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Radiation Measurements 32 (2000) 105–111

Radiation Measurements

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Simulation and measurement of air generated electron contamination in radiotherapy

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Received 23 June 1999; received in revised form 1 October 1999; accepted 6 October 1999

Abstract

Monte Carlo simulations using MCNP4A and experimental work have been performed to evaluate the contribution of electrons that are produced in air from a 6 MV x-ray beam produced by a medical linear accelerator. Results show that up to 9% of applied dose is delivered to a patient's skin surface from electrons excited in the irradiated air column. For most field sizes this constitutes approximately 30% of dose delivered to this region. This study gives clinically relevant information on the origins and quantity of electrons at the skin of patients undergoing radiation therapy. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The use of medical linear accelerator x-ray beams for radiotherapy applications produces a 'dose build up' (Butson et al., 1996a; Nilsson and Sorcini, 1989; Biggs and Russell, 1983) which provides a skin sparing effect where a lower dose is given near the surface compared to dose at greater depths. Two main contributions to the dose at the skin site (which for our purposes extends from the surface of interaction down to 2 mm depth) are (i) electrons generated by primary and secondary photon interactions within the patient and (ii) electrons produced outside the patient but incident on the patient (electron contamination).

To evaluate electron contamination produced by the air column located between the x-ray source and the patient's skin, Monte Carlo simulations are set incident on a water phantom with varying configurations of air and vacuum for a high energy 6 MV x-ray spectrum. Experimental measurements where electrons excited from within the air column are eliminated are reported. By comparing Monte Carlo simulations and experimental work, an estimate of the percentage contributions to dose from the electrons originating in the air column, other sources of electron contamination and in phantom photon interactions can be made for the basal cell layer (0.07 mm) (Williams et al., 1989; Turesson and Thames, 1989) and the dermal layer (1 mm) of skin.

2. Materials and methods

Monte Carlo simulations were performed to simulate both the x-ray in-phantom interactions and the dose deposition from the air column above the patient. The Monte Carlo Neutron Photon 4A (MCNP 4A), Monte

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1350-4487/00/$ - see front matter
PII: S1350-4487(99)00263-2

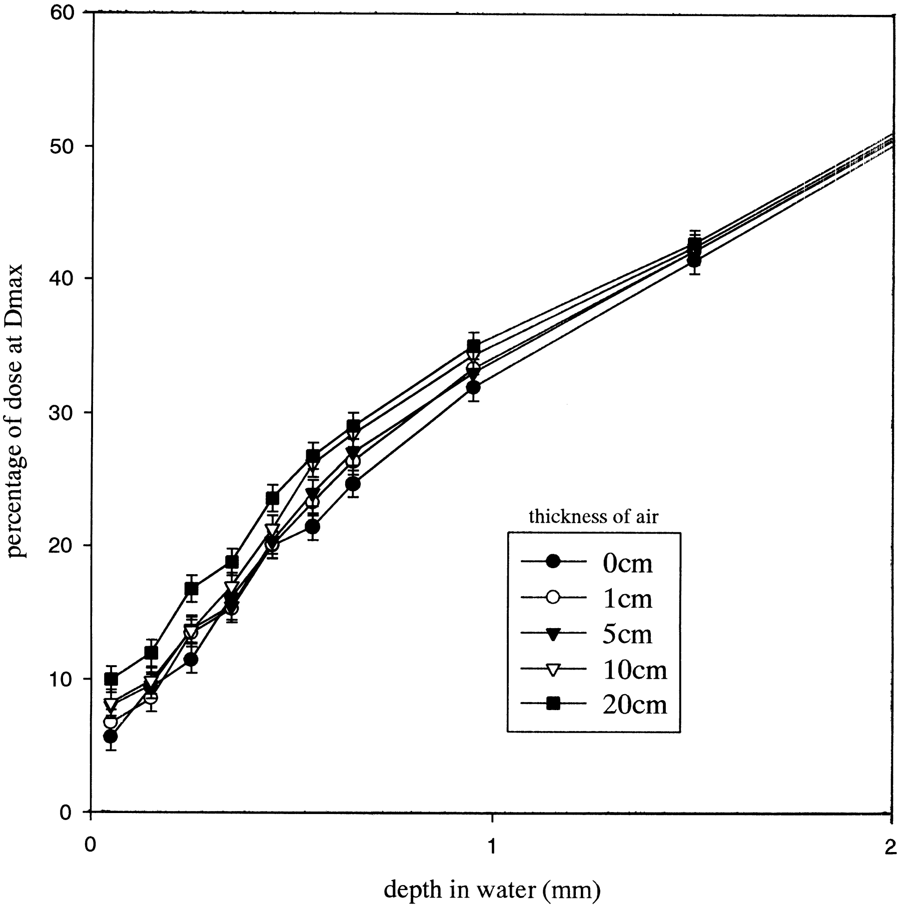

Fig. 1. Dose calculated by Monte Carlo simulations in the first 2 mm of water with varying thicknesses of air directly above the phantom.

Carlo code (Breismeister, 1993) was used where varying volumes of air were simulated by changing the boundary conditions for a layer of air above the simulated water phantom. This approach accounts for electrons generated directly by x-ray interactions within the air. It does not simulate accelerator head produced electron contamination or 'knock on' electrons produced in the air column by accelerator head produced electrons. A 6 MV spectrum which calculates depth dose within 2% of the experimental results from dmax to 30 cm was used (Mohan et al., 1985). In each case, 20 Million histories were scored. Voxel size was variable depending on the accuracy of results required and ranged from 0.1 mm thickness up to 5 cm thickness. That is, 0.1 mm thick voxels were used in the first 2 mm. 1 mm thick voxels were used from 2 to 20 mm. 1 cm thick voxels were used from 2 to 10 cm and 5 cm thick voxels from 10 to 30 cm. All voxels had a surface area of 5 × 5 cm for simulations.

For experimental removal of air generated electron contamination a helium bag system was constructed from 0.05 mm thick plastic with thin wire edges and a valve with dimensions 40 × 40 × 20 cm. Wire edges were inserted firstly to add weight to the device and secondly so the device could be molded to form an irregular patient shape if required. The helium bag was positioned under the x-ray beam with direct contact to the phantom to eliminate air near the measuring chambers. Percentage dose build up curves were measured on the central axis of a 6 MV x-ray beam for various beam configurations and energies. Measurements were performed with an Attix parallel plate ionisation chamber (Kron and Ostwald, 1995) in the build up region in a solid water slab phantom (Constantinou et al., 1982) of dimensions 30 × 30 × 30 cm. Reproducibility of measurements for this configuration was found to be ±0.5%. The over response of this type of chamber was calculated to be less than 1% at the surface for 6 MV x-ray beams (Rawlinson, 1992). The electron contamination pro-

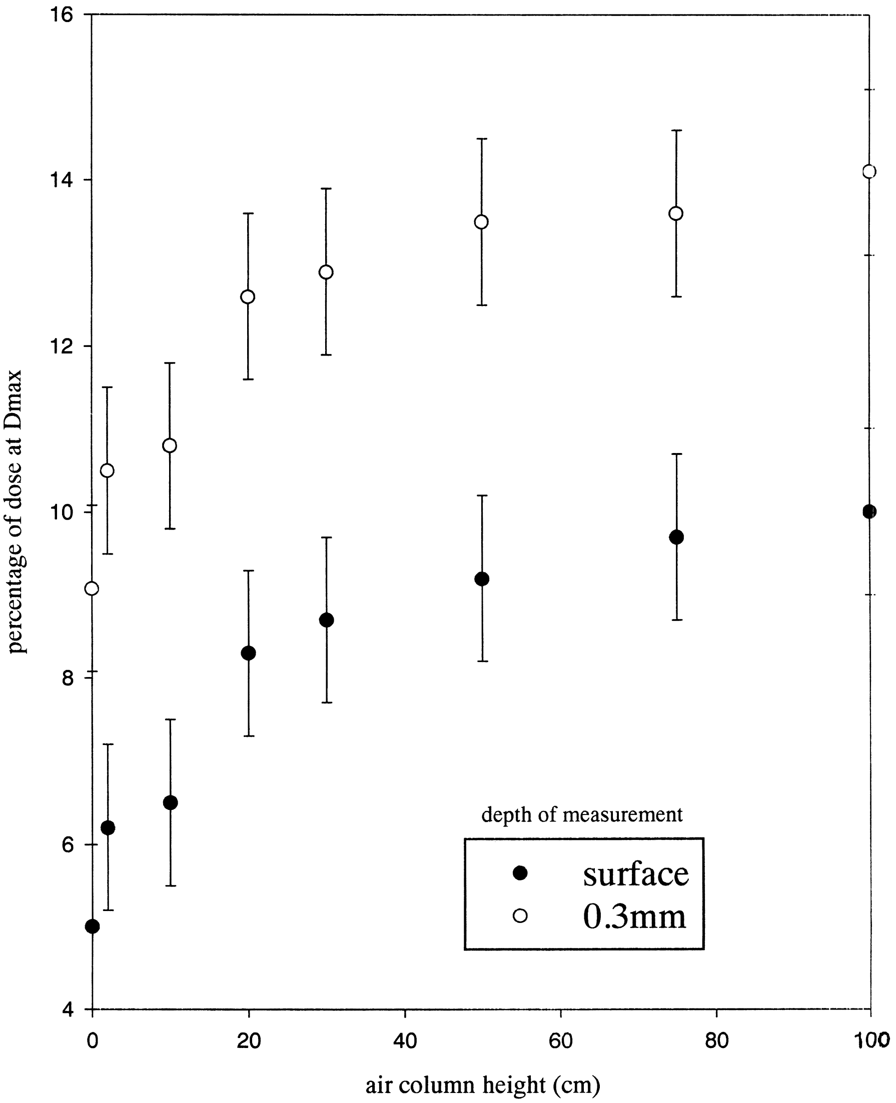

Fig. 2. Calculated percentage surface dose and dose at 0.3 mm in water for a 6 MV x-ray beam as the air thickness above the phantom is increased from 0 to 100 cm.

duced by the air column was calculated by comparison of the build up dose results for open fields with and without the helium bag system.

3. Results

Fig. 1 shows Monte Carlo simulations in the first 2 mm of water as the thickness of air directly above the phantom was varied. All results were normalized to 100% at $D_{\max}$. Results quoted are for a 10 × 10 cm field size at 100 cm SSD. An increase in extrapolated surface dose of approximately $4 \pm 1\%$ was seen when the thickness of air directly above the phantom was increased from 0 to 20 cm. A further increase in surface dose of 1.5% was seen when the air thickness was increased to cover the entire 100 cm SSD. These results are shown in Fig. 2 which also shows a percentage dose at 0.3 mm depth as the air column height is increased. A negligible increase in percentage dose was recorded beyond a 3 mm depth with the MCNP simulations when the air thickness was varied.

Measured percentage surface dose for open fields, calculated surface dose for MCNP simulations with a vacuum and including 100 cm of air are shown in Fig. 3 as a function of square field size. Percentage surface dose increases negligibly when only photon in-phantom scatter is considered as shown by the MCNP/vac-

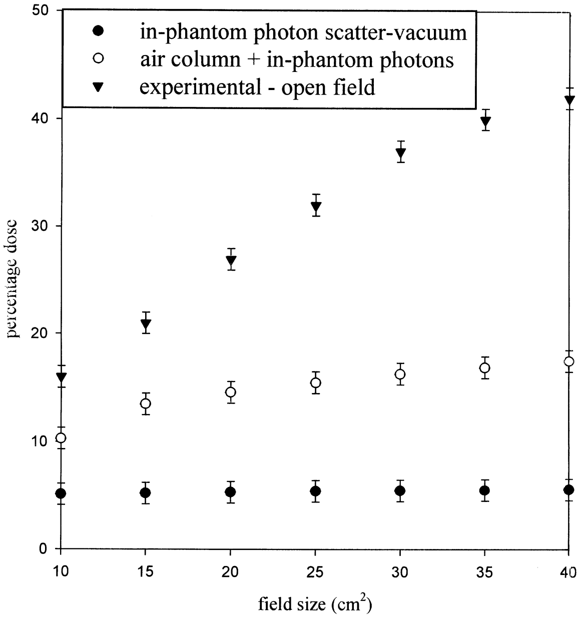

Fig. 3. Surface dose as a percentage of dose at $D_{\max}$ for 6 MV x-rays in three beam configurations. Experimental data shows a large surface dose due to all electron contamination. Monte Carlo generated results with an air column and vacuum have smaller surface doses.

uum results. Approximately 4–6% of $D_{\max}$ is recorded at the surface for field sizes from 10 × 10 cm up to 40 × 40 cm. When air is introduced to the simulations, surface dose increases with field size from 10% at 10 × 10 cm up to 18% at 40 × 40 cm. Large increases were seen in experimental data which include photon in phantom scatter, air generated electrons and other accelerator head produced electrons.

Results for experimental verification of the quantity of electrons excited within the air column are shown in Fig. 4. These values are obtained subtracting percentage dose results for helium measurements from open field results. The dose removed is maximum at the surface and falls off quickly. At a depth of 3 mm virtually no difference is seen in the dose which corresponds to Monte Carlo simulations. The short range of dose deposition implies that the contamination electrons produced in the air directly above the patient are relatively low energy.

4. Discussion

Monte Carlo simulations show an increase in the number of electrons excited in the air by x-ray interactions as field size is increased. An increase from 10 to 18% is seen from field sizes 10 × 10 cm to 40 × 40 cm. Measured contributions to surface dose from the air column are 4% of the dose at dmax for 10 × 10 cm, 6% for 20 × 20 cm and 7.5% for 40 × 40 cm respectively. These values are 4%, 7% and 9% respectively for MCNP simulations with the same configuration of air column. The helium is expected to contribute a small amount to the production of electrons. However, its density compared to air is 6.8 times less, thus we expect experimental results to be approximately 15% smaller than simulations for the amount of measured contamination.

The physical density of air at NTP is 1.205 kg/m^3, compared to 1000 kg/m^3 for water. The relative electron density is 0.0012, producing a range of electrons in air approximately 3 orders of magnitude larger than their range in water. Monte Carlo simulations show that the last 20 cm of air produce approximately 70% of dose due to the entire air column. Thus statistically, 30% of the electrons produced should have a range in air greater than 20 cm or 0.2 mm in water. Experimental results show that less than 40% of the dose at the surface is measured at a 1 mm depth. Experimentally, air is still present above the helium layer and electrons generated would travel a greater distance due to the presence of helium.

By comparing the measured and simulated percentage build up dose results at 0.07 mm and at a 1 mm depth, due to photon in-phantom dose and air generated electrons, Figs. 5 and 6 were produced. They show the percentage by ratio contribution to basal layer (0.07 mm) and a dose at 1 mm for each component. At the basal layer, only a small contribution is deposited by photons and the majority by machine head produced electrons and air generated electrons. (Machine head produced electron contamination was assumed to be all dose remaining at this site after the photon component and air generated component have been separated.) At 1 mm, phantom scatter deposits the majority of the dose however at larger field sizes, head generated electrons deposit a comparable dose to the phantom scatter.

5. Conclusions

Significant contributions to skin dose in radiotherapy for 6 MV x-rays are due to electrons excited in the air column between the target and the patient. The last 20 cm of air seems to contribute to the majority of electrons. Experimental verification of the contribution to skin dose from the air column is in agreement with the Monte Carlo simulations. This study may give some clinically relevant information on the origins of electrons on the skin of patients undergoing radiation therapy. By placement of the helium bag over a patient's skin during radiotherapy to eliminate the air column, a reduction in the skin dose up to 6% of the applied dose could be achievable.

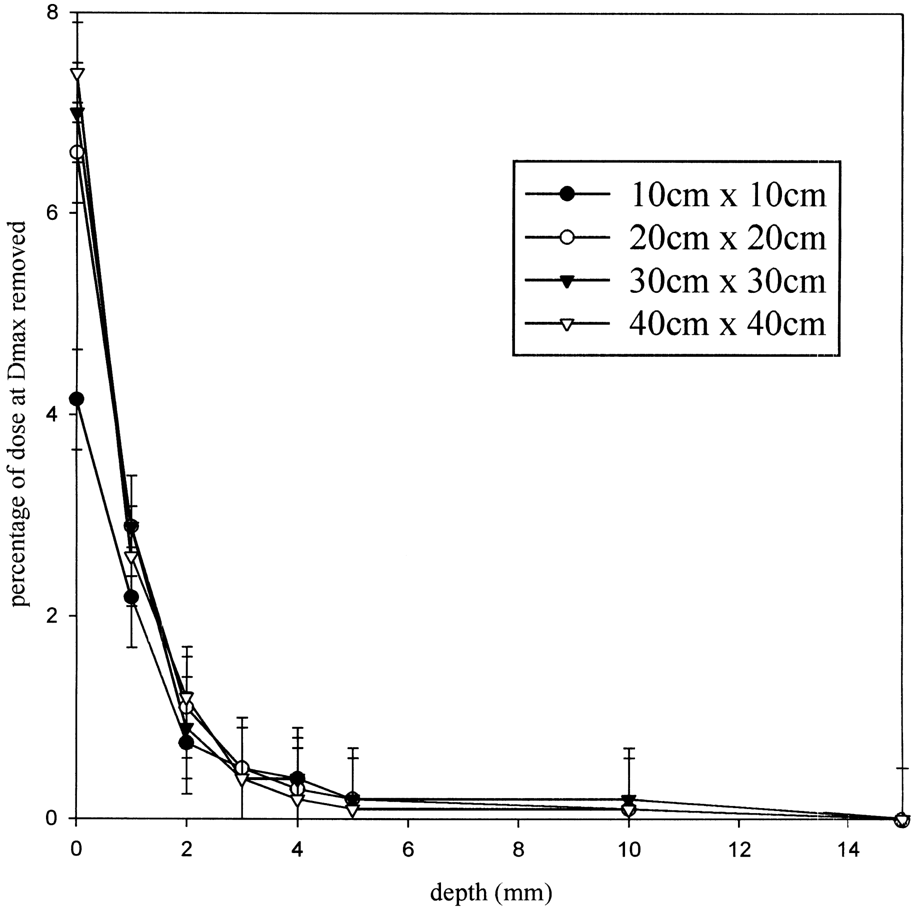

Fig. 4. Measured electron contamination produced within the air column by x-ray interactions. Results are derived from the subtraction of a percentage build up of dose measured with helium in the beam compared to an open field build up dose.

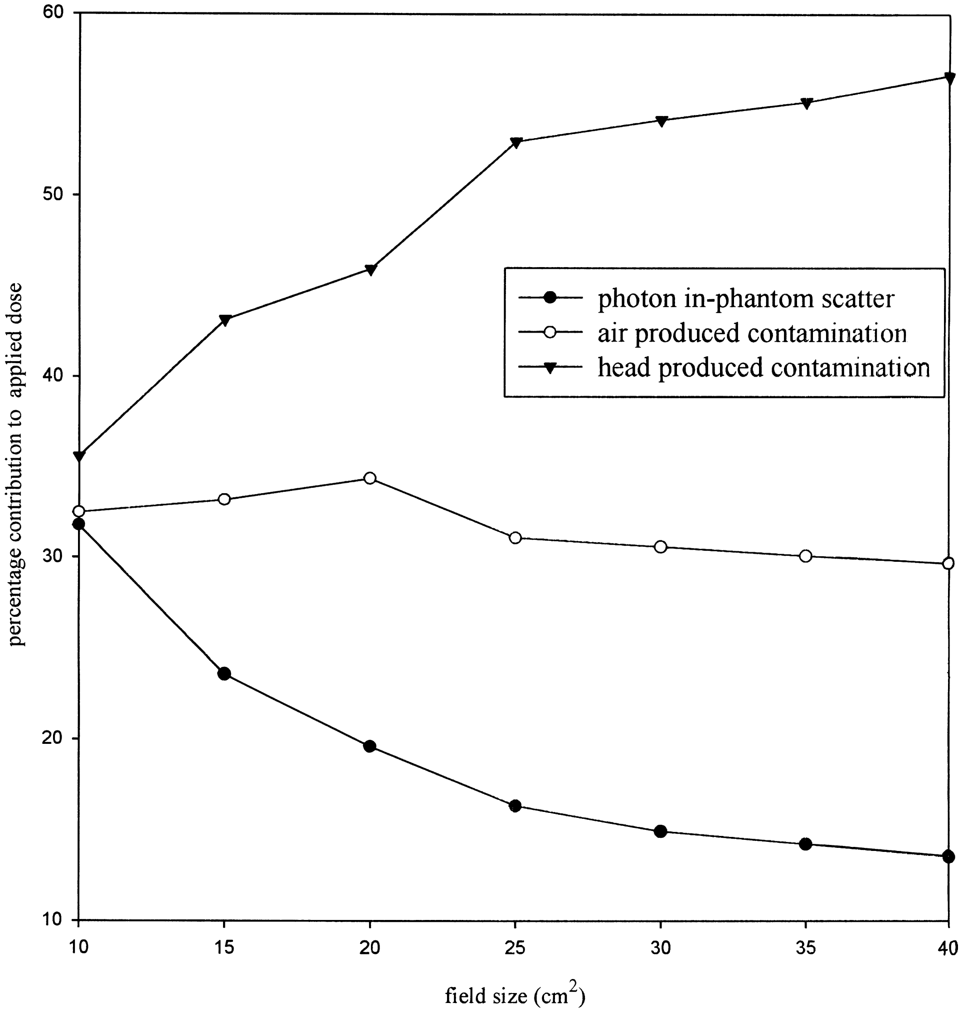

Fig. 5. Percentage dose contribution to skin at the basal cell layer (0.07 mm) from the photon interactions in phantom, air generated electron contamination and accelerator head generated electron contamination.

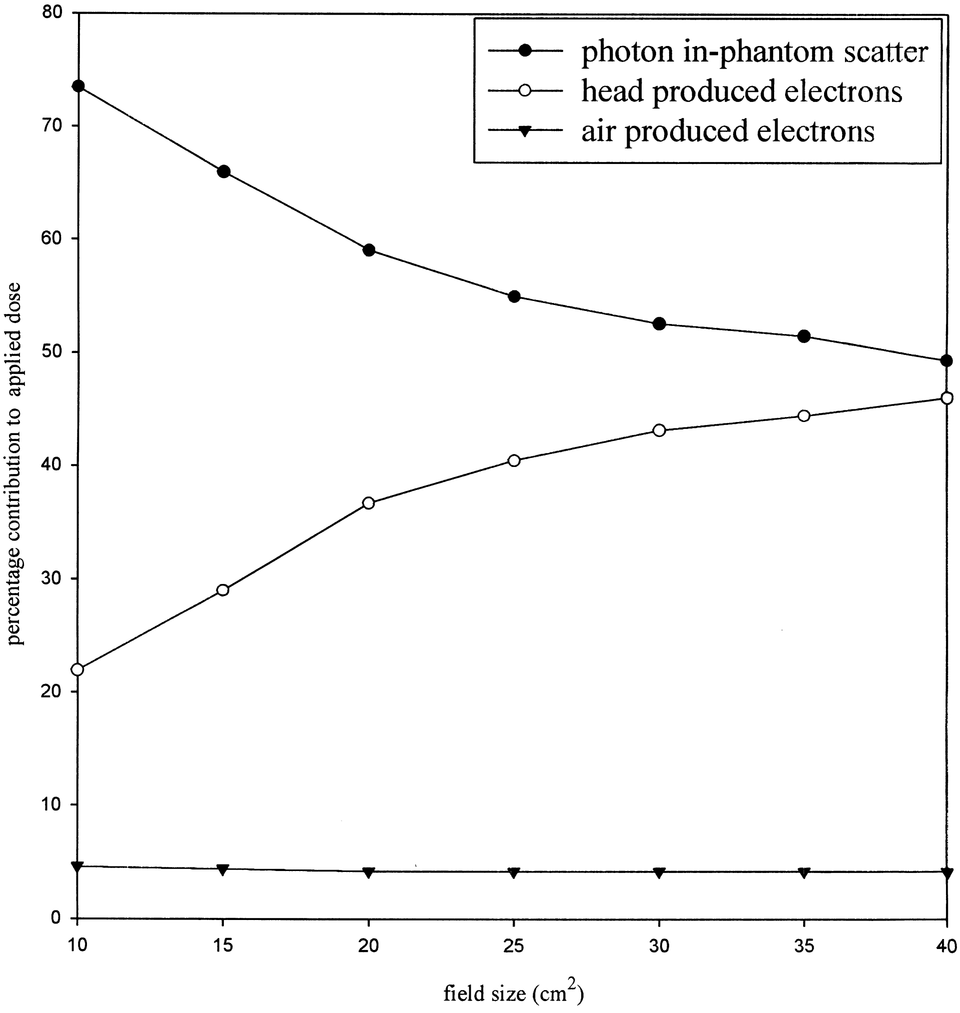

Fig. 6. Percentage dose contribution to skin at the dermal layer (1 mm) from the photon interactions in phantom, air generated electron contamination and accelerator head generated electron contamination.

Acknowledgements

This research was financed in part by grant No. 9030722 from the City University of Hong Kong.

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