlo calculations were less than 1%, which is comparable to the quoted 1.5% value of uncertainty for BSFs listed in the AAPM TG-61 protocol (Ma *et al* 2001).

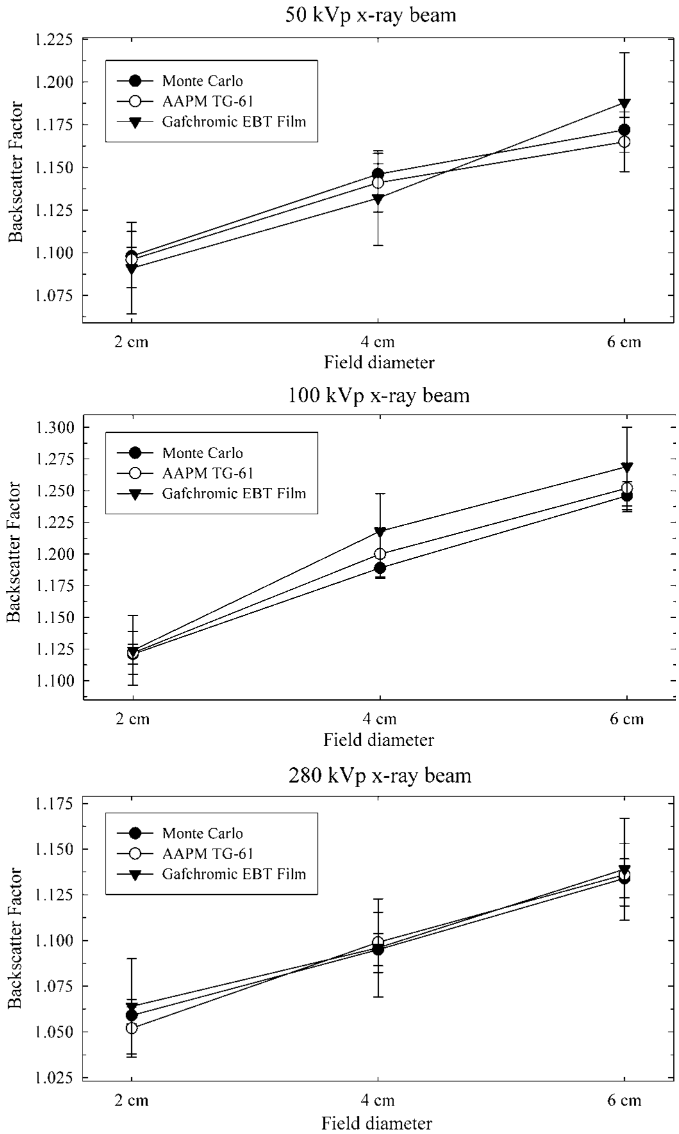

Figure 4. Comparison of measured (EBT film), Monte Carlo-calculated (EGSnrc/BEAMnrc) and published (AAPM TG-61) backscatter factors for a range of field sizes and beam energies.

In the comparison of BSFs from Monte Carlo calculations and EBT film, the agreement for the 280 kVp x-ray beam was better than 0.5%. There were larger differences for the 50 and 100 kVp beams of up to 2.5%, with the maximum difference occurring for the 100 kVp x-ray beam with the 4 cm diameter cone. It should be noted that for this combination of 100 kVp x-ray beam and 4 cm diameter cone, we found the largest difference between AAPM TG-61 and EBT film BSFs. However, all of these differences are within the calculated uncertainties of the EBT film measurements.

We note that systematic uncertainties in the Monte Carlo code may also contribute to the calculated BSFs. These systematic uncertainties can be attributed to limitations in low energy physics (e.g. stopping power values and energy loss straggling below 1 keV, as well as cross-section data for electron scattering and electron impact ionization). Ali and Rogers (2008) suggest that the limitations of EGSnrc at very low energies may result in systematic uncertainties of up to 3% for backscatter simulations.

3.3. Comparison of BSFs and discussion

In general, we find slightly larger differences between our measured and AAPM TG-61 protocol BSFs for the larger field sizes and lower energy x-rays. This may be attributed to a larger variation in the OD of the EBT film for larger field sizes as a result of increased scattering from secondary photons and electrons generated in the walls of the treatment cone or even from other points of the film. Klevenhaegen *et al* (1982) suggested that there is a higher probability of scattered electrons entering the sensitive volume of the ionization chamber for smaller field sizes. However, we do not find larger differences for smaller field sizes.

The recent calculations of BSFs by Rosenschöld *et al* (2008) using BEAMnrc for 120 and 200 kVp x-ray beams included variations in thickness of scoring dose volume. Their determination of BSFs used the photon fluence methodology of Grosswendt (1984). They found that the BSFs varied by as much as 3% depending on the thickness of the scoring volume and showed improvement in dose to water determination when they used their own calculated BSFs. Other recent Monte Carlo work by Chica *et al* (2008) showed that the absorbed dose can vary as much as 11% (3σ) as a result of uncertainties in BSFs and mass-energy absorption coefficients if the beam quality is defined using only the HVL. This uncertainty is reduced to within 3% once the beam is better characterized and the associated BSF is better determined using knowledge of the photon spectra. Our results are consistent with these analyses.

Nahum (1997) has suggested that the idealized geometry used in Monte Carlo simulations may not properly take into account the scatter that is produced from the cone, which can contribute to dose in the scoring volume. In our work, we have properly characterized the beam by modeling the photon spectra, verified by the HVL, as well as the treatment cone. The AAPM TG-61 BSFs are based in part on calculations by Grosswendt (1984), which did not take into account the treatment cone and used photon spectra taken from catalogues data. The fact that our results agree so closely with the AAPM TG-61 BSFs indicates that the dose contribution from radiation scattered from the cone is not primarily responsible for the uncertainties in BSFs.

We note that the BSFs reported here for the 280 kVp x-ray beam for an open-ended-type cone are new. To date, the BSF for this beam quality could only be deduced from the existing protocols by interpolation of the tabulated data. The agreement we find between the BSFs for our specific kilovoltage unit and the AAPM TG-61 values is remarkably good, considering that the AAPM TG-61 values are based on a combination of independent Monte Carlo calculations and ionization chamber measurements conducted over 20 years ago. This suggests that the existing generic BSFs tabulated in the AAPM TG-61 protocol (and by implication, the IPEMB protocol) are not outdated for our particular x-ray unit. However, where equipment specific values are needed in the clinic, we recommend EBT film measurements as an appropriate dosimeter for BSF determination.

Further work could be done to reduce the uncertainty of the Monte Carlo calculations by including a more detailed geometry of EBT film. This could further reduce the differences between the measured and calculated BSFs by using the exact materials and separating the active layers from the surface layers. Additionally, it is possible that the approximately 100 μm depth below the surface at which the active layer of the EBT film was located is insufficient to achieve full charged particle equilibrium or to completely remove contaminant electrons from the filter, particularly for the 280 kVp. However, we used the BEAMDP utility provided with BEAMnrc to determine the electron spectra in the phase space file and found that for the 280 kVp x-ray beam, the maximum electron energy was 80 keV. We note that the range of an 80 keV electron in water is approximately 98 μm (Johns and Cunningham 1983); therefore, we believe that the active layer of the EBT film is in a region of charged particle equilibrium, and uncertainties due to contaminants to be negligible.

The Monte Carlo calculations could also be further refined by using the purpose-built EGSnrc user code customized for backscatter calculations (see Ali and Rogers (2008)). However, further improvements in the low energy physics models used by EGSnrc are needed to reduce systematic uncertainties in the Monte Carlo backscatter calculation.

4. Summary and conclusions

BSFs were investigated and compared using three different sets of data: Gafchromic EBT film measurements, Monte Carlo calculations using EGSnrc/BEAMnrc and AAPM TG-61 published data. All BSFs for a given beam energy and field size agreed within 2.5%. The AAPM TG-61 data and new Monte Carlo-calculated data were found to be in excellent agreement, with differences of less than 1%. The differences between our Monte Carlo-calculated and the AAPM TG-61 BSFs may be attributed to interpolation of the published data as well as uncertainty in evaluating beam quality using only the HVL and systematic uncertainties in the Monte Carlo calculations resulting from limitations of EGSnrc at very low energies.

BSFs measured using EBT film were in good agreement with AAPM TG-61 values, which demonstrates the suitability of EBT film as a dosimeter for kilovoltage x-ray dosimetry, particularly for measuring BSFs. The largest differences (up to 2.5%) compared to Monte Carlo calculations, which were found for the 100 kVp x-ray beam, can be primarily attributed to uncertainties in the optical density measurements. We have also presented new BSFs based on measurements and Monte Carlo calculations for 280 kVp x-rays with an open-ended cone, for which no data have been previously reported.

Our results demonstrate that where equipment-specific BSFs are desired, EBT film is suitable for measurements across the energy range of kilovoltage x-rays and for a range of field sizes. Additionally, our updated Monte Carlo calculations confirm that existing BSFs published in kilovoltage dosimetry protocols still remain valid.

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