The Measurements of Energy and Distribution of Scattered Electrons in Therapeutic X-Ray Beam

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Accurate knowledge of the distribution of contamination electrons (which comes from mainly gantry head by Compton scattering, pair production, and tray: henceforth called leptons) at the surface and in the first centimeters of tissue is essential for the clinical practice of radiation oncology. Such lepton tends to reduce or eliminate the 'skin-sparing' advantage of megavoltage photon beam radiotherapy. This information is needed to prescribe a absorbed dose to a skin volume at a few millimeter depth in high energy therapeutic radiation photon beam. All experiments were done with 15 MV photon beam from a dual energy linear accelerator (Clinac 1800, Varian). Field size is defined by ranged from 10.0×10.0 to 30.0×30.0 cm^2. The absorbed dose and distribution of leptons in therapeutic radiation beam (15 MV) are investigated by means of variable blocked beams of 30.0×30.0 cm^2 and dose beam profiles partly removed leptons with a copper plate. A numerous leptons mainly are distributed as shape of broad cone in the central photon beam and leptons path length in the water are shorter than 2.5 cm because of the leptons energy having around 3.0 MeV. These results clearly appears that the subtraction of leptons from the total depth dose curve not only lower the absolute dose in the buildup region and surface dose, it also causes a shift of d_{max} to a deeper depth.

Keyword : contamination electron, filter, mean energy

INTRODUCTION

One great merit of treatment of high energy photon beams lies in the basic property of their low surface dose. High energy photons are most favored in treating malignant tumors that occur at deep depths well below the skin because the maximum dose delivered to the tumors by these beams occurs a few centimeters below the surface with minimum damage to the skin[1]. However, the skin-sparing advantage of high energy photons is degraded by leptons, which severely increase the surface dose with increasing field size. Most photon beams used in radiation therapy are contaminated by leptons. It is believed that these leptons are created from the processes of Compton interaction and pair production of high energy primary photons in the field flattening filter, the primary and the secondary collimators, the plastic sheet and the air column between the source and treatment or phantom surface[2-7]. These leptons have been investigated and characterized by a number of authors throughout the years[8-13]. Some of authors[14,15] used different types of concentrated magnetic fields to sweep the leptons away from the radiation fields. Clinically, these leptons increase the entrance dose and become worse the buildup region in the field compared to if the field is free from leptons.

In this study, the relative quantity and the partial elimination of leptons in a therapeutic radiation photon beam (15 MV) have been investigated. First, we have measured the relative surface charge and the relative surface dose due to leptons, primary and

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scattered photons as a function of field size by custom-made charge detectors[16]. The absorbed dose and distribution of leptons in therapeutic radiation beam (15 MV) are investigated by means of a variable blocked beams of $30.0\times30.0\,cm^2$ and dose beam profiles partly removed leptons with a copper plate. The quantity of leptons in therapeutic radiation photon beam (15 MV) was investigated by means of measuring variation of relative surface dose due to leptons partly removed with or without a copper plate filter with thickness of $0.27\,g/cm^2$. The leptons are distributed as shape of broad cone type in the central beam. The another method of investigation for distribution of leptons in the photon beam is that the surface charges due to leptons, primary and secondary photons, are directly measured by charge detector.

MATERIALS AND METHODS

All experiments were done with a 15 MV photon beam from a linear accelerator (Clinac 1800, Varian). Field sizes were defined by the rectangular collimators of the linacs and ranged from 10.0×10.0 to $30.0\times30.0\,cm^2$. The thimble chamber (PTW-0.3 cm^3, M233641) was used in Multi-Data 3-dimensional water phantom for percent depth dose measurements and beam profile as function of depth variation from surface to 3.0 cm below. Dosimetry electrometer (Sun Nuclear 1010) was used to measure signals of ionization chamber and charge detectors.

1. Center and Off-Center Measurements

The distribution of scattered photons and leptons is measured by shifting of 10.0 cm thick block each interval 0.65 cm to off-center at the level of tray holder to produce variable blocked fields in order to investigate the distribution across the field size. The central and off-central axis depth dose beam data about half-blocked and variable beam size were obtained by scanning the beam each 1.0 cm moving interval of block from center to 8.0 cm off-center in Fig. 1.

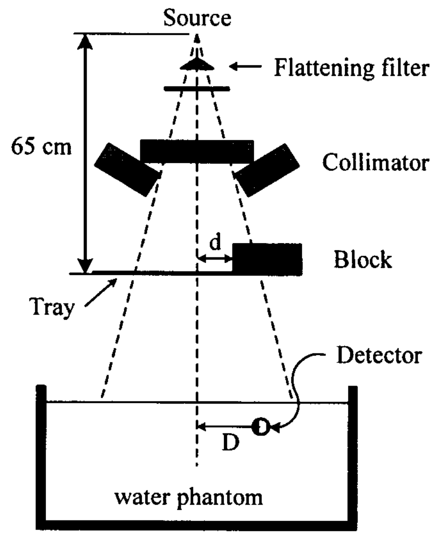

Fig. 1. The setup for measuring the distribution of leptons about central and off-central axis depth dose with respect to blocked variable beam size.

2. Copper plate Filtering

The copper plate filter with thickness of $0.27\,g/cm^2$ attached to the tray holder can exclude only leptons partly and attenuate very few photons for 15 MV photon beam. The reasons the photons with 15 MV energy pass through the copper plate with thickness of $0.27\,g/cm^2$ without interactions are as follows[1].

1) Photon Mean Energy

LaRiviere performed a combination of calculations based on published spectra and measurements of experimental depth dose curves and showed an excellent agreement between PDD(10) and the dose-weighted mean energy of photon beams, E_{mean} (MeV)[11]

$$E_{mean}\,(\mathrm{MeV}) = 10^{[PDD(10) - 55.37]/28.68} \qquad (1)$$

The term of PDD(10) is the percentage depth dose at 10 cm depth in a $10\times10\,cm^2$ field at a source to surface distance (SSD) of 100 cm. The photon beam with energy of 15 MV correspondents to about 6 MeV mean energy of linear accelerator (Clinac 1800 - Varian).

2) Transmitted Photon Through Copper-Plate With Thickness of 0.27 g/cm^2

Since the photons with mean energy 6 MeV have a small total mass attenuation coefficient for copper-metal component, a very few photons are attenuated by copper-plate (0.27 g/cm^2) for that energy. It is important to recognize that the minimum absorption coefficient in copper occurs at about 5 to 10 MeV[1].

$$N = N_0 B(h\nu, X, A, L) \exp[(-\mu/\rho)X] = 0.992 N_0 B \quad \text{for copper-plate thickness}(0.27\ g/cm^2) \tag{2}$$

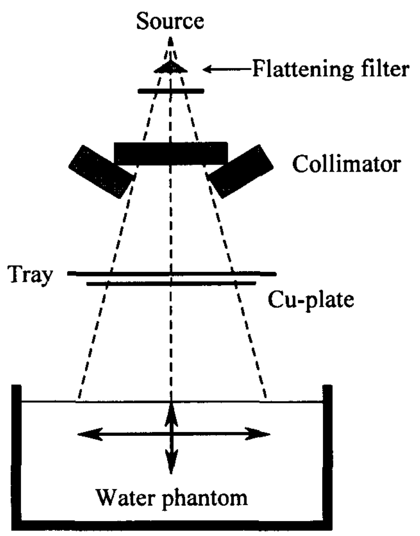

Fig. 2. The measurement of the difference of absorbed dose by copper filtering in beam profile as function of depth and position of across the beam.

where the symbols of N and N_0 are the numbers of transmitted and total incident photons respectively, B is a rather complicated factor, sometimes called a photon buildup factor, that takes account of the photons scattered by the attenuator. The symbols in parentheses indicate the dependence on energy, thickness, area, and distance respectively. Most of photons with 6 MeV mean energy could transit without interaction through the copper plate with thickness of 0.27 g/cm^2. This copper plate attenuates the photon intensity by 0.8% of the total incident photon beam. Since mean energy 6 MeV photons have a smaller total mass attenuation coefficient for copper metal component, a very few photons are attenuated by Cu-plated in Table 1.

3) Leptons Energy in Photon (E_{mean}=6 MeV) Beam

The incident photon with a mean energy 6 MeV generally produces leptons which have energy with 2.5~3.5 MeV range by Compton and Pair production process, assuming that leptons have an approximate mean energy 3.0 MeV[17].

The total mass stopping power of leptons with 3 MeV energy for Cu and Pb-plate are as follows[18]

$$\left[\frac{1}{\rho}\left(\frac{dE}{dl}\right)_{tot}^{Cu}\right]_{3\,MeV} = 1.448\ MeV\,cm^2/g \quad (12.974\ MeV/cm) \tag{3}$$

$$\left[\frac{1}{\rho}\left(\frac{dE}{dl}\right)_{tot}^{Pb}\right]_{3\,MeV} = 1.406\ MeV\,cm^2/g \quad (15.958\ MeV/cm) \tag{4}$$

Table 1. The total mass attenuation coefficient of copper and lead for 15 MV photon beam (mean energy : ~6 MeV)

Photon Energy (MV)	Cu Z=29		Pb Z=82	
	μ/ρ	μ_{en}/ρ (m^2/kg)	μ/ρ	μ_{en}/ρ (m^2/kg)
3.0	3.599 × 10^{-3}	2.016 × 10^{-3}	4.234 × 10^{-3}	2.351 × 10^{-3}
5.0	3.176 × 10^{-3}	1.991 × 10^{-3}	4.272 × 10^{-3}	2.600 × 10^{-3}
6.0	3.108 × 10^{-3}	2.019 × 10^{-3}	4.391 × 10^{-3}	2.730 × 10^{-3}
8.0	3.074 × 10^{-3}	2.092 × 10^{-3}	4.675 × 10^{-3}	2.948 × 10^{-3}

Cu-plate has very large value of total mass stopping power like Pb-plate for leptons but smallest value for photons. Therefore, the copper plate with thickness of 0.27 g/cm^2 could not attenuate photons but filters out partial quantity of the total incident leptons in the photon beams used in radiation therapy.

3. Direct Measurement of Leptons Using a Charge Detector

1) Pancake Type Charge Detector (Faraday Cup)

We describe an experimental method for direct measurement of the negative signals induced by lepton component as function of radiation field sizes in a photon beam. The charge detector used in measuring the lepton is shown schematically in Fig. 3.

The Faraday Cup consists of a copper disk of 1.0 cm diameter with thickness of 2.24 g/cm^2 and has a guard ring with same thickness connected to the ground. This thickness of copper slab is greater than the maximum continuous slowing down approximation range (R_{CSDA}) of leptons with 3.0 MeV energy to be detected[1]. A shielded cable connects the copper disk collector to a electrometer, used in the current or Coulomb modes. The Coulomb (C) measured by the electrometer when the charge detector is irradiated by photon beam with leptons, will consist of three components.

$$_{photon}C^{small\ beam}_{exp.} = {}_{photon}C^{small}_{primary} + {}_{photon}C^{small}_{scattered} + {}_{photon}C^{small}_{lepton} \quad (5)$$

$$_{photon}C^{large\ beam}_{exp.} = {}_{photon}C^{large}_{primary} + {}_{photon}C^{large}_{scattered} + {}_{photon}C^{large}_{lepton} \quad (6)$$

where the terms of (C) mean the Coulomb signal intensities of Faraday Cup for lepton, primary and scattered photon beams, small and large field size respectively. The left side terms of net Coulomb are measured by electrometer using Faraday Cup. Practically, irrespective of radiation beam size, the signals of Coulomb induced by primary photon beam are almost constant values,

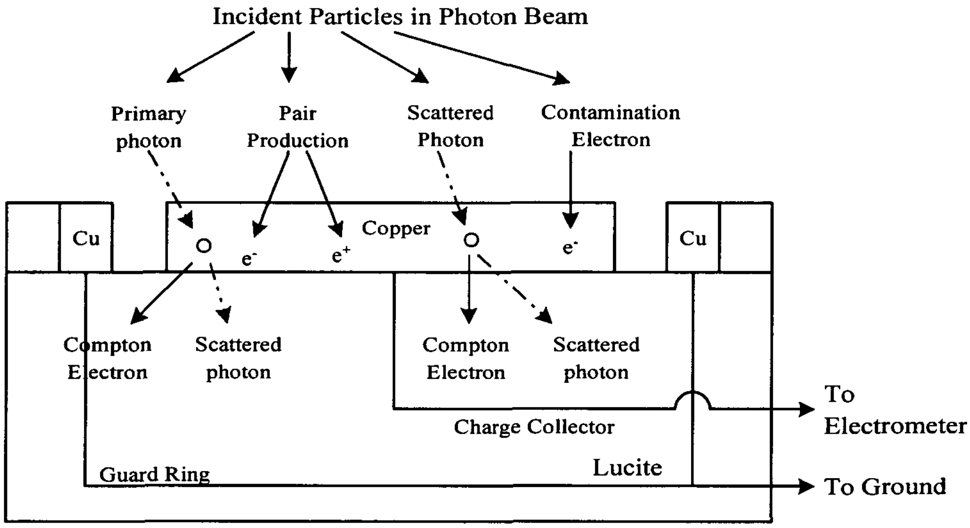

Fig. 3. The copper cylindrical disk of 1.0 cm diameter (charge collector), which immediately measure the surface charges due to leptons, primary and scattered photons, and guard ring are embedded in Lucite plate with it's dimension being 25×25 cm^2 area and thickness of 2.5 cm.

$$ {}_{photon}C^{small}_{primary} \approx {}_{photon}C^{large}_{primary} \qquad (7) $$

As the field size decreases from 25×25 to 5×5 cm^2, the surface charge or dose contributed by scatter radiation decrease and the scatter doses slowly diminish until at around 5×5 cm^2 they become essentially negligible,

$$ {}_{photon}C^{large}_{scattered} \gg {}_{photon}C^{small}_{scattered} \qquad (8) $$

Clearly, the megavolt radiation beams contain leptons which is negligible for small radiation fields but slowly increases with field size to reach a sizeable proportion of the total dose in the buildup region or surface charge and dose due to leptons for large fields[19-23]. The leptons are the most prominent on the surface and becomes negligible at depths around the d_{max} of the photon beam. The larger field size, the more amount of leptons exist in the photon beam,

$$ C^{large}_{lepton} \gg C^{small}_{lepton} \qquad (9) $$

If the leptons, such as the terms of C^{large}_{lepton} and C^{small}_{lepton}, can be removed in the photon beam from both formula (5) and (6) but it can not eliminate the terms of scattered photon, compare (5) with (6), and then,

$$ {}_{photon}C^{large}_{exp.} \gg {}_{photon}C^{small}_{exp.} \qquad (10) $$

Resultantly, the signals of surface charge or dose for large field size is always larger than that of small beam size.

RESULTS AND DISCUSSIONS

The distribution of leptons and scattered lower energy photon is measured by shifting of shielding 10.0 cm thick alloy block in the photon beam at the level of tray holder on the Lucite plate to produce variable blocked fields. The thimble chamber is used in water phantom for percent depth dose measured due to scattered leptons only from surface to 20.0 cm depth on the blocked area and beam profile as function of depth variation from surface to 8.0 cm below.

For the purpose that the ion chamber must be "exposed" only by the scattered photons and leptons from the machine and accessories, it was placed at the off-center distance 1.0 cm from the central axis at SSD 100 cm and under 10.0 cm thick block which was closed up to the central axis. Step by step, the block is shifted from center to off-center 0.65 cm distance and then ion chamber also is moved to 1.0 cm (D_{cm} = 1.0) distance same direction at SSD 100 cm in order to measure percent depth dose of leptons with same condition as function of off-center position as shown in Fig. 1.

All points across the field, the closer the center results in a larger amounts of leptons dose. The upper curve (D_{cm} = 1.0) followed by a rapid fall-off is typical of surface dose of leptons and the relatively slow fall-off at positions beyond 8.0 cm is due in large part to scattered photons. Qualitatively, the slope is greater at closer center than at farther. Therefore, there is a greater magnitude of leptons at the center in Fig. 4.

The percent depth dose partly removed leptons by copper plate (0.27 g/cm^2) not only lower absolute

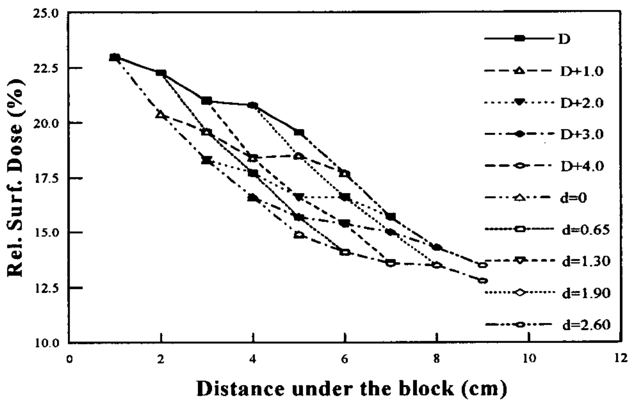

Fig. 4. The magnitude of surface dose of leptons and scattered photons as function of off-central displacement from the central axis under the block measured for several points.

dose in the buildup region, it also causes a shift of d_{max} to a deeper depth. The copper plate filters only leptons existed in the buildup region and attenuate a very few photons in or beyond buildup region in Fig. 5.

Clearly, in Table II megavoltage radiation beams used in radiation therapy contain a great deal of leptons. They are negligible for small radiation fields but slowly increase with field size to reach a sizeable proportion of the total dose in the buildup region for large fields.

The leptons in photon beam as a function of depth beam profile was studied. The lepton can be effectively reduced by locating a copper plate(0.27 g/cm^2) immediately below the blocking tray. It can be noticed that an optimum thickness of 0.27 g/cm^2 copper plate is suitable for eliminating only leptons except photons in 15 MV photon beams. Variations in beam profile as function of depth from 0.25 cm to 3.0 cm below are noticed between the open and the blocked beam with filter. Since the copper plate (0.27 g/cm^2) in 15 MV photon beam path can not attenuate the photons but filter a great deal of the only leptons in Fig. 6.

The differences of absorbed dose in beam profiles with respect to depth mean the distributions of lepton in photon beam according to depth and position of across the beam. The curve at shallow depth (0.25 cm) has a large difference (~10%), it follows that there is a many leptons in that depth. Gradually, the deeper depth, the smaller amount of leptons. Finally, at depth of 3.0 cm the curve has no difference between open and blocked with copper, it means that there is no more leptons in that depth. The depth of 3.0 cm water could absorb enough all of leptons in the photon beam because of leptons

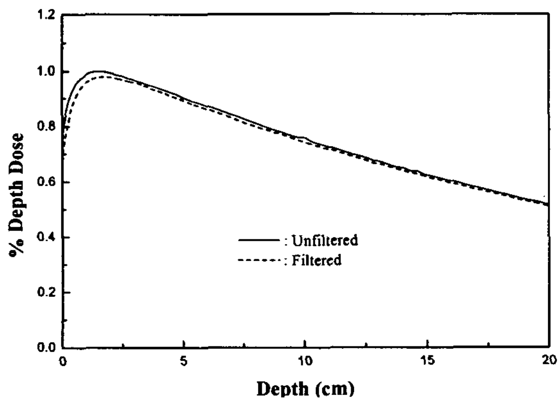

Fig. 5. Percent depth dose of photon used in radiation therapy and photon beam partly removed leptons by Cu-plate in the central beam.

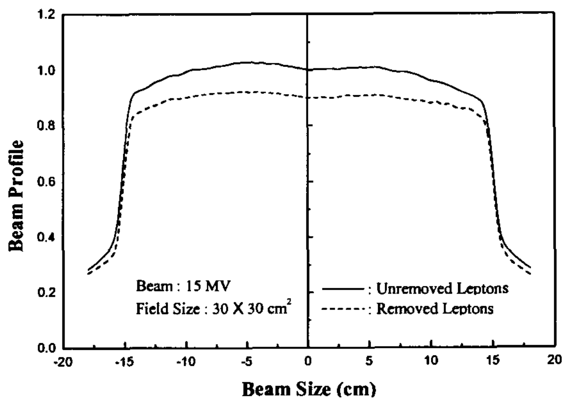

Fig. 6. Beam profiles of general photon used in radiation therapy and photon beam partly eliminated leptons by Cu-plate with respect to depth (0.25 cm).

Table II. The difference of relative surface dose and d_{max} for photon (15 MV) and beam partly removed leptons by Cu-plate.

Field Size (cm^2)	Without Cu-Plate		With Cu-Plate	
	Surface Dose(%)	d_{max}(cm)	Surface Dose(-%)	$d_{max(+)}$(cm)
10×10	38.5	2.8	35.1 (-3.4%)	2.8 (0.0)
15×15	45.5	2.6	41.1 (-4.4%)	2.8 (+0.2)
20×20	53.1	2.1	48.2 (-4.9%)	2.4 (+0.3)
25×25	60.0	2.0	54.1 (-5.9%)	2.3 (+0.3)
30×30	76.5	1.6	67.4 (-9.2%)	2.0 (+0.4)

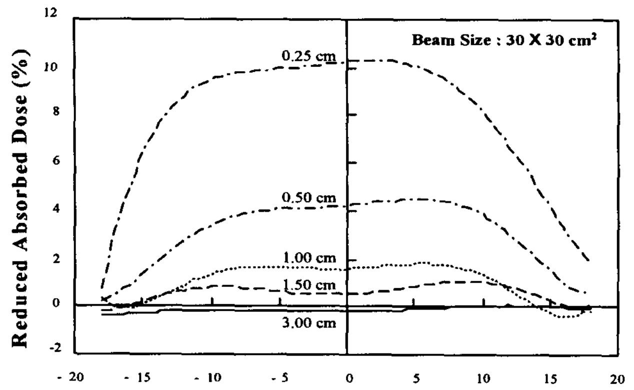

Fig. 7. The difference of absorbed dose as function of depth in beam profile between the general photon (15 MV) and photon beam removed leptons by Cu-plate. They follows leptons are mainly distributed in center.

energy having smaller than 3.5 MeV. All curves appear that the distributions of lepton are spread widely, but they are mainly distributed in the central beam in Fig. 7.

CONCLUSIONS

The maximum path length of lepton from 15 MV photon beam used in radiation therapy is 3.0 cm distance in water phantom because of lepton's energy having lower than 3.5 MeV. Qualitatively, the larger field size and closer to the central beam, there are a more amount of leptons. The copper plate (0.27 g/cm^2) could filter the only leptons but a very few attenuation (0.8%) of photons in the photon beam. A lots of leptons mainly are distributed in the central beam as shape of broad cone type as shown in Fig. 7.

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치료 방사선 선속(Flux)에 포함된 산란전자의 분포와 에너지 측정

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치료방사선 선형가속기에서 출력되는 광자선의 선속 (flux)에는 gantry head로부터 발생되는 오염전자를 포함하고 있으며, 오염전자의 발생은 주로 gantry head의 부속장비 또는 방사선 치료를 위해 gantry head 밑에 설치되는 부속장치 등에서 광자선과 매질의 전자쌍생성, 또는 컴프톤 산란전자 등의 물리적 현상으로 발생된다. 오염전자는 표면영역의 수cm 깊이의 선량 분포에 영향을 주고 있으며, 이것은 방사선 치료 시 skin-sparing 효과를 감소시키는 등 임상적인 측면에 영향을 주고 있다. 그러므로 선형가속기에서 발생되는 오염전자의 특성을 이해 할 필요가 있다. 본 연구는 선형가속기 (Clinac 1800, Varian) 에서 출력되는 15 MV 광자 선속에서 조사야의 크기가 $10.0\times10.0\ cm^2$에서 $30.0\times30.0\ cm^2$ 대해 구리판 (Cu)의 부분적 오염전자 제거 능력과, 조사야의 부분 차폐 방법을 이용하여 물팬톰 내의 선량분포의 변화를 측정하므로써 오염전자의 특성을 분석하였다. 그 결과 오염전자는 조사야의 중심축으로부터 넓게 퍼진 cone 모양의 분포를 하고 있었으며, 또한 오염전자가 갖는 평균 에너지는 약 3.0 MeV로 나타났다. 그러므로 오염전자는 표면으로부터 2.5 cm 깊이까지 분포하였다. 이러한 결과로써 광자선속에 포함된 오염전자를 제거하고 순수한 광자선을 이용한다면 buildup 영역 및 표면선량이 감소되고, 최대선량지점이 좀더 깊어진다.

중심 단어 : contamination electron, filter, mean energy