1. INTRODUCTION

The loss of charged-particle equilibrium (CPE), together with the geometrical phenomenon of ‘source occlusion’ (due to the finite size of the effective x-ray source) makes the dosimetry of small, sub-equilibrium megavoltage photon fields particularly challenging. We compared the well-established dosimetry procedures for ‘large fields’,1,2 In this study, the absorbed dose in bone and lung-equivalent materials embedded in water, compared to that in uniform water, is investigated from ‘large’ to very small field sizes for 6 MeV and 15 MV photon beams. We have also determined the range of field sizes at which qualitatively different behaviour in bone and lung-equivalent materials. Ultimately the aim is to quantify possible errors in non-Monte Carlo based treatment plans involving heterogeneities such as lung and bone in small fields.

2. METHODS AND MATERIALS

Previously validated Monte-Carlo (MC) models of a Varian 2100CD and 2100CD Plus megavoltage photon beams at 6 MeV and 6 MV photon beams respectively have been employed.1,3

2.1. Computation of absorbed dose as a function of depth and field size

Cylindrical phantoms (outer radius 15 cm, height 30 cm) consisted of 3 cm water, then 7 cm lung-equivalent material (ρ = 0.21 g cm$^{-3}$) then 20 cm water (Fig 1B) and 5 cm bone-equivalent material (ρ = 1.8 g cm$^{-3}$), then 25 cm water (Fig 1A). Additionally, a homogenous (water) phantom of the same dimensions was modelled.

D$_{\text{Kermas}}$ could then be obtained as a function of field size using D$_{\text{Kermas}}$ at each point in space and in the same medium. In addition to the bone-equivalent and lung-equivalent media, D$_{\text{Kermas}}$ was also determined for homogeneous water at depths of 3.975 cm and 6.475 cm for both beams at the full range of field sizes described above.

2.2. Inhomogeneity dose-perturbation factor as a function of field size

The inhomogeneity dose perturbation factor, DPF, is defined as the ratio of the dose in the heterogeneous phantom, D$_{\text{hetero}}$, at depth, z, to the dose in the homogeneous water phantom, D$_{\text{med}}$, at the same physical depth, z, and for the same beam quality.

\[
\text{DPF} = \frac{D_{\text{hetero}}}{D_{\text{med}}}
\]

where ‘hetero’ and ‘med’ indicate the heterogeneous (water-bone-lung) phantom and the same medium, respectively. From Eqs (2) and (3), one can quantify the effect of the inhomogeneity on the dose relative to that in uniform water at the same depth. The DPFs were derived from Eq (3) at 3.975 cm depth in bone and 6.475 cm in lung along the beam central axis in both beams.

2.3. Results

3.1. Absorbed dose as a function of depth and FS

In Fig 2 (a), dose build-down and build-up occur at the proximal and distal end respectively of the lung inhomogeneity. The dose build-up (≤ 0.75% cm$^{-1}$) at the proximal end of the bone inhomogeneity is due partly to backscattering of the secondary electrons from bone which has a higher atomic number than water. The dose build-down (≤ 0.75% cm$^{-1}$) at distal end of the bone inhomogeneity is partly attributable to decreased backscattering of the secondary electrons from the water in lung. In other words, these effects are reversed. A similar pattern is observed at 15 MV, though in this case (low atomic number) electronic disequilibrium is amplified because of the greater electron range compared to 6 MV.

In the bone inhomogeneity the dose is increased (vs. homogeneous water) for field size $\times 1 \times 1$ cm$^2$ at 6 MV and $\times 3 \times 3$ cm$^2$ at 15 MV, at 0.25 $\times$ 0.25 cm$^2$ field size 3.975 cm depth dose enhancements of 10.8% at 6 MV and 28.7% at 15 MV were obtained – this can be explained in terms of reduced (lateral) electronic disequilibrium in bone compared to the overlying and underlying water regions due to the small mass density of bone. Also, in bone, now at the quasi-equilibrium field size 0.25 $\times$ 0.25 cm$^2$ at 15 MV and 5 $\times$ 5 cm$^2$ at 15 MV the dose is reduced (vs. homogeneous water) both at 3.975 cm depth – this is due to the slightly lower value of $\mu_{\text{bone}}/\mu_{\text{water}}$ in bone compared to water. In the lung inhomogeneity, dose reductions (vs. homogeneous water) of 53% (6 MeV) and 67.3% (15 MeV) were seen at 6.475 cm depth in the 0.25 cm$^2$ field, due to increased electronic disequilibrium in the lower density lung, compared to in water. However, dose reduction (vs. homogeneous water) in the lung inhomogeneity is negligible for field size $\times 5 \times 5$ cm$^2$ at 6 MV and $\times 16 \times 16$ cm$^2$ at 15 MV, there is a partial CPE.

3.2. MC-derived DPFs as a function of FS

Table I. MC-derived DPFs to bone-water, and lung-water, computed using Eq (2) at depths of 3.975 cm (bone) and 6.475 cm (lung) vs. FS for both beams. The Type A uncertainties are ± 2 standard deviations.

Constant dose-perturbation factors are reached for FS ≥ 2 $\times$ 2 cm$^2$ (6 MV) and ≥ 5 $\times$ 5 cm$^2$ (15 MV) in bone and ≥ 25 $\times$ 25 cm$^2$ and 216 $\times$ 216 cm$^2$ in lung at 6 MV and 15 MV respectively; hence at these large field sizes depth differences no longer play any role.

4. Conclusions

The behaviour of the absorbed dose in heterogeneous media irradiated by small sub-equilibrium megavoltage photon fields is complex. Once the field is large enough for quasi-CPE to be established in the homogeneous, the dose is consistent with that predicted by ‘large photon cavity’ theory. These Monte Carlo simulations contribute to an improved understanding of the impact of tissue heterogeneity in small, sub-equilibrium photon fields; our results are consistent with those of Scott et al.2,4

REFERENCES


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