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TBI arc therapy

Arc therapy for total body irradiation – A robust novel treatment technique for standard treatment rooms

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ABSTRACT

Background and purpose: We developed a simple and robust total body irradiation (TBI) method for standard treatment rooms that obviates the need for patient translation devices.
Methods and materials: Two generic arcs with rectangular segments for a patient thickness of 16 and 20 cm (arc16/arc20) were generated. An analytical fit was performed to determine the weights of the arc segments depending on patient thickness and gantry angle. Stability and absolute dose for both arcs were measured using EBT3 films in a range of solid water slab phantom thicknesses. Additionally ionization chamber measurements were performed every 10 cm at a source surface distance (SSD) of ~200 cm.
Results: The measured standard deviation for arc16 is ±3% with a flatness ⩽9.0%. Arc20 had a standard deviation of ±3% with a flatness ⩽7.3% for all measured thicknesses. The theoretical curves proved to be accurate for the prediction of the segment weightings for the two arcs. In vivo measurements for the first 22 clinical patients showed a dose deviation of less than 3%.
Conclusions: Arc therapy is a convenient and stable method for TBI. This cost-effective approach has been introduced clinically, obviating the need for field patches and to physically move the patient.
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For decades, total body irradiation (TBI) has successfully been part of an interdisciplinary treatment regimen for "conditioning" of patients undergoing bone marrow transplantation for leukemia and lymphoma. The purpose of conditioning is to suppress the immune system to allow engraftment of donor cells, to kill malignant cells and to eradicate cell populations with genetic disorders [1,2]. TBI has been used in conjunction with chemotherapy as a conditioning regimen, for bone marrow transplantation or peripheral blood stem cell transplantation [3,4].

The challenge in TBI is the creation of a relatively uniform dose distribution along all of the patient's body, therefore necessitating the use of large treatment fields and extended SSD. Two additional dosimetric challenges are different anatomical thicknesses of the patient and the introduction of local dose inhomogeneities to spare critical organs. The predominant critical organ is the lung, which is at risk of developing pneumonitis as a serious, potentially lethal side effect [5,6].

TBI techniques typically comprise a combination of various opposing field setups in a sitting or lying patient position at very extended SSDs [7–10]. Another technique utilizes a translation couch, where the patient is moved through the field at a constant speed at SSD ~200 cm [11–14]. A modification of this approach is the "sweeping-field" technique, where the patient lies on the floor at a distance of 200 cm to the accelerator head and the gantry is sweeping over him. The dosimetric requirements for TBI are described in the AAPM report 17 [15] which defines a prescription point and recommends a dose homogeneity within ±10%. Conventional treatment planning systems (TPS) have been extensively used to optimize TBI/TMI plans [16,17].

We propose a treatment technique that has been implemented clinically and provides optimal dose homogeneity without extra resources in standard treatment rooms, based on the arc paradigm and present first measurements for 22 clinically treated patients.

Materials and methods

Patient setup and clinical treatment technique

A total body CT of the patient is taken in prone and supine position two weeks before treatment to assess patient thickness and to provide a basis for contouring of lung blocks for patients that are to receive a total dose of >8 Gy. Clinical delivery is performed twice daily with 2 Gy per fraction. Total dose ranges between 4–12 Gy,

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delivered in 2–6 fractions on the morning and evening of 1–3 consecutive days with at least 7 h in between the fractions. The patient is treated with two arcs, one in supine and one in prone position, with a source to couch distance of 219 cm. For the alignment point the belly button directly below the isocenter was chosen. To provide optimal skin coverage, a buildup "spoiler" plate is introduced between the accelerator head and the patient. The spoiler consists of 1 cm transparent polycarbonate screen and can be adjusted in height between 29 and 49 cm from the couch surface approximately 20 cm above the patient. Fig. 1 depicts the whole treatment setup.

To limit the lung dose below 10 Gy, specially manufactured lung blocks were positioned directly on the patient's skin. They consist of stacked lead (Pb) plates cut to the desired shape of the individual patient. Prior to treatment the position of the lung blocks is verified by digitally readable and X-ray sensitive film cassettes. When designing the blocks the divergence of the beam including its movement component is taken into account and the isocenter was set to the lower end of the lungs to reduce dose blurring caused by the arc delivery. For 12 Gy prescription dose and 18 cm phantom thickness a required thickness of 12 mm was found corresponding to 12 plates. For 10 Gy prescription 8 mm lead plates are used. The lead thickness was determined by measurements with an inhomogeneous lung phantom and therefore took into account the inhomogeneity of the lung. This resulted in a dose reduction to a maximum of 8–9 Gy midline dose in the lungs. The maximum dose rate in the middle of the body is about 100 cGy/min and in the lung, under the lung blocks, between 60 and 80 cGy/min. Even for single dose/hypofractionated TBI, Sampath et al. [5] could not detect a dose rate effect in treatment series with dose rates up to 41 cGy/min. Recently, three clinical TMI/TBI tomotherapy manuscripts reported the successful use of dose rates $\gg$100 cGy/min [18–20].

Before the first treatment of a new patient, the arc is calibrated for absolute dose. During patient treatment, in vivo dosimetry is performed with one in vivo ion chamber and nine semi-conductor detectors (T60010MP, T60010RO, PTW, Freiburg, DE). Diodes are an established tool for in vivo dosimetry [21–23]. Calibration for the diodes is done during the QA measurements. Standard detector positions are head, neck, lung, blocks, isocenter, chest and abdomen.

Development of a theoretical model for arc TBI

The basic condition was one arc between gantry angles of 320° and 60° with 10 × 40 cm field size with a homogeneous dose area that extends over a length of 200 cm. In addition the arc was then split into ten segments which were weighted according to their gantry angle (see Table 1). The weighted MUs per degree can be fitted using a straight forward approach from the inverse square law and the known polystyrene (RW3, slab phantom material) and polycarbonate (Makrolon®, spoiler material) attenuation coefficients. This provides a starting point and thus reduces measurement steps necessary for individual patient thicknesses. The relative weighting factors can be obtained by the ratio of the radiation intensities at 0° segment to the radiation intensity at angle α segment $\left(wf(\alpha) = \frac{I(0^\circ)}{I(\alpha)}\right)$.

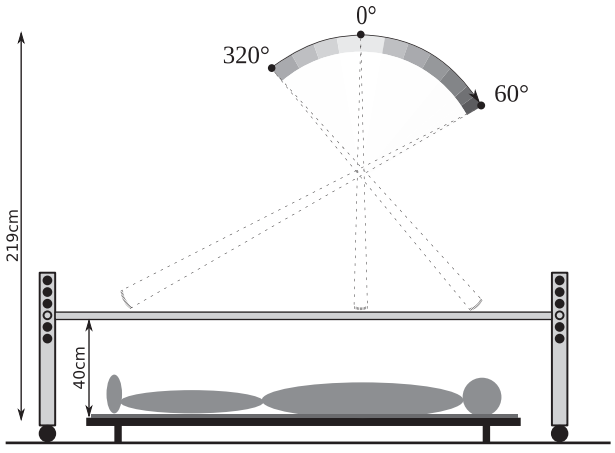

Fig. 1. Patient setup.

The attenuation coefficients were determined with an energy spectrum obtained by Monte Carlo simulations [24] from an Elekta Synergy® 6 MV beam. They were calculated as $\mu_p \approx 0.0707\ \mathrm{cm}^{-1}$ for RW3 and $\mu_s \approx 0.0797\ \mathrm{cm}^{-1}$ for Makrolon®. The other relevant parameters are of geometrical nature. The functions $p(\alpha)$ and $s(\alpha)$ are the distances the beam has to travel through the phantom and the spoiler, respectively. The initial intensity is I_0 and the radii at gantry angle 0° and gantry angle α are $r(0)$ and $r(\alpha)$.

$$wf(\alpha) = \frac{\frac{I_0}{r(0)^2}}{\frac{I_0}{r(\alpha)^2}} \cdot \frac{e^{(-\mu_p \cdot p(0))}}{e^{(-\mu_p \cdot p(\alpha))}} \cdot \frac{e^{(-\mu_s \cdot s(0))}}{e^{(-\mu_s \cdot s(\alpha))}} \tag{1}$$

For the inverse square law the distances to the plane with the flat profile have to be known. Here the variable d_I denotes the distance from source to isocenter and is fixed to 100 cm, d_{IPC} is the distance from isocenter to the center of the phantom, s_0 is the thickness of the spoiler and p_0 is half the phantom thickness. The angle alpha denotes the gantry angle of a given segment. In Eq. (2) $s(\alpha) = \frac{s_0}{\cos\alpha}$ and $p(\alpha) = \frac{p_0}{\cos\alpha}$ have been inserted. Using simple geometric arguments, it can be shown that $r(0) = d_I + d_{IPC}$ and $r(\alpha) = d_I + \left(\frac{d_{IPC}}{\cos\alpha}\right)$ which has been used in the final Eq. (2).

$$wf(\alpha) = \frac{\left(d_I + \left(\frac{d_{IPC}}{\cos\alpha}\right)\right)^2}{\left(d_I + d_{IPC}\right)^2} \cdot e^{\left(-\mu_p \cdot p_0 \cdot \left(1 - \frac{1}{\cos\alpha}\right)\right)} \cdot e^{\left(-\mu_s \cdot s_0 \cdot \left(1 - \frac{1}{\cos\alpha}\right)\right)} \tag{2}$$

Using this formula, a starting point has been determined for arcs with larger or smaller phantom thicknesses. The calculated arc always needs to be experimentally verified since only relative and no absolute dosimetry is included in the equation.

Dose verification measurements

To get a DICOM compliant plan the tel.file of MONACO® v2.04 (Elekta, Crawley, UK) was modified with the theoretical segment weightings. Two reference measurements for a patient thickness of 16 and 20 cm (arc16 and arc20) were performed using an ionization chamber which was positioned at a depth of 8 and 10 cm, respectively, in a solid water slab phantom (30 × 90 × 16/20 cm^3) with the spoiler in place. The phantom consisted of three stacks with the measurement chamber in the middle in order to simulate patient scatter. Moving the phantom across the irradiation field of the two arcs a measurement point was acquired every

Table 1
Normalized weighting factors for each segment for arc16 and arc20.

Segment number	Angle (°)	Normalized weighting factor	
		Arc16 (MU/°)	Arc20 (MU/°)
1	320–330	1.424	1.464
2	330–340	1.184	1.199
3	340–350	1.060	1.065
4	350–10	1.000	1.000
5	10–20	1.060	1.065
6	20–30	1.184	1.199
7	30–40	1.424	1.464
8	40–50	1.907	2.008
9	50–55	2.645	2.869
10	55–60	3.562	3.562