4-, 6-, 10-MV X-선원에서 공기동이 흡수선량에 미치는 효과 : 후두모형

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Air Cavity Effects on the Absorbed Dose for 4-, 6- and 10-MV X-ray Beams : Larynx Model

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Purpose : When an x-ray beam of small field size is irradiated to target area containing an air cavity, such as larynx, the underdosing effect is observed in the region near the interfaces of air and soft tissue. With a larynx model, air cavity embedded in tissue-equivalent material, this study is intended for examining parameters, such as beam quality, field size, and cavity size, to affect the dose distribution near the air cavity.

Materials and Methods : Three x-ray beams, 4-, 6- and 10-MV, were employed to perform a measurement using a 2cm (width)×L (length in cm, one side of x-ray field used)×2cm (height) air cavity in the simulated larynx. A thin window parallel-plate chamber connected to an electrometer was used for a dosimetry system. A ratio of the dose at various distances from the cavity-tissue interface to the dose at the same points in a homogeneous phantom (observed/expected ratio, O/E), normalized buildup curves, and ratio of distal surface dose to dose at the maximum buildup depth were examined for various field sizes. Measurement for cavity size effect was performed by varying the height (Z) of the air cavity with the width kept constant for several field sizes.

Results : No underdosing effect for 4-MV beam for fields larger than 5cm×5cm was found. For both 6- and 10-MV beams, the underdosing portion of the larynx at the distal surface was seen to occur for small fields, 4cm×4cm and 5cm×5cm. The underdosed tissue was increased in its volume with beam energy even for similar surface doses. The relative distal surface dose to maximum dose was changed to 0.99 from 0.95, 0.92, and 0.91 for 4-, 6-, and 10-MV, respectively, with increasing field size, 4cm×4cm to 8cm×8cm. For 6- and 10-MV beams, the dose at the surface of the cavity is

이 논문은 1997년 5월 2일 접수하여 1997년 10월 28일 채택되었음.

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measured less than the predicted by about two and three percent, respectively, but decrease was found for 4-MV beam for 5cm×5cm field. For the 4cm×L×Z (height in cm), varying depth from 0.6 to 4.8cm, cavity, O/E>1.0 was observed regardless of the cavity size for any field larger than about 8cm×8cm.

<u>Conclusion</u>: The magnitude of underdosing depends on beam energy, field size, and cavity size for the larynx model. Based on the result of the study, caution must be used when a small field of a high quality x-ray beam is irradiated to regions including air cavities, and especially the region where the tumor extends to the surface. Low quality beam, such as, 4-MV x-ray, and larger fields can be used preferably to reduce the risk of underdosing, local failure. In the case of high quality beams such as 6- and 10-MV x-rays, however, an additional boost field is recommended to add for the compensation of the underdosing region when a typically used treatment field, 5cm×5cm, is employed.

Key Words: Electronic nonequilibrium, Interface dosimetry, Photon beams, Air cavity, Larynx

INTRODUCTION

When high quality photon beams are incident on an interface of two different materials, electrons set in motion in the surface layers of the tissue travel appreciable distances in the tissue medium before coming to rest[1]. Energy extracted from the high quality photon beam by interaction processes in the surface layers will not, in general, be dissipated in these layers, but in layers below the surface. If as much energy is dissipated in the surface layers by the passage of these electrons as it carried away by electrons set in motion in the layers through photon interaction, the surface is said to be in a state of electronic equilibrium. At a depth below the tissue surface equal to the maximum range of the secondary electrons, electronic equilibrium is achieved by photon interactions in the medium itself. Under certain circumstances like air-tissue interfaces, it is possible for the number of electrons reaching the tissue surface to be greatly reduced from the number required to produce the equilibrium state. Under such conditions the amount of energy absorbed by the surface will be less than the amount absorbed at the depth of tissue equal to the maximum range of the secondary electrons, the dose-buildup effect. This results from the combination of the density change, a thousandfold difference, at the interface and geometric factors involving both photon-beam dimensions and electron scattering[2].

There have been significant advances in the calculation of doses when external photon beams encounter an inhomogeneous media, such as an air-tissue interface. Unfortunately, however, there is a difficulty in accurate dose computation near interface due to the lack of electronic equilibrium and none of the current dose computation models implemented in commercially available treatment planning systems can predict the interface doses accurately[3], although the doses at larger distances beyond the air-tissue interface can be estimated with good accuracy. Experimental data are therefore required to quantify the magnitude of the dose reduction in the vicinity of air-tissue interfaces. A similar situation exists when air cavities are present in the patient. In particular, the air-tissue interface, for example, upper airway (larynx) where air gaps of greater than 1cm are encountered over significant lengths, Fig. 1, that gives rise to the skin-sparing effect for high energy photon beam, is of clinical concern and must be taken into account if the tumor extends to the surface.

The presence of an air cavity can yield either an underdosing or overdosing effect by the competing effects of increased transmission and lack of scattered electrons and photons[4, 5]. Appreciable underdosing of the surface layers of a lesion could occur as a result of the lack of electronic equilibrium[6-9]. Extensive measurements of surface doses behind various cavities using a parallel-plate chamber were reported for ^{60}Co gamma rays and 10MV x-ray beams. In the study, the interface doses as much as 15% less than the homogeneous (no cavity) doses was observed with the clinically encountered air cavity dimensions by 10MV x-ray beam but no appreciable effect for cobalt-60 was reported. Several studies were performed to measure (distal and proximal) air-tissue interface doses using thermoluminescent dosimeters (TLDs)[10-13], films[12, 14], and diodes[14], which differ considerably from the results by ionization chambers, and evaluated by Monte Carlo simulation[14].

In this study, a larynx was simulated as an example of an air-soft tissue interfaces, air cavity embedded in tissue-equivalent material. When an early glottic carcinoma is treated using a megavoltage photon beam, two parallel opposing lateral beams are used using a small field, typically 5cm ×5cm. Because many radiation therapy clinics now treat head and neck cancers with 4- or 6-MV (or sometimes 10-MV) x-ray beam, dosimetric effect on the energy should be verified in addition to the field size effect. By examining parameters such as energy, field size, and cavity size, it is hoped that this study can offer a guideline for the amount of boost field irradiation for compensating the underdosing region in the case of the field containing air cavities.

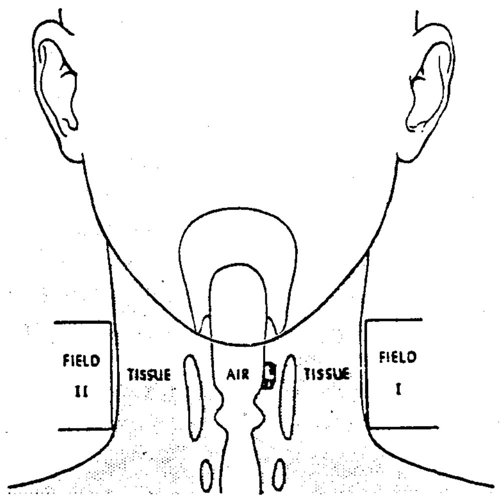


Fig. 1. Schematic diagram of coronal section of a larynx, a portion of the tracheo-laryngeal air passage to show the tissue inhomogeneities, soft tissue-air-soft tissue geometry.

MATERIALS AND METHODS

Experiments were performed with 4-MV (CLINAC 600C) and 6- and 10-MV (CLINAC 1800, Varian, CA) x-ray beams available in the Radiation Oncology Department of our medical center. A thin window parallel-plate chamber (Type 23343, PTW-Freiburg, Germany), having a 0.055 cm^3 active volume and a 0.03mm membrane thickness, which was connected to a PTW IQ4 electrometer with 300-V detector bias voltage, was chosen for a dosimetry system. In order to study the surface dose on the exit side of an irradiated larynx, a custom-made phantom which incorporates an ionization chamber in the distal side of a variable air cavity was employed. Tissue-equivalent material used for the custom-made phantom was an acrylic, $\rho = 1.180 \times 10^3$kg/m^3, $Z_{eff} = 6.65$, and electron density $n_0 = 3.80 \times 10^{29}$ m^{-3}, which is close to those of soft tissue, $\rho = 1.040 \times 10^3$kg/m^3, $Z_{eff} = 7.64$, and electron density $n_0 = 3.480 \times 10^{29}$ m^{-3} [15].

The first set comprised a layered geometry in which the pre- and post-cavity thicknesses of tissue equivalent material, 4cm each, and a 2cm × 30cm × 2cm, width × length × height, cavity is shown in Fig. 2. Length of the cavity was 30cm but actual cavity length was confined to the one side of the field size (hereafter L denotes the one side of x-ray fields used for the measurements in cm). Doses were measured at longitudinal interface taken distal from the beam source following a cavity with varying overlying soft tissue thickness, and therefore depth. Field sizes at the distal surface of

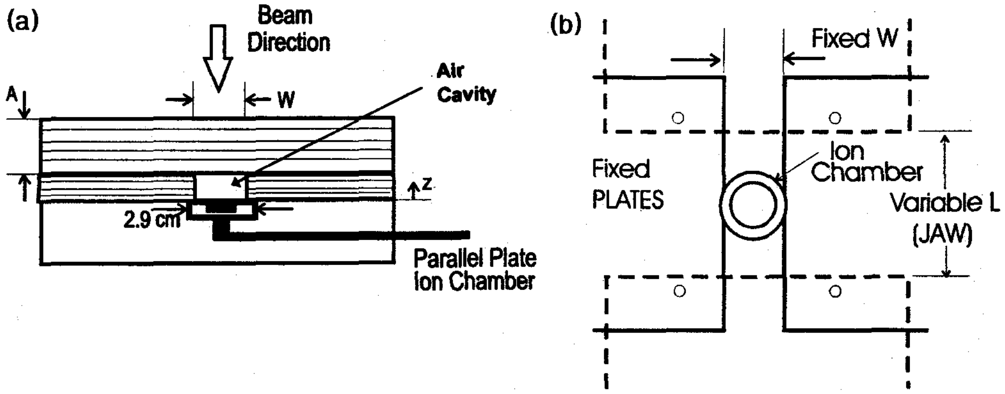


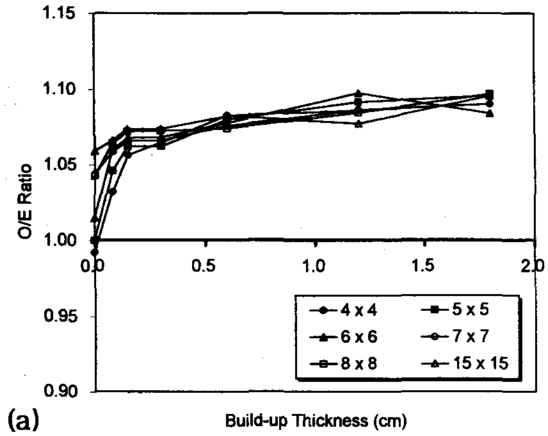
Fig. 2. Side- and top-views of the measurement geometry for the cavity, simulated larynx. An incident photon beam encounters a precavity soft tissue (A), 4 cm, followed by a cavity of dimensions W (width)×L (length)×Z (height), 2cm×L (cm, one side of field size used)×2cm, followed by a distal region of soft tissue (Not drawn to scale): (a) Side-view; (b) Top-view.

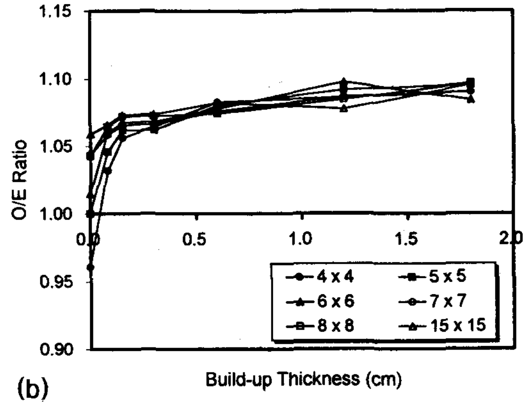
the cavity ranging from 4cm×4cm to 15cm×15cm were examined with all measurements performed at a fixed source-to-distal surface of the cavity distance of 100cm for all beams and therefore source-to-phantom surface distance = 94cm. For each measurement, three consecutive readings were taken. A ratio of the dose measured at various distances from the distal surface of the cavity-tissue interface to the dose measured at the same points in a homogeneous phantom, observed/expected (O/E) ratio, the concept borrowed from Epp et al.[7,8], was determined for a variety of field sizes and tissue depths. Normalized buildup curves are also presented, giving a direct visualization of the tissue effects and the ratio of distal surface dose to dose at the maximum of the buildup curve (beyond the cavity), the buildup reduction factor, defined in previous works[7,8].

The second set, independent of the first, was for the change of the cavity size effect on the O/E ratios for a particular x-ray beam, 6-MV. Field size, defined at the distal surface of the cavity, was ranged from 5cm×5cm to 15cm×15cm. Cavity size was changed by varying the height (Z) from 0.6 to 4.8cm with fixed width and length, 4cm and L, respectively, which is different from that of the cavity for the first set of experiment 2cm (width)×L (length in cm)×2cm (height). Simulated cavity was positioned at the mid-depth of the overlying soft tissue/air cavity/underlying soft tissue, 4cm / Z / 4cm, geometry with the fixed source-to-distal surface of the cavity distance of 100cm, source-to-frontal surface of the phantom distance = 94cm, for all measurements. The O/E ratio measurement was performed on the distal surface of the cavity, depth = 0.0cm.

RESULTS

In Fig. 3, the O/E ratios on the central axis for the simulated larynx cavity, 2cm×L×2cm, are presented as a function of buildup thickness, depth, beyond the cavity for a variety of field sizes in 4-, 6- and 10-MV x-ray beams. For the smallest field used, 4cm×4cm, O/E=0.99 is found, which in turn shows that an underdosing portion can be seen for 4-MV beam. For both 6- and 10-MV beams, the underdosed portions of the larynx are seen to occur for 4cm×4cm and 5cm ×5cm fields. Field sizes of greater than 6cm× 6cm can apparently be used with both energies without underdosing the distal surface. Fig. 4 is a plot of the amount of tissue that may be underdosed, O/E<1.0, for three small fields, 4cm×4cm, 5cm×5cm, and 6cm×6cm, using three x-ray beams of different quality. For a typical treatment field for early glottic cancer, 5cm×5cm, underdosing depth into soft-tissue is found to be increased to





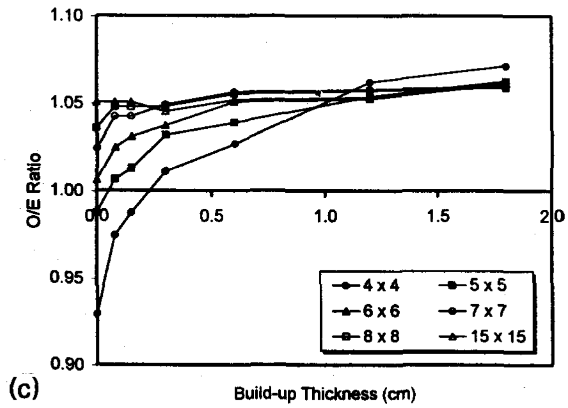


Fig. 3. Comparison of central axis O/E ratios versus tissue depth beyond a 2cm (width) × L (cm, length) × 2cm (height) cavity, open at both ends, for various field sizes (cm × cm). Note the horizontal line at O/E = 1.00 : (a) 4-; (b) 6-; (c) 10-MV.

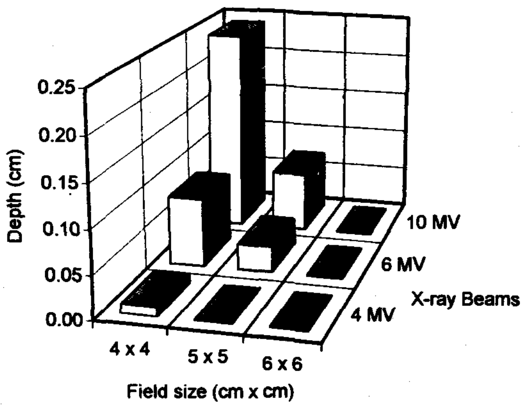


Fig. 4. Tissue depths over which the dose is less than predicted (O/E<1.0). For three small field sizes, 4-, 6-, and 10-MV x-ray beams are used. These depths are indicative of the increased volume of tissue that is underdosed at the beams of higher qualities.

0.07cm for 10-MV beam. No underdosing effect for 4-MV beam for fields larger than 5cm × 5cm is found even though there is minor decrease in distal surface dose in 4cm × 4cm field. A marked increase is seen for all field sizes as the beam energy drops, with 6-MV falling roughly midway between 4- and 10-MV x-ray beams. The ratio of distal surface dose to dose at dmax (beyond the cavity) using a variety of square fields is shown in Fig. 5. As the field size increases from 4cm × 4cm to 8cm × 8cm, the O/E ratios go to 0.99 from 0.95, 0.92, and 0.91 for 4-, 6-, and 10-MV beams, respectively. Measurements of depth dose in the tissue equivalent acrylic phantom with and without an air cavity, 2cm × 5cm × 2cm, for a 5cm × 5cm field, are shown in Fig. 6. The solid circles and open squares represent measurements made in the absence and presence of the air cavity, respectively. This percent depth doses demonstrate the dose variation below the lesion surface as electronic equilibrium tends to be reestablished. Fully reflected is the increased photon fluence present as a result of the introduction of the air cavity. For 6- and 10-MV beams, the dose at the surface of the air cavity is measured to be about two and three percents less than predicted, respectively, by the depth dose curve given by the solid circles which would be used for ignoring the air cavity. No reduction of depth dose was found for x-ray of lower quality, 4-MV, below the distal surface of the cavity within one percent.

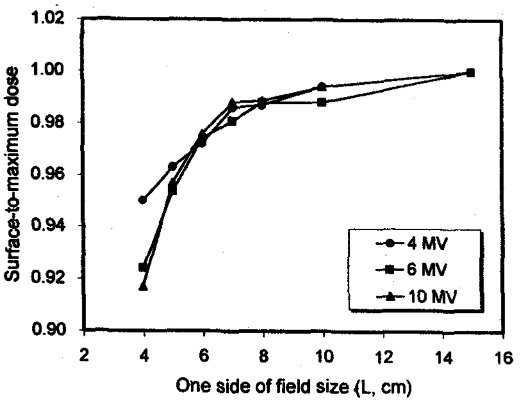


Fig. 5. Surface-to-maximum dose curves for a 2cm×L(cm, one side of field size)×2cm cavity irradiated by square fields ranging from 4cm×4cm to 15cm×15cm for three x-ray beams.

Fig. 7 shows the effect of changing the air cavity size by varying height Z, Z = 0.6 to 4.8cm, on the O/E ratios for a 6-MV beam, all at a width of 4cm, which means that air cavity size was 4cm ×L×Z. It is clear that for field sizes greater than about 8cm×8cm, the observed surface dose will be greater than expected, O/E ratio>1.00, regardless of the height of the air cavity with a constant width, 4cm.

DISCUSSIONS

The presence of an air cavity in the radiation field can produce lower dose, depending on various parameters, such as the quality of the photon beam used, field size, size of the air cavity, and distance from the interface, and the underdosing occurring at the distal surface of

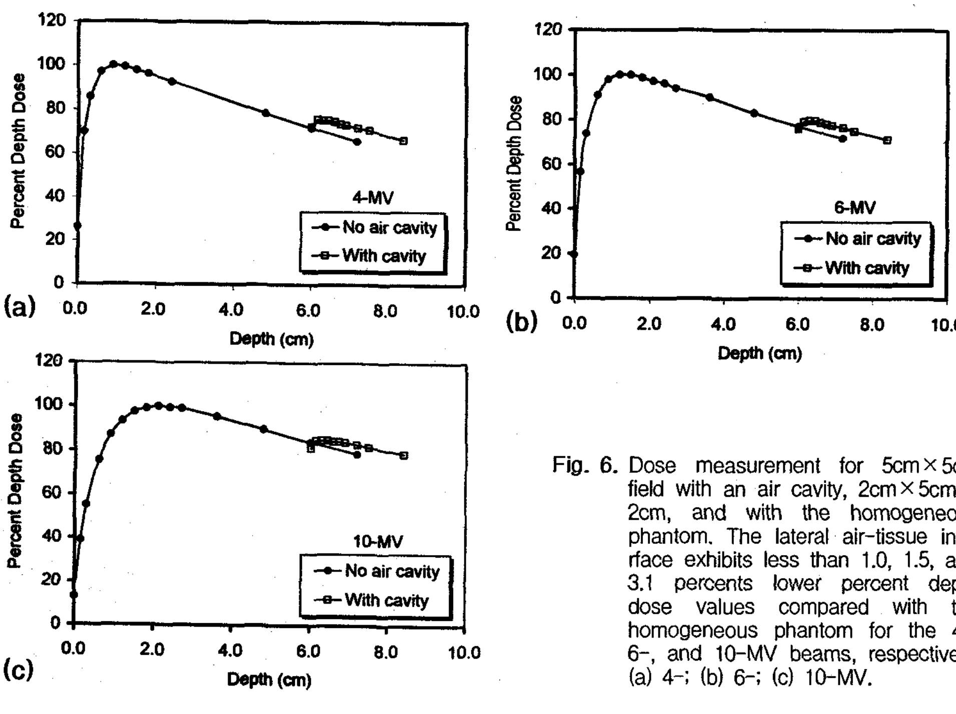


Fig. 6. Dose measurement for 5cm×5cm field with an air cavity, 2cm×5cm×2cm, and with the homogeneous phantom. The lateral air-tissue interface exhibits less than 1.0, 1.5, and 3.1 percents lower percent depth dose values compared with the homogeneous phantom for the 4-, 6-, and 10-MV beams, respectively: (a) 4-; (b) 6-; (c) 10-MV.

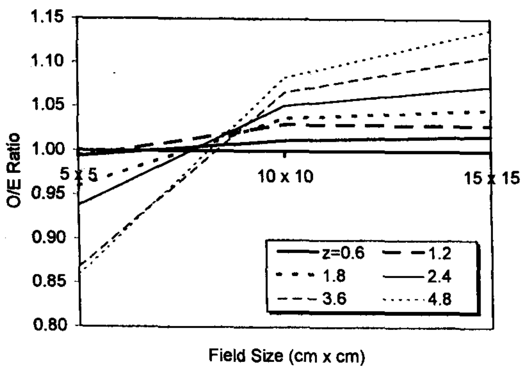


Fig. 7. Cavity size effect on O/E ratios for different field size (cm×cm) for 6-MV beam. Cavity size was changed by varying height Z, Z=0.6 to 4.8cm. Projected cavity size from the top, overlying soft tissue thickness (A)=4cm, was 4cm (width)×L (length in cm, one side of the field size used), open at both ends. Note the horizontal line at O/E=1.00.

air-tissue interface is due to electronic nonequilibrium. Reduction in interface dose is observed distal to the air cavity in comparison to the homogeneous case for higher quality beam. This dose reduction is due to loss in lateral scatter from the soft tissue displaced by an air cavity, which overrides any increase in backscatter resulting from an increased primary contribution. Although the effect is small, about two and three percents for the 6- and 10-MV beams, respectively, for 5cm×5cm field which is typically used treatment field for early glottic carcinoma, at the border of the air cavity and magnitudes decrease within a few millimeters beyond the interface, the small effect may be significant in the treatment of laryngeal lesion located immediately on an air-tissue interface. The parallel opposed reconstruction for an idealized larynx geometry(rectangular channel) shows that the underdosing at the internal along the central axis is 10% and larger for 15-MV[16]. For small fields, such as, 4cm×4cm and 5cm×5cm, it appears that low quality beam, 4-MV, would be preferred over the x-ray beams of high quality, 6- or 10-MV. The underdosed tissue layer is increased with the increase of the beam quality even for similar surface doses with the field size kept constant. From the data presented here, the 10-MV dose distribution demonstrates that the underdosage is intact at 2.5mm beyond the interface (Fig. 4). This is in effect the amount of tissue sparing on the exit side of the cavity but it does not take into account the fact that the doses beyond a cavity are generally elevated by the presence of the cavity. This data would therefore be useful in interpreting computerized treatment plans which include the dose elevation effects of cavities but not the effects of loss of charged particle equilibrium(Fig. 5).

Most calculation algorithms commercially available predict a dose increase well beyond a cavity based on straight line calculations, for example, TAR (tissue-air-ratio) and Batho, but do not predict the dose reduction taking place very near the interface[1-3]. Any straight line method relying on TAR data does not take into account the loss of electronic equilibrium or influence of electron transport from one medium to another. Calculation models that attempt to incorporate these phenomena in an approximate way have been reported by many authors[10, 17-20]. The apparent discontinuity near the boundary for the Petti's algorithms related to the manner in which that algorithm assigns the material composition at a boundary[18-19]. In this model, loss of lateral equilibrium is accounted for by scaling field size with the density of the material. A nonlinear function to account for scattered photons was introduced to correct for electronic nonequilibrium near the interface[17]. Electron transport[20] is modeled with exponentional functions using parameters determined from Monte Carlo data[19]. While these models have been shown to be useful for densities near lung, they do not provide accurate results near air-tissue interfaces and it is far away from the clinical application for treatment planning[18, 19, 21].

The data presented here cannot directly be used to correct the doses under all circumstances systematically but the clinical implication is significant. Better local control and survival of early vocal cord cancer treated with ^{60}Co versus 8-10 MV photons are reported by Izuno et al.[22]. When a smaller field, such as 5cm×5cm in the experiment, is employed for treatment portal for early glottic carcinoma, tumor stage of T1 or T2, the underdosage along the air passage has a potential local failure at the air-tissue interface. As a commonly used dose-fraction schedule is 6120-7200cGy given in 180cGy fractions[23], after the treatment schedule is completed, about 100 and 220cGy boost irradiation is necessary to compensate for the underdosing region for 6- and 10-MV beams, respectively. The problem is not limited to the larynx[24-25] and, anywhere a precavity thickness is smaller than the range of the secondary electrons for a given radiation energy, there will be severe underdosing at the distal interface of the cavity. The magnitude of the underdosage that occurs at the distal interface is proportional to the distance between the proximal and distal layers, height of the cavity, while underdosage at the proximal interface is fairly consistent. Increase in field size alleviate some of the dose lost to displaced forward scatter by increasing lateral scatter. Based on the result of cavity size effect on the O/E ratio, Fig. 7, for field sizes greater than about 8cm×8cm, the observed surface dose is greater than expected, regardless of the cavity size, height in the experiment. This finding results from the fact that any loss of buildup is contracted by an increase in primary and scatter dose from the side walls. As the cavity size increases, the field size over which makes O/E>1.0 is larger from 6cm×6cm for Z=0.6cm to 8cm×8cm for 4.8cm for 6-MV beam. This behavior is expected the same for different beam quality. Based on this, following can be concluded : for small field for the treatment of a region containing large air cavity, a few boost irradiation is required to compensate the underdosing, which is potential local failure, at the air-tissue interface. This will be quantified for the variety of cavity size, varying width and length, and/or height, in near future.

CONCLUSIONS

Dose distributions along the central axis well beyond an air cavity can be estimated reliably using very simple algorithms but distributions immediately after the cavity are complex to calculate. The magnitude of underdosing depends on cavity size, field size, and beam quality. Larynx irradiation using a large field is not likely to be compromised by the loss of charged particle equilibrium in the air cavity as long as field sizes of roughly 6cm×6cm or greater are used, regardless of the quality of the beam, 4- to 10-MV x-rays. The distal depth of underdosage for 10-MV is deeper, yielding an overall larger underdosed volume, compared to 4- and 6-MV photon beams. This agrees with the better clinical results reported when a lower energy is used for smaller field in larynx therapy. From the data presented here, regions within 1.5cm of the edge of large fields irradiating the simulated larynx, open-ended cavity, will suffer some dose reduction at the distal surface of the cavity. This would suggest the use of reasonable margins when treating lesions which are less than 2.5mm beyond the surface of the cavity when the higher energy x-ray beam is used. Based on the result of the study, caution must be used when photon beams of higher quality are used to irradiate regions including air cavities, such as a glottic carcinoma of early stage, and especially the region where the tumor extends to the surface. Lower quality beam can be used preferably to reduce the risk of underdosing, which results in local failure, the region to be treated. In the case of high quality beams such as 6- and 10-MV x-rays, however, an additional boost field is recommended to add for the compensation of the underdosing region when a typically used treatment field, 5cm×5cm, is employed.

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4-, 6-, 10-MV X-선원에서 공기동이 흡수선량에 미치는 효과 : 후두모형

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목 적 : 공기동을 포함한 병소 부위에 X-선원을 조사할 경우 공동과 근접한 영역에서의 저흡수선량 효과는 잘 알려져 있다. 공기-연조직 사이의 불균질면의 한 예로 후두 모형 즉, 조직 등가물질과 그 사이에 삽입되어 있는 공기동을 만들었다. 본 연구에서는 방사선의 선질 · 조사면의 크기 · 공기동의 크기에 따른 공동 가까이에서의 흡수선량의 변화를 살펴보았다.

대상 및 방법 : 4-, 6-, 10-MV X-선원을 이용하여 2cm(폭)×L(cm, 길이)×2cm(높이)인 공기동을 포함한 후두 모형의 아크릴 팬톰에 대하여 흡수선량을 측정하였다. 흡수선량의 측정장비로 평행판전리함과 전리계를 이용하였다. 제작한 후두의 기하학적 치수는 상부 연조직 · 공기동 · 하부 연조직의 두께가 각각 4-, 2-, 4-cm이었다. 공기동이 없이 균일한 연조직 팬톰에 대한 공기동이 있는 경우의 흡수선량의 비(O/E)를 공기 공동-연조직의 경계로부터 거리를 변화시키면서 측정하였다. 표준화된 중강곡선과 최대흡수선량에 대한 입사면 반대쪽 표면에서의 흡수선량의 비를 조사면의 크기를 변화시키면서 측정하였다. 공기동의 크기에 따른 효과를 알기 위하여 여러 가지 조사면에 대하여 투영된 크기가 4cm(폭)×L인 공기동의 높이(Z)를 변화시켜서 측정하였다.

결 과 : 4-MV선원에서 5cm×5cm 이상의 조사면에서는 저흡수선량 효과가 없었다. 6-이나 10-MV선원에서 작은 조사야 즉, 4cm×4cm와 5cm×5cm에서는 후두에 저흡수선량 부위가 나타났으며 6cm×6cm 이상의 조사면에서는 이 효과가 관찰되지 않았다. 선원의 선질이 증가할수록 저흡수선량인 조직층이 증가하였고 이때 표면 흡수선량의 크기는 변하지 않았다. 조사면의 크기가 4cm×4cm에서 8cm×8cm로 증가할 때 최대흡수선량에 대한 입사면 반대쪽의 공기동의 표면선량은 4-, 6-, 10-MV 선원에서 각각 0.95, 0.92, 0.91에서 0.99로 증가하였다. 6-이나 10-MV 선원에서 공기동 표면에서의 흡수선량은 5cm×5cm 조사면에 있어서 예상값보다 각각 2-, 3-퍼센트의 감소가 있었고 또 4-MV에서는 감소효과를 발견할 수 없었다. 4cm×L×Z 공기동에서 그 높이(Z)를 0.6에서 4.8cm까지 변화시켰을 때 조사면의 크기가 8cm×8cm에서 공동의 크기에 무관하게 O/E>1.0이 관찰되었다.

결 론 : 조사면내 공기동에 의한 저흡수선량 효과는 방사선의 선질 · 조사면의 크기 · 공기동의 크기에 의존된다. 이상의 연구 결과에서 고선질 선원이 공동을 포함한 병소 특히, 종양이 공기동의 표면까지 미치는 부위에 조사될 때 특별한 주의가 필요함을 알 수 있다. 이 경우 가능하면 조사되는 부위가 저선량이 되지않도록 저선질의 선원(예를 들면, 4-MV)을 쓰고 또 조사면을 넓혀야 한다. 6-이나 10-MV 등의 고선질의 X-선을 쓰는 경우에는 조사면의 부위에 저선량 부위가 생기므로 한번의 추가 조사를 더 시행할 필요가 있다.