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NOTE

Measurement of dose reductions for superficial x-rays backscattered from bone interfaces

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Abstract
Accurate measurement and knowledge of dose delivered during superficial x-ray radiotherapy is required for patient dose assessment. Some tumours treated near the surface (within the first few centimetres) can have large posterior bone structures. This can cause perturbations to dose delivered due to changed backscatter contributions from the bony structure as compared to full water or tissue scattering conditions. Measured results have shown that up to 7.5% of D_{max} reductions in dose can occur near the water/bone interface for 100 kVp, using 10 cm diameter field sizes when a 1 cm thick slab of bone is located at 2 cm depth. At smaller field sizes such as 2 cm diameter these values reduce to 2% for the same energy. Larger variations (up to 12.5% of maximum) have been seen at the phantom surface when the bone layer is directly behind the point of interest (within 0.5 mm) and smaller effects (up to 5% of maximum) at depths down to 5 cm. Interesting to note is the fact that for larger field sizes, an increase in percentage dose is found at the water/bone interface due to the production of low energy backscattered electrons similar to the effect found in lead. However, they are much smaller in magnitude and thus would not cause any significant dosimetric effects. In the case where large bony structures lie relatively close to the surface and the tissue above this region is being treated, a dosimeter such as radiochromic film can be used to estimate the dose reduction that may occur due to the changed backscatter conditions.

Introduction

Superficial x-ray beams are used for the treatment of tumours located at or near the skin surface often up to a depth of a few centimetres (Locke *et al* 2001, Caccialanza *et al* 2003a, 2003b, Wolstenholme and Glees 2006). Their dose characteristics define a maximum delivered dose at the surface and a sharp fall-off in percentage absorbed dose with depth. Dose is often prescribed to the maximum (surface dose) or sometimes to a given depth (within a few centimetres) based on dosimetric results obtained from water phantoms. Sometimes, clinical treatments occur in areas where a large higher density material such as bone is located within a few centimetres posterior to the tumour bed. Specifically areas such as the cheeks, scalp or near the shoulder blades are regions where this occurs. The interactions of superficial x-rays with bone and the subsequent perturbations in backscattered radiation (Ma and Seuntjens 1999) can affect the dose delivered above the bone material and within the treatment volume. Loss of a backscatter material can also cause similar effects (Healy *et al* 2008). This short note investigates and provides some quantitative clinical results for reductions seen in absorbed dose due to a high-density bone interface introduced at shallow depths and suggests a simple method using radiochromic film to estimate dose changes that occur in these situations.

Material and methods

Dosimetry has been performed for the measurement of percentage dose changes related to the introduction of analogue bone as a backscatter material at kilovoltage energies with the use of an Attix parallel plate ionization chamber and EBT Gafchromic, radiochromic film. With the results, 100% of dose refers to the dose at zero depth for a homogeneous solid water phantom with the same irradiating conditions (energy and collimation).

A Gulmay[4] D3300 orthovoltage machine was used to deliver x-ray exposures, at 50 kVp (HVL: 1.4 mm Al), 100 kVp (HVL: 3.72 mm Al) and 150 kVp (HVL: 0.627 mm Cu) energies. The given radiation exposure levels are based on absorbed dose to water calibrations performed with a Farmer thimble-type ionization chamber according to the IPEMB protocol for kilovoltage x-rays (IPEMB 1996, Aukett *et al* 2005). The phantom material used was a RMI[5] solid water phantom (Constantinou *et al* 1982) of dimensions 30 cm $\times$ 30 cm $\times$ 30 cm. Hill *et al* (2005) examined the radiation absorption equivalency of RMI solid water to water and found a match within 1% over the energy range 75 kVp to 300 kVp. Ma and Seuntjens (1999) also highlighted the fact that tissue and water do not deviate significantly (less than 1%) in their mass energy absorption coefficients. Thus solid water can provide an adequate simulation of tissue. The RMI bone analogue material was a 20 cm $\times$ 20 cm $\times$ 1 cm slab of analogue, dense bone with a measured density of 1.60 g cm^{-3}. It was used to simulate the effects of a high-density bone material such as the cheek, skull or shoulder beneath a tissue treatment site during superficial radiotherapy.

Point dose measurements on the beam central axis were performed using an Attix parallel plate ionization chamber (Gerbi 1993). Its collection electrode diameter is 1.27 cm and its front window thickness is 0.025 mm. These characteristics together with its solid water construction make it useful for the measurement of backscattered dose in superficial treatments. To measure the effect on backscattered dose, the Attix chamber was placed upside down within a solid water stack to provide a measurement at the defined distance (d) from the analogue bone/solid water interface as shown in figure 1. This measurement technique introduces an approximately 2% difference in measured dose when compared to the measurement with the chamber placed 'right side up'. This is taken into account where needed. Measurements were also made with a 5 mm thick lead slab (as the interface material) for the comparison of dose changes as would occur during internal shielding. The distance between the point of measurement and the depth

[4] Gulmay Limited, Chertsey, Surrey, KT16 9EH, UK.
[5] GAMMEX RMI, Middleton, WI 53562-0327, USA.

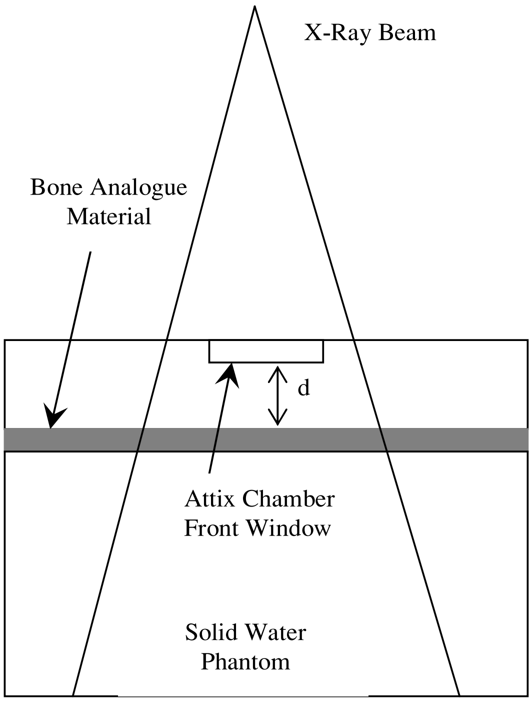

Figure 1. The experimental set-up for backscatter experiments is shown. The Attix chamber was placed upside down within the phantom to measure as close as possible to the bone/solid water interface.

of the bone slab was varied from 0 to 20 cm. Comparisons were made for dose measured with only the solid water backscatter material compared to solid water with the 1 cm thick bone analogue slab at a defined distance below the Attix chamber measurement site. With this assembly, measurements of dose could be performed at a minimum depth of 2 cm solid water. Measurements were also performed at a depth of 5.0 cm. Measurements were made in close proximity to the bone slab using thin plastic sheets with a water equivalent thickness of 0.1 mm.

EBT Gafchromic film (ISP Technologies Inc.[6], batch number 35322-0031) was also used to measure changes in backscattered dose at the phantom surface (Butson *et al* 2007). EBT Gafchromic film was used and handled as outlined in TG-55 (Niroomand-Rad *et al* 1998) and the medical radiation dosimetry with radiochromic film report series (Butson *et al* 2003). The effective atomic number of the EBT film is $Z_{\mathrm{eff}} = 6.98$ (ISP Corp 2007) compared to water $Z_{\mathrm{eff}} = 7.3$, a comparatively close match compared to other radiochromic film types and radiographic film. It provides a low-energy dependence (Butson *et al* 2006) and has an overall water equivalent thickness of approximately 300 μm, thus making the effective depth of measurement 0.15 mm. All films were analysed using a PC desktop scanner and Image J software on a PC workstation at least 24 h after irradiation to minimize the effects from post-irradiation colouration (Cheung *et al* 2005). The scanner used was an Epson Perfection V700 photo, dual lens system desktop scanner using a scanning resolution of 150 pixels per inch. The images produced were 24 bit RGB colour images. These images were analysed

[6] International Specialty Products, Wayne, NJ 07470, USA.

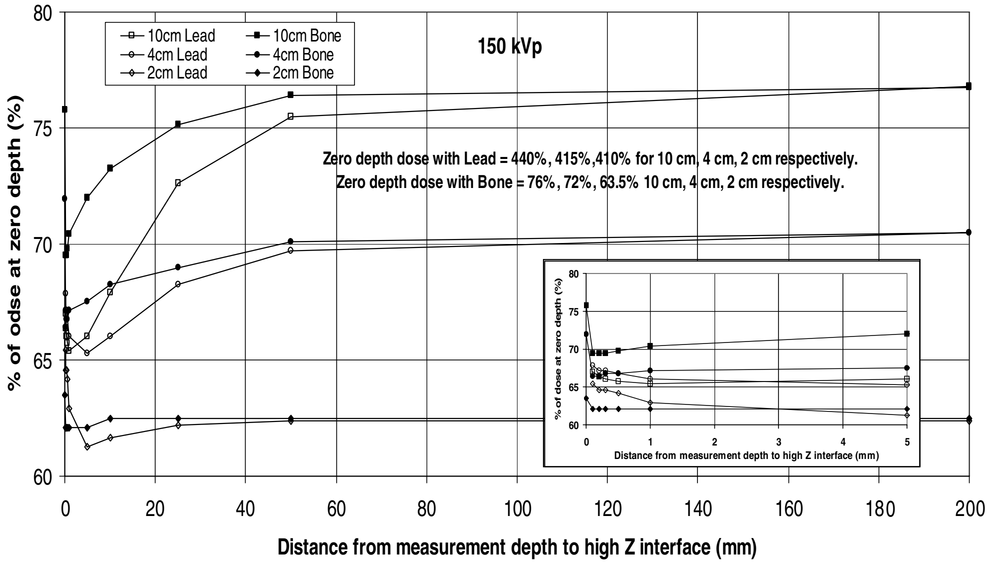

Figure 2. The measured percentage dose compared to dose at zero depth in front of a bone/water or lead/water interface for a 150 kVp x-ray beam at various field sizes at a measurement depth of 2 cm is shown. The *Y* axis has been truncated and does not show the high percentage doses measured at the lead interface.

with the full RGB components (Butson *et al* 2005). Net reflective optical density (ROD) (film fog levels were subtracted from the results) for all films was calculated to find dose delivered to the film. ROD is defined as the log of the ratio of the incoming light and the transmitted light, which has passed twice through the media by reflecting off a white background material and been collected on the same side of the film as the source of the incoming light. Net ROD was converted to dose measurements using a second-order polynomial calibration equation. Calibrations of Gafchromic film were performed under standard conditions (30 cm FSD and 10 cm diameter field size) using doses ranging from 0 Gy to 3 Gy in 0.25 Gy steps. Results are calculated by the comparison of experimental reflective optical densities to the calibration optical densities. This method produces an uncertainty of measured dose of ± 4% (2SD) in the range of doses measured.

Results and discussion

Figure 2 shows the effects on backscattered dose for a 150 kVp superficial x-ray beam with the introduction of both bone (1 cm thick slab) and lead (0.3 cm thick slab) as a backscatter material. Measurements are shown for field sizes of 10 cm, 4 cm and 2 cm diameter circular fields. The inset is an expanded version of the results over the first 5 mm of the *x*-axis. The *x*-axis shows the distance between the point of measurement and the high-density material. For example at a distance of 25 mm, there is 25 mm of solid water between the point of measurement and the bone or lead. Results show two stages in the percentage dose change for both lead and bone. Lead produces a significant increase (up to 400%) in dose very close to the interface, which is specifically due to low-energy photoelectrons produced and backscattered off the higher density interface. Similar results have been found before (Hill *et al* 2005,

Table 1. Percentage of dose at zero depth reduction from bone backscatter perturbations (at depth of 2 cm).

Cone size (cm) Diameter	Distance of measurement from bone interface (mm)	Reduction (%) Energy (kVp) 50	100	150
		(±0.5%)		
10	0.1	5.0	9.5	7.5
10	0.2	6.0	9.0	7.0
10	0.5	6.0	9.0	7.0
10	1	5.0	8.5	6.5
10	5	3.5	6.0	5.0
10	10	2.5	4.5	3.5
10	25	0.5	1.5	1.5
10	50	0	0.5	0.5
10	200	0	0	0
4	0.1	4.0	4.0	4.0
4	0.2	4.0	4.5	4.0
4	0.5	3.5	4.0	3.5
4	1	3.0	4.0	3.5
4	5	2.5	2.5	3.0
4	10	1.0	1.5	2.5
4	25	0.5	0.5	2.0
4	50	0.5	0.5	1.5
4	200	0	0	0
2	0.1	1.5	2.0	0.5
2	0.2	1.5	1.5	0.5
2	0.5	2.0	2.0	0.5
2	1	1.5	1.5	0.5
2	5	1.0	1.0	0.5
2	10	0.5	0.5	0.5
2	25	0	0	0
2	50	0	0	0
2	200	0	0	0

Das *et al* 1995). The effect however is less pronounced for bone producing percentage dose results which are comparable to the original dose at that point if no bone material is present. Thus, clinically there should be no significant problems associated with the high photoelectron backscattered dose at the bone tissue interface. However, the shape of the curve shows that there is a measurable effect from photoelectrons. For example at 150 kVp, the interface percentage of dose at zero depth for a 10 cm diameter field was 76% versus 77% without any bone material present. In comparison, at 0.2 mm from the interface, the percentage dose was 69.5% (7.5% lower). After the initial increase in percentage dose due to photoelectrons, both lead and bone material introduce a significant reduction on delivered dose as shown in figure 2. This equates to approximately 7.5% of dose at zero depth for bone at a 10 cm field size and 0.5% of dose at zero depth for a 2 cm diameter field. These reductions (especially for the larger field sizes) occur for a significant distance (1–5 cm) between the point of measurement and the bone interface.

Table 1 shows percentage dose results for similar experiments performed using 50 kVp and 100 kVp as well as 150 kVp beams and bone interfaces. Table 2 shows results at depths

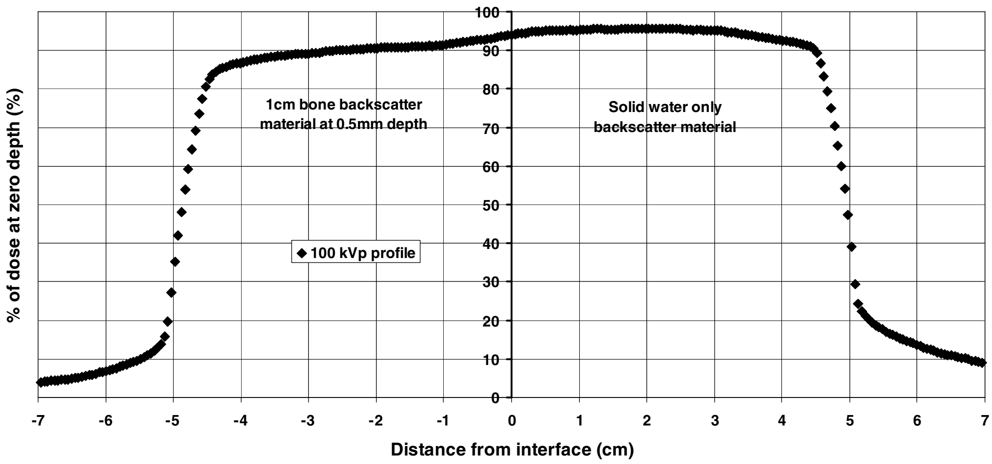

Figure 3. A measured percentage dose compared to dose at zero depth profile showing the dosimetric effects of a posterior bone interface on a 100 kVp x-ray beam in a solid water phantom is shown.

Table 2. Percentage of dose at zero depth reduction from bone backscatter perturbations at the surface and at 5.0 cm depth.

Cone size (cm) Diameter	Distance of measurement from bone interface (mm)	Reduction (%) Energy (kVp) 50	100	150
		(±2%)		
(Surface dose)				
10	0.2	7.0	12.5	10.5
4	0.2	4.5	6.5	5.5
2	0.2	2.5	3.5	2.5
(Depth 50 mm)				
10	0.2	4.0	5.0	4.5
4	0.2	2.5	3.0	2.5
2	0.2	1.0	1.5	1.0

of 5.0 cm and at zero depth. The 100 kVp beam produces the largest change in absorbed dose with an up to 12.5% change found at $d = 0$ cm with a 10 cm diameter field (table 2) for the measurements performed. This was expected as the largest difference in backscatter factor ratios of water to bone was found in this experimental configuration. This value is 9.5% at 2 cm depth and 5% at 5 cm depth. The effects of the bone interface are still significant up to 1 cm away with up to 4% of dose at zero depth reduction occurring.

When treatments occur in regions such as the head or shoulders, large bony areas can be located below the treatment site either providing full or partial backscatter perturbations. The skin and subcutaneous tissue to be treated may be only a few millimetres to a few centimetres away from these high-density interfaces. If such treatments occur, the delivered dose may be different from the results calculated using water phantom data. These differences in our experiments were found to be up to 12.5% at 100 kVp. Results calculated using bone to water backscatter factors such as Ma *et al* (1999 or 2001-AAPM) do not necessarily provide an accurate estimate of the dose reductions as they account for the total replacement of water/tissue with the bone material and thus would overestimate the change that would occur. A novel way to estimate the change occurring could be with the use of Gafchromic film placed on the patient surface to estimate the skin dose within the treatment field. This is shown in figure 3 where a 1 cm thick slab of bone covers half of the treatment field as a backscatter material. As can be seen, the resultant profile shows a reduced dose delivered to both sides of the treatment field compared to a water phantom only field (100%) with a larger reduction occurring on the bone side. This dose is reduced by an average of approximately 10% whereas the solid waterside is reduced by an average of approximately 4% as a result from the changed backscatter conditions. These results are measured with an uncertainty of ±3% and are reproducible. These results could then be used to estimate the effect at depth using a table produced to measure the changes in perturbation at depth, similar to our given results.

Conclusion

It has been found that bone does affect backscattered dose by reducing applied dose levels compared to water only phantom measurements by up to 12.5% of dose at zero depth with a 1 cm thick slab of a 1.60 g cm^{-3} density analogue bone material. The incorporation of bone backscatter perturbation factors into clinical planning and calculation of dose may minimize the impact of dose variations occurring in these situations and may need to be taken into account by the planning radiation oncologist during superficial treatment. Gafchromic film could be used as a surface dosimeter to estimate the effects of dose reduction from large bony areas affecting backscatter conditions.

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