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Physics Contribution

Peripheral Dose Heterogeneity Due to the Thread Effect in Total Marrow Irradiation With Helical Tomotherapy

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Summary

We investigated the dose heterogeneity at different skeletal sites in total marrow irradiation with helical tomotherapy. We found that the unique characteristics of the helical beam junctioning effect, referred as to the thread effect, significantly affected dose homogeneity in the extremities, particularly for large patients. Use of a favorable pitch value and adjustment of arm position could minimize the thread effect and reduce dose heterogeneity.

Purpose: To report potential dose heterogeneity leading to underdosing at different skeletal sites in total marrow irradiation (TMI) with helical tomotherapy due to the thread effect and provide possible solutions to reduce this effect.

Methods and Materials: Nine cases were divided into 2 groups based on patient size, defined as maximum left-to-right arm distance (mLRD): small mLRD (≤47 cm) and large mLRD (>47 cm). TMI treatment planning was conducted by varying the pitch and modulation factor while a jaw size (5 cm) was kept fixed. Ripple amplitude, defined as the peak-to-trough dose relative to the average dose due to the thread effect, and the dose−volume histogram (DVH) parameters for 9 cases with various mLRD was analyzed in different skeletal regions at off-axis (eg, bones of the arm or femur), at the central axis (eg, vertebrae), and planning target volume (PTV), defined as the entire skeleton plus 1-cm margin.

Results: Average ripple amplitude for a pitch of 0.430, known as one of the magic pitches that reduce thread effect, was 9.2% at 20 cm off-axis. No significant differences in DVH parameters of PTV, vertebrae, or femur were observed between small and large mLRD groups for a pitch of ≤0.287. Conversely, in the bones of the arm, average differences in the volume receiving 95% and 107% dose (V95 and V107, respectively) between large and small mLRD groups were 4.2% ($P=.016$) and 16% ($P=.016$), respectively. Strong correlations were found between mLRD and ripple amplitude ($r_s=.965$), mLRD and V95 ($r_s=-.742$), and mLRD and V107 ($r_s=.870$) of bones of the arm.

Conclusions: Thread effect significantly influences DVH parameters in the bones of the arm for large mLRD patients. By implementing a favorable pitch value and adjusting arm position, peripheral dose heterogeneity could be reduced. © 2013 Elsevier Inc.

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Introduction

Total body irradiation (TBI) has been widely used as part of the conditioning regimen for hematopoietic cell transplantation. Relapse is a major obstacle to the success of bone marrow transplantation (1-4). Radiation dose-escalation studies have shown lower relapse rates for acute and chronic myelogenous leukemia but increased treatment-related mortality (5, 6). The conformal radiation treatment delivered by the helical tomotherapy (HT) was shown to have the potential to enhance the therapeutic ratio (dose to tumor/organs at risk [OARs]) (7). Using this rationale, targeted total body irradiation, referred as to total marrow irradiation (TMI), is becoming an important investigative treatment as a conditioning regimen for hematologic malignancies (7-17).

In patients with acute leukemia, it is generally assumed that leukemic cells are distributed throughout the skeletal bone marrow. Although it is well known that relapse of leukemia or multiple myeloma from extremities is rare, several groups reported localized relapse of acute lymphoblastic leukemia in bone marrow of extremities (18) or the relapse of multiple myeloma from humerus where TBI was used as a part of conditioning regimen (19). On the other hand, chronic skeletal system complications including avascular bone necrosis and clinically evident osteoporosis have been observed after compensator-based intensity-modulated total body irradiation of 12 Gy (20). Homogeneous dose delivery to the entire skeletal region including extremities, pelvic bone, and vertebrae is therefore essential in TMI treatment planning. Although the dosimetric and physical aspect of TMI with HT are yet to be thoroughly investigated (7, 14, 21-23), the detail dose heterogeneity in various skeletal sites including arm bones, vertebrae, and femur has not been reported so far.

HT offers a high-intensity-modulated beam with multileaf collimator while translating the couch into the gantry (24, 25). This unique feature shows a dose variation pattern that manifests as a ripple that is the result of helical beam junctioning, referred to as the thread effect (26, 27). This characteristic of TMI may lead to heterogeneity of the irradiation dose delivered to the skeleton. To our knowledge, no report has been published that investigates the impact of thread effects on the dose−volume histogram (DVH) in TMI treatment plans in which largely off-axis targets (eg, bones of the arm such as the humerus, radius, and ulna), moderately off-axis targets (eg, femur), or near-central axis targets (eg, vertebrae) are included. Here we report peripheral dose heterogeneity of TMI treatment delivery, particularly in extremities with HT due to the thread effect.

Methods and Materials

Treatment planning was done with TomoTherapy HiArt Planning Station (Accuray, Inc, Madison, WI). Nine computed tomography data sets were divided into 2 groups based on patient size, defined as maximum left-to-right arm distance (mLRD): small mLRD (<47 cm; n=4) and large mLRD (≥47 cm; n=5).

Treatment planning

Target and OARs including eyes, lungs, heart, kidneys, liver, brain, and peritoneum were contoured on a Pinnacle treatment planning system (Philips Medical Systems, Palo Alto, CA). Planning target volume (PTV) was generated by adding 1-cm margin to entire skeletons. To analyze the thread effect at various skeletal sites, we separately contoured bones of the arm including humerus, radius, and ulna; the femur; and the vertebrae.

The prescription of 18 Gy in 3 fractions was used for planning simulation to cover PTV with the 85% isodose line. All TMI treatment plans of various pitches of 0.200, 0.287, 0.397, 0.430, 0.556, and 0.754 were conducted with a fixed jaw size (5 cm) to keep treatment time within 40 minutes. The preset modulation factor was also changed from 2.5 to 3.0. Treatment planning for 9 cases was conducted with a pitch of 0.287 and a modulation factor of 2.5 to analyze the differences in DVH parameters between large and small mLRD groups. Furthermore, for the 5 cases in the large mLRD group, a treatment plan with the pitch of 0.200 was also conducted.

For optimization, the same dose constraints for both the PTV and OARs were used for 9 cases.

Analysis of the thread effect

We recorded the dose on a slice-by-slice basis in transverse planes at the identical position of off-axis distances of 0, 10, 15, and 20 cm. These approximately correspond with vertebra, ribs, outer side of the femur, and bones of the arm.

Ripple amplitudes due to the thread effect, defined as the peak-to-trough dose relative to the average dose as shown in the Equation 1 (26, 27), were calculated at near the central axis, and the off-axis distances of 10, 15, and 20 cm.

$$\text{Ripple amplitude}(\%) = \frac{2(\max(D) - \min(D))}{\max(D) + \min(D)} \times 100 \qquad (1)$$

The correlation between the mLRD and the ripple amplitude was analyzed by Spearman's rank correlation coefficient using Dr. SPSS II software (IBM, New York, NY).

For real time in vivo measurement of thread effect, we placed a GafChromic EBT3 film (ISP Technologies, Wayne, NJ) on the forearm during a TMI delivery. The film was scanned by a flatbed scanner (EPSON, Nagano, Japan) as described in references 28 and 29 and then analyzed with Dkan2 software (Oras, Osaka, Japan).

Plan evaluation

We evaluated the DVH parameters including median dose (D50), the dose received to 5 cc of the volume (D5cc), and the volumes at the dose level of 95% (V95), 107% (V107), and 110% (V110) of the prescription doses in the regions of bones of the arm, vertebrae, femur, and PTV for the 9 cases. Statistical analysis was done using Dr. SPSS II software. The correlations between mLRD and these DVH parameters and the statistical significances between large and small mLRD groups were evaluated by Spearman's rank correlation coefficient and Mann-Whitney *U* test, respectively. For the statistical significance of DVH parameters between pitches of 0.287 and 0.200 of the patients in the large mLRD group, 2-tailed paired *t* test was performed with the null hypothesis that the mean values of DVH parameters in bones of the arm between pitches of 0.200 and 0.287 were not different. Statistical significance was set at a P value of <.05.