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The Treatment of Extensive Scalp Lesions Combining Electrons with Intensity-Modulated Photons

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Abstract – This study was to investigate the feasibility and potential benefits of combining electrons with intensity modulated photons (IMRT+e) for patients with extensive scalp lesions. A case of a patient with an extensive scalp lesion, in which the target volume covered the entire front half of the scalp, is presented. This approach incorporated the electron dose into the inverse treatment planning optimization. The resulting doses to the planning target volume (PTV) and relevant critical structures were compared. Thermoluminescent dosimeters (TLD), diodes, and GAFCHROMIC EBT films were used to verify the accuracy of the techniques. The IMRT+e plan produced a superior dose distribution to the patient as compared to the IMRT plan in terms of reduction of the dose to the brain with the same dose conformity and homogeneity in the target volumes. This study showed that IMRT+e is a viable treatment modality for extensive scalp lesions patients. It provides a feasible alternative to existing treatment techniques, resulting in improved homogeneity of dose to the PTV compared to conventional electron techniques and a decrease in dose to the brain compared to photon IMRT alone.

I. INTRODUCTION

Extensive lesions of the scalp have traditionally been treated with electron radiation techniques. The relatively high surface dose provided by the electron beam, as well as the limited particle range, allows for adequate dose to the superficial target volume while sparing the underlying normal tissues, principally the brain. For large lesions, however, the matching of adjacent electron fields presents a considerable problem. Although this problem has been addressed directly by introducing "spoilers" to broaden the beam penumbra [1], the typical approach is to shift the field borders during the course of treatment by either overlapping or smooth transition between adjacent fields to accomplish dose homogeneity [2-4]. Electron arc techniques can also be used, though designing the arc so that the entire target receives sufficient dose is difficult. To eliminate the problems of adequate field-matching with electrons, several investigations have been made into the use of photon fields [5, 6]. The use of arcing photon fields was reported [7], whereby four coplanar arcs were used to completely irradiate the craniofacial surface. Energy and intensity-modulated electron beams have also been investigated [8-11]. Another interesting alternative is the use of intensity-modulated radiation therapy (IMRT) as it is able to modulate the photon fields, thereby customizing the dose distribution more specifically to the patient. Locke *et al.* [12] evaluated the use of tomotherapy with the Peacock device (NOMOS Corporation, Sewickley, PA) for this type of problems. It was found that IMRT provided improved dose homogeneity in the planning target volume (PTV) compared with the more conventional technique, but resulted in higher doses to the brain and lens. More recently Bedford *et al.* [13] further examined the possibility of using IMRT for extensive scalp lesions. They compared photon IMRT with either two or four matched electron fields and arcing electron fields. Their comparison result showed that IMRT offers a feasible alternative to electron techniques for treatment of extensive scalp lesions. The PTV dose distribution with IMRT does not suffer from problems of matching static electron fields and is considerably more homogenous than with either static or arcing electrons. Although it is considered to be clinically acceptable, the brain dose is higher with photon IMRT. Here, we report a new method for treating extensive scalp lesions, utilizing a combination of static electron fields and photon IMRT beams that are optimized to account for the dose contributions of the electrons. We refer to this method as IMRT+e. The goal of this study is to further assess the potential benefit of this method using established dosimetric parameters, as compared with photon IMRT for extensive scalp lesions. The rare occurrence of large scalp lesions precludes presentation of a wide variety of patients and tumor locations. Moreover, the large variation in possible tumor size and proximity to normal structures such as the eye suggest that little specific trend would be observed in a number of patients. We therefore present a specific case, drawing attention to the distinguishing features of the two techniques, and then provide a number of physical validations and investigations to address the issues that might arise with the use of IMRT+e treatment for this type of lesions.

II. MATERIALS AND METHODS

A case is presented for an 83-year-old male patient with poorly differentiated recurrent squamous cell carcinoma of the scalp, recently treated at the Memorial Sloan-Kettering Cancer Center (MSKCC). The lesion covered the entire forehead scalp and both temporal surfaces. The patient was positioned in a supine position, and his previous surgical scars were wired. Then he was immobilized using an

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Aquaplast facemask for both simulation and treatment (Fig. 1). After CT scanning, the physician outlined the PTV and critical structures, and prescribed 63 Gy in 35 fractions, IMRT+e was used for the treatment. The patient received low dose Carboplatin weekly x 8 cycles given concomitantly with Radiation Therapy. Four doses of Carboplatin AUC 1.5 (133 mg) were given. The dose was then reduced to an AUC 1.1 (100 mg) for the last 4 treatments due to fatigue. The following retrospective comparison is focus on the radiotherapy treatment given to the scalp area.

Figure 1

This patient was retrospectively re-planned with photon IMRT alone for the purpose of comparison with IMRT+e using our in-house treatment planning system. The IMRT+e approach incorporated the electron component into the inverse treatment planning optimization. The resulting doses to the PTV and relevant critical structures were analyzed and compared. A 1.5-cm bolus was used for both plans. The IMRT and IMRT+e planning were carried out on a planning system developed in-house. Our photon-only IMRT plan used 6-MV photons with 5 equally-spaced coplanar beams. For IMRT+e plan, a single electron field using 9 MeV was added. Normally, a large enface electron field arrangement was sufficient to achieve the acceptable tolerance levels for critical structures. When these acceptable levels could not be met, alteration of electron energy or differential weighting of electron plan was attempted. In general, the electron field was manually weighted to contribute about 50% of the prescribed dose. The quality of a plan was evaluated using dose-volume histograms (DVHs). The photon IMRT plan was designed to be delivered using the dynamic multileaf collimator (DMLC) technique and the electron field to be treated with a custom electron cutout.

The IMRT optimization algorithm uses an iterative gradient search method to minimize an objective function [14, 15]. The objective function consists of terms corresponding to the targets and the organs at risk (OAR).

$$F = F_{target-1} + F_{target-2} + \cdots + F_{OAR-1} + F_{OAR-2} + \cdots \tag{1}$$

The term for the target is given by:

$$F_{\text{target}} = \frac{1}{N_t}\left[\begin{array}{l} \sum_{i=1}^{N_t}(D_i - D_{presc})^2 \\ + w_{t,\min}\cdot\sum_{i=1}^{N_t}(D_i - D_{\min})^2\cdot\Theta(D_{\min} - D_i) \\ + w_{t,\max}\cdot\sum_{i=1}^{N_t}(D_i - D_{\max})^2\cdot\Theta(D_i - D_{\max}) \end{array}\right] \tag{2}$$

where N_t is the number of points in the target, D_i is the dose to point i, and D_{presc} is the prescription dose. The second and third terms inside the brackets implement the target dose homogeneity criterion: D_{min} and D_{max} are the desired minimum and maximum target doses, and $w_{t,min}$ and $w_{t,max}$ are the penalties associated with under- and overdosing. $\Theta(x)$ is the Heaviside function, defined as:

$$\Theta(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{3}$$

Similarly, the term for the organ-at-risk (OAR) is given by:

$$F_{OAR} = \frac{1}{N_{OAR}}\left[\begin{array}{l} w_{OAR,\max}\cdot\sum_{i=1}^{N_{OAR}}(D_i - D_{\max})^2\cdot\Theta(D_i - D_{\max}) \\ + w_{OAR,dv}\cdot\sum_{i=1}^{N_{dv}}(D_i - D_{dv})^2\cdot\Theta(D_i - D_{dv}) \end{array}\right] \tag{4}$$

where the first term inside the brackets implements a maximum dose constraint D_{max} on the OAR and the second term implements a dose-volume constraint. The relative penalty weights are given by $w_{OAR,max}$ and $w_{OAR,dv}$ respectively. N_{OAR} is the number of points in the OAR and N_{dv} the number of points whose dose must be below the dose-volume constraint dose D_{dv}. The dose to point i, D_i, is the sum of dose contributions from all rays:

$$D_i = \sum_{j=1}^{N_r} x_j a_{ij} \tag{5}$$

where N_r is the number of rays, x_j is the intensity of the j-th ray, a_{ij} the dose deposited to the i-th point per unit intensity of the j-th ray, and the product is summed over all j. The goal of optimization is to find the set of ray intensities x_j that minimizes the objective function given by expression (1).

The above-described methodology is, in principle, applicable not only to intensity-modulated photons, but also electrons or combination of both. At this time, medical linear accelerators are not equipped with electron MLC (EMLC), thus intensity-modulated electron plans can not be delivered. As a result, inverse planning is routinely performed for

IMRT photons only. However, to fully take advantage of the finite range of electron beams, it may be beneficial to combine electrons with IMRT photons for certain disease sites. This can be accomplished by optimizing IMRT photons over a manually planned electron dose distribution. In this case, D_i in the above expressions is substituted with $D_i + D_{i,\,electron}$, where $D_{i,\,electron}$ represents the electron dose distribution. $D_{i,\,electron}$ is manually determined by the planner and is not varied by the optimization algorithm. Figure 2 presents a representative photon IMRT field, in which a low intensity region corresponding to the electron field was created to spare the brain.

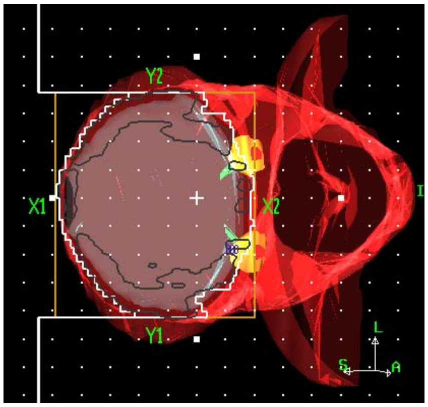

Figure 2

For valid comparison with the IMRT+e plan, the photon IMRT plan was designed with the same photon energy (6MV), and the same number of photon beams. A total of approximately 28,000 rays from the 5 photon beams were included in the optimization. The spatial resolution of each ray was 0.2 cm in the leaf travel direction by 0.5 cm along the leaf width. The total number of dose calculation points used in the optimization was approximately 25,000. The total computing time was about 1 to 2 minutes for each run of optimization (~100 iterations) using a PC-based treatment planning system, with a CPU of 3.2 GHz and 1 GB RAM. Multiple runs (~20-40) of optimization were needed to determine the best dose constraints and penalties for each organ involved.

The target coverage was measured by the dose covering 95% (D95) of the PTV, the volume of the target receiving at least 95% (V95) of the prescription dose and the maximum and minimum target doses. For comparison between the two techniques, the PTV D95 from both plans was normalized to be the same for this patient in order to accurately determine the differences between the critical structure doses.

The IMRT+e treatment was verified with ionization chamber measurements, films dosimetry for the individual fields, thermoluminescent dosimeters (TLD), and diodes for *in-vivo* measurements. The films were of type GAFCHROMIC EBT (International Specialty Products, Wayne, NJ). The EBT films were cut into narrow pieces and placed on the scalp under the bolus during patient's treatment. The initial treatment was also verified by placing TLDs and diodes to the external surface of the scalp.

III. RESULTS AND DISUCSSION

The PTV for this patient was 103 cm^3. This exceptionally convex-shaped PTV was a challenge to obtain acceptable target dose coverage and dose homogeneity. Nevertheless, both planning techniques provided equivalent target dose coverage. The D95 for IMRT and IMRT+e were 97%. As expected, V95 also yielded similar results, being 98% for both IMRT and IMRT+e plans. The mean doses of the brain for IMRT and IMRT+e were 14.0 Gy and 13.6 Gy, respectively. Both techniques also demonstrated good normal tissue sparing capability. The doses to all optic structures for both plans were similar and far below the clinical tolerances. However, the IMRT+e plan exhibited an advantage in further reducing the doses to the brain.

Figures 3a-3b show the typical isodose distributions of two representative orthogonal images from an IMRT+e plan. The blue contour represents the PTV and the prescription isodose line (100%) is in orange. Figure 4 shows the dose volume histogram (DVH). The *in-vivo* measured data for the IMRT+e technique agreed well with the calculated dose distribution within ± 5%.

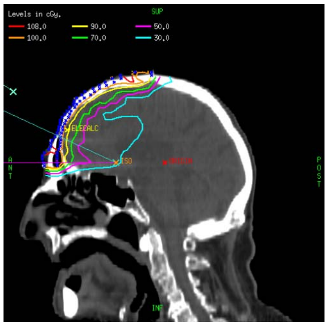

Figure 3a

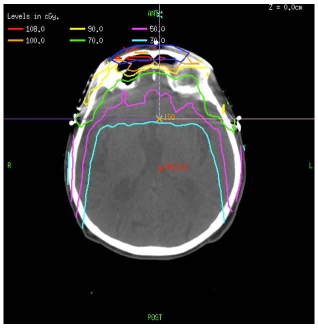

Figure 3b

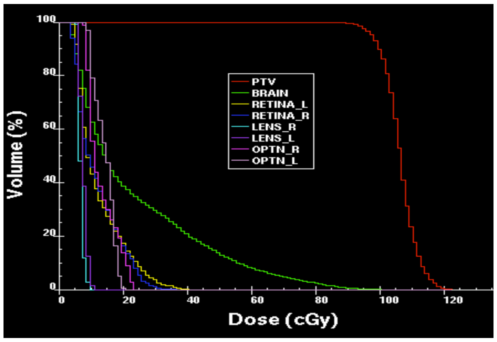

Figure 4

Extensive scalp lesions present a challenge to radiation therapy because of the superficial target volume and the fact that it surrounds critical structures (e.g. brain and optic structures). To search for the best treatment option, a variety of planning techniques have been developed and tested.

Bedford *et al*. [13] demonstrated that IMRT offers a feasible alternative to electron techniques for treatment of extensive scalp lesions. The PTV dose distribution with IMRT does not suffer from problems of matching static electron fields and is considerably more homogenous than with either static or arcing electrons. However, the brain dose is higher with IMRT, but it is considered to be clinically acceptable. With IMRT+e, the brain dose can be further reduced. Locke *et al.* [12] found that brain and eye doses to be unacceptable with tomotherapy for total scalp treatment. Although photon IMRT is a powerful tool for treating tumors that extend deeply into tissue below the skin surface, the excessive photon exit dose makes IMRT alone sub-optimal for treating very shallow targets, such as scalp lesions.

In theory, tumors with both deep and superficial extensions can be best treated with a combination of photon IMRT and modulated electron radiation therapy (MERT) [16]. Unlike photon IMRT, MERT can provide both intensity and energy modulation. However, the delivery of MERT plans requires an EMLC, which is not available on current commercial medical linear accelerators. Thus, IMRT+e is a promising alternative approach in which a conventionally delivered electron contribution is incorporated into the inverse treatment planning process. The rapid dose falloff of electron beams makes them a preferable treatment modality for the shallow parts of the PTV. Conceptually, such a combined modality plan would consist of multiple photon beams with the same low photon energy and electron beams with different energies, depending on the target depth. Dose conformity in the depth direction would be achieved by the use of different electron energies. Dose conformity and uniformity in the lateral direction would be achieved by photon beam intensity modulation. In the present study, a single energy was used for the electron aperture and the weight of the electron beams was manually set prior to optimization of the photon IMRT beams, but the dosimetric advantages of this method relative to photon IMRT alone was clearly demonstrated.

Our study showed that IMRT+e is viable treatment method for extensive scalp lesions. Adding the electrons takes an experienced planner using the MSKCC planning system approximately 30 minutes longer than IMRT alone. Our estimate is that IMRT+e treatment time will be 15 minutes longer than IMRT alone, based on our observation of this patient recently treated in our clinic. Thus, in terms of planning and delivery time, the IMRT+e technique is competitive with photon IMRT and is a practical alternative.

IV. CONCLUSION

In conclusion, we have explored the feasibility of treating an extensive scalp lesion using IMRT+e, a combination of photon IMRT and static electron beams, where the optimization of the IMRT fields accounted for the dose contributions of the electrons. Based on the results of this study, we find that this new technique is straightforward, available on existing linear accelerators and improves target dose coverage and normal tissue sparing compared to non-IMRT methods and photon-alone IMRT.

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