RESEARCH PAPER

Total body irradiation for standard treatment rooms: a robust sweeping beam technique with respect to the body shape

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ABSTRACT

Background: The purpose of this work is to improve a sweeping beam technique for total body irradiation (TBI) on a low flat couch using a varying patient thickness model. We designed a flat couch for total body irradiation in supine and prone position. Three generic arcs with rectangular segments for a patient torso thickness of 16, 22 and 28 cm were generated with respect to varying patient thickness of four particular parts of the body: head, torso, thighs and calves.

Materials and methods: Longitudinal and transversal dose profiles were measured using an ionization chamber and the EBT3 gafchromic film in a solid water slab phantom. The robustness of the method was examined in phantoms of different thicknesses.

Results: Measured dose homogeneity stays within ±10% of prescribed dose for all of the three patient thickness models. The robustness of the method was evaluated as the increase in dose in the phantom center of 0.7% per 1 cm reduction in phantom thickness.

Conclusion: The method is applicable for the broad range of patient sizes, comfortable for patients, robust and suitable for standard treatment rooms with a standard linear accelerator. It requires minimal investments into equipment.

Key words: total body irradiation; TBI; arc therapy; sweeping beam technique; patient comfort

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Introduction

Total body irradiation (TBI) has been part of leukemia and lymphoma treatment for many decades. Combined with intensive chemotherapy, TBI enables myeloablative high dose therapy and immuno-ablative conditioning treatment prior to subsequent transplantation of haematopoietic stem [1]. Many different dose fractionation schemes have been reported; however, the total TBI prescription dose should not be essentially higher than 12 Gy. For example, 12 Gy in 6 fractions on 3 days is a very common scheme [2, 3]. At our department, 12 Gy in 8 fractions on 4 days is used most often.

TBI techniques typically use a combination of opposing large fields in a standing, sitting or lying patient position at very extended distances of around 400 cm from source to patient. Other techniques use a dynamic movement of source or patient or their combination [4]. The dynamic approach allows the use of smaller irradiation fields in smaller source-to-patient distances. In the sweeping beam technique, the patient lies on a low couch near the floor at a distance of 200 cm to the

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linear accelerator head and the gantry is sweeping over him. Such a technique can be performed in an irradiation room of a standard size, whereas the static techniques with extended distances require more space. In the case of constant dose rate used in the sweeping beam technique, the couch has to be curved to compensate the source-to-patient distance. This is unfortunately very uncomfortable for the patient when lying in a prone position. The treatment fraction typically lasts around 45 minutes or even more. More accurate, tough more challenging to implement, are the techniques that have emerged in recent years. They involve dynamic fields and active shielding of critical organs using an multi-leaf collimator [5, 6].

The dosimetric requirements for TBI are described in AAPM Report 17 [4], which recommends a dose homogeneity within ±10%. To reduce the lung dose, e.g. to 70%–80% of the target dose, individually shaped shields of calculated thickness are used.

Since the equipment for TBI is not unified, each radiotherapy department uses its own technique specially developed for the specific conditions. At our department the sweeping beam technique with a curved couch has been used for a long time. Because of an uncomfortable and, therefore, unstable patient position, we adopted an improved sweeping beam technique presented by Jahnke et al. [7]. Moreover, we extended the model to a broad-er range of patient sizes and improved the patient model to differentiate four main parts of the body to take into account their different thickness.

Materials and methods

All measurements were performed in a standard treatment room equipped with TrueBeam linac (Varian Medical Systems, Palo Alto, USA), photon energy of 6 MV, using a flattening filter.

A low flat couch is positioned on the floor so that the rotational plane of the gantry intersects the longitudinal axis of the couch (Fig. 1). The patient lies on the couch in a supine and then prone position while obtaining the prescribed dose in two arcs — the first arc in a supine and the second arc in a prone position. Gel boluses are spread over the lower limbs and polymethyl methacrylate (PMMA) plates resting on couch supports cover the upper body. These materials of 1 cm thickness compensate for the build-up effect in patient's skin. The PMMA plates also serve as a holder for lung shielding blocks. The couch top is 200 cm long, 78 cm wide and its surface is placed 110 cm below the isocenter. For measurement purposes, a coordinate system was established (Fig. 2) using coordinates d, w and h. Isocenter projection corresponds to $d = 45$ cm and $w = 0$ cm. At this position, the center of patient's chest and the central point of shielding blocks is considered.
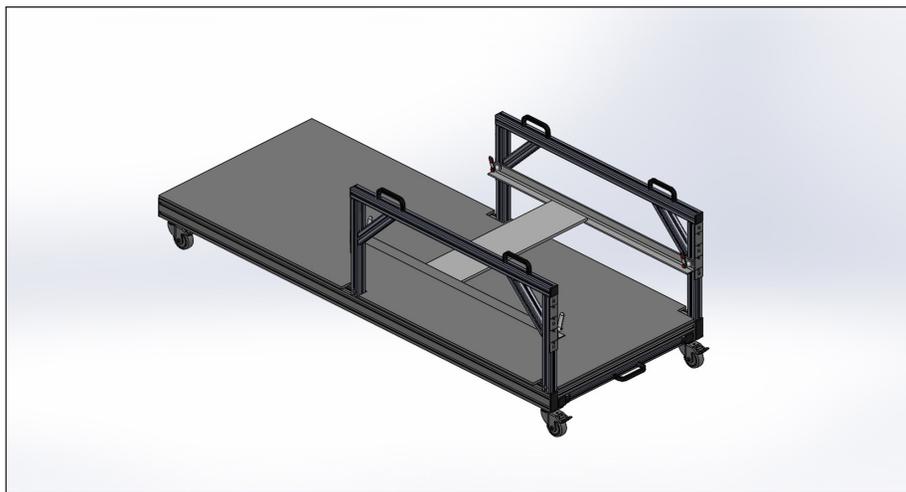

Figure 1. The flat couch design. The patients' head is located right. Polymethyl methacrylate (PMMA) plates covering the upper body rest on couch supports. The elevation of the supports is adjustable between 20–35 cm. The supports can be fully removed. The socket located under the forefront of the couch can be pushed out and a computed radiography (CR) casette can be placed there. The couch is equipped with small wheels for easy movement
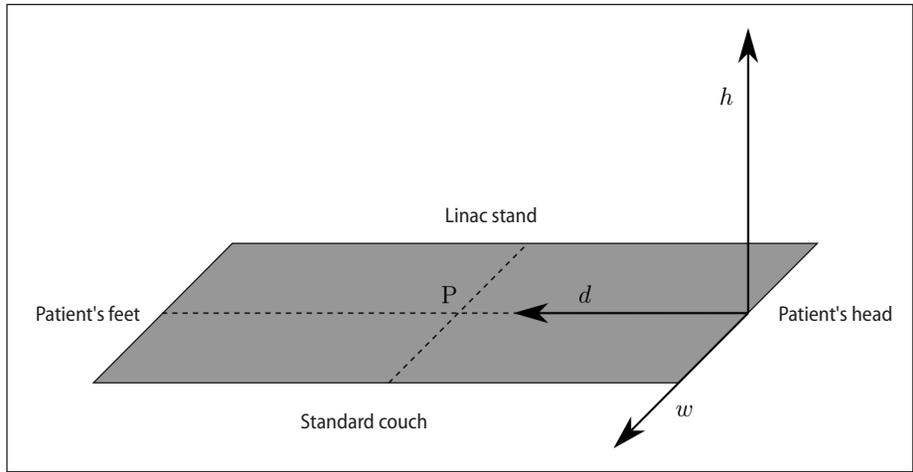
Figure 2. Coordinate system connected with the flat couch (gray rhomboid). The dashed lines are identical to the projections of laser positioning system. Point P is the vertical projection of the isocenter on the couch top and its coordinates are (d, w, h) = (45 cm, 0 cm, 0 cm)
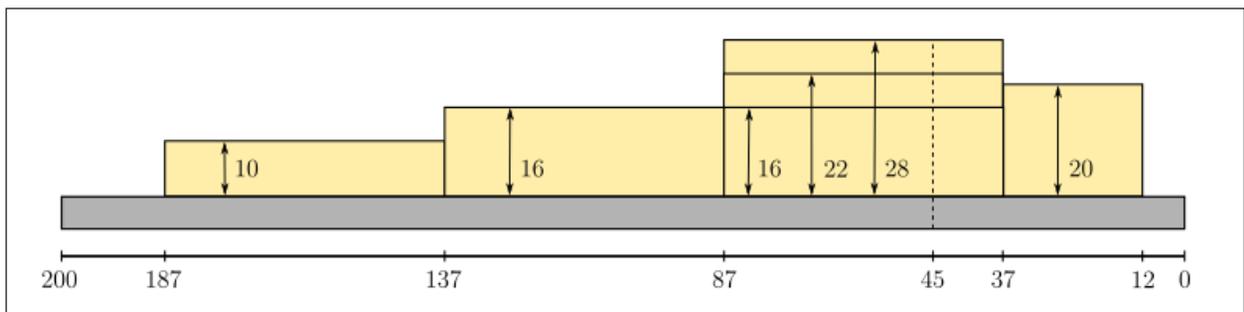

Figure 3. Schematic drawing of the patient models. From right to left, the individual blocks represent head, torso (three different diameters), thighs and calves. The gray rectangle represents the couch. The dimensions are in centimeters

Based on the patient data from our department, three simplifying patient models were created. Since a body cannot be represented by one value of its diameter, it was divided into four parts: head, torso (chest and abdomen), thighs and calves (including feet). Head, thigh and calf diameters were assigned values of 20, 16 and 10 cm, respectively. Depending on the choice of patient model, the torso thicknesses were 16 cm for a slim patient, 22 cm for a medium patient and 28 cm for a large patient. More detailed description is presented in Figure 3. A slab phantom made of RW3 material was used as the model representation during the measurements.

As for the irradiation technique, we adopted and modified the sweeping beam technique proposed by Jahnke et al.[7] The collimator was rotated 0° and the solid jaws limited the field size to 10 cm in the direction of the gantry rotation. The perpendicular jaws were fully opened to 40 cm. The prescribed dose is to be delivered in two arcs in the range of 325 to 65 degrees. Due to the flat couch surface, source-skin distance (SSD) varies during gantry rotation and so does the dose. Therefore, each arc was divided into 12 segments (Table 1) and these segments were assigned a specific number of monitor units (MUs). Each segment was represented by its central angle α, e.g., α = 20° for a segment with the range of 15 to 25 degrees.

In order to determine the number of MUs in the individual segments, a concept of relative MUs (rMUs) was used. The intersection of central axis of the beam (CAX) and phantom central plane is referred to as a point of interest (POI) and is fully defined by gantry angle α and phantom thickness p. Relative MUs are then calculated as

$$rMU(\alpha, p) = \frac{I(\alpha, p)}{I_{ref}} \quad (1)$$

Table 1. Final monitor units (MU) sequences for the three types of patients — slim (arc16), medium (arc22) and large (arc28). Irradiation with one arc corresponds to the midline dose of 1 Gy. The segments are assigned to the anatomical areas into which the radiation field is projected in the given range of angles. Each segment is represented by its central angle α.

Body part	Gantry angle [°]	[°]	MU		
			arc16	arc22	arc28
Head	325–335	330	516		
	335–345	340	409		
	345–355	350	390		
Torso	355–5	0	367	382	401
	5–15	10	378	383	413
	15–25	20	413	432	458
Thighs	25–35	30	474		
	35–45	40	611		
Calves	45–50	47.5	359		
	50–55	52.5	451		
	55–60	57.5	592		
	60–65	62.5	592		

where $I(\alpha, p)$ is the measured radiation intensity in the point of interest and I_{ref} is the intensity in reference point which is defined by $\alpha = 0°$ and phantom 22 cm thick. Both intensities are measured under the same conditions, i.e., using the same number of MUs evenly distributed over the arc. The collimator settings match the description above. Patients are always irradiated with PMMA spoiler above, hence the use of the spoiler during all measurements. rMU distribution can also be estimated by a theoretical calculation, as suggested by Jahnke et al. [7]. Nevertheless, dosimetric verification of these calculations is recommended.

Intensities $I(\alpha, p)$ were measured in the longitudinal axis of the phantom using a Farmer ionization chamber (IC) with sensitive volume of 0.6 cm³ (type TM30013, PTW-Freiburg, Germany). Relative MUs were calculated for all central angles α representing the segments and all patient models. Subsequently, the sequences were calibrated in terms of absorbed dose in the reference point and arc16, arc22 and arc28 were created (the numbering denotes the torso thickness of the models considered).

The required dose homogeneity in the central plane was verified via dose profile measurements. The phantom was irradiated with two arcs calibrated to 0.75 Gy from each arc in the central plane and the dose profiles were checked with the Farmer ionization chamber and gafchromic film (Gafchromic® EBT3, Ashland Advanced Materials, USA).

First, the dose profiles in the longitudinal axis were measured. The ionization chamber was used in the same manner as described above, but in different points of interest. In addition, the gafchromic film was placed between slabs in mid-depth of the phantom and after irradiation evaluated on the desktop scanner Epson Perfection V850 Pro (Seiko Epson Corporation, Japan). This procedure was applied to all investigated types of patients. A similar measurement was performed in the medium patient in the transverse direction at the level of the lungs, i.e., in the axis defined by coordinates $d = 45$ cm and $h = 11$ cm.

Additionally, the robustness of the method was examined in the phantoms of different thicknesses using sequence arc28. The absorbed dose was measured in the points defined by the phantom's central plane and coordinates $d = 45$ cm, $w = 0$ cm by an ionization chamber.

Results

Table 1 shows the resulting arcs as sequences of MUs. The results correspond to the prescribed dose of 1 Gy in the central plane of the phantom delivered in one arc. In case a different dose in one arc is necessary, the values in the table will be adjusted proportionally. It is necessary to keep in mind that two arcs are always applied — the first arc in a supine and the second arc in a prone position.
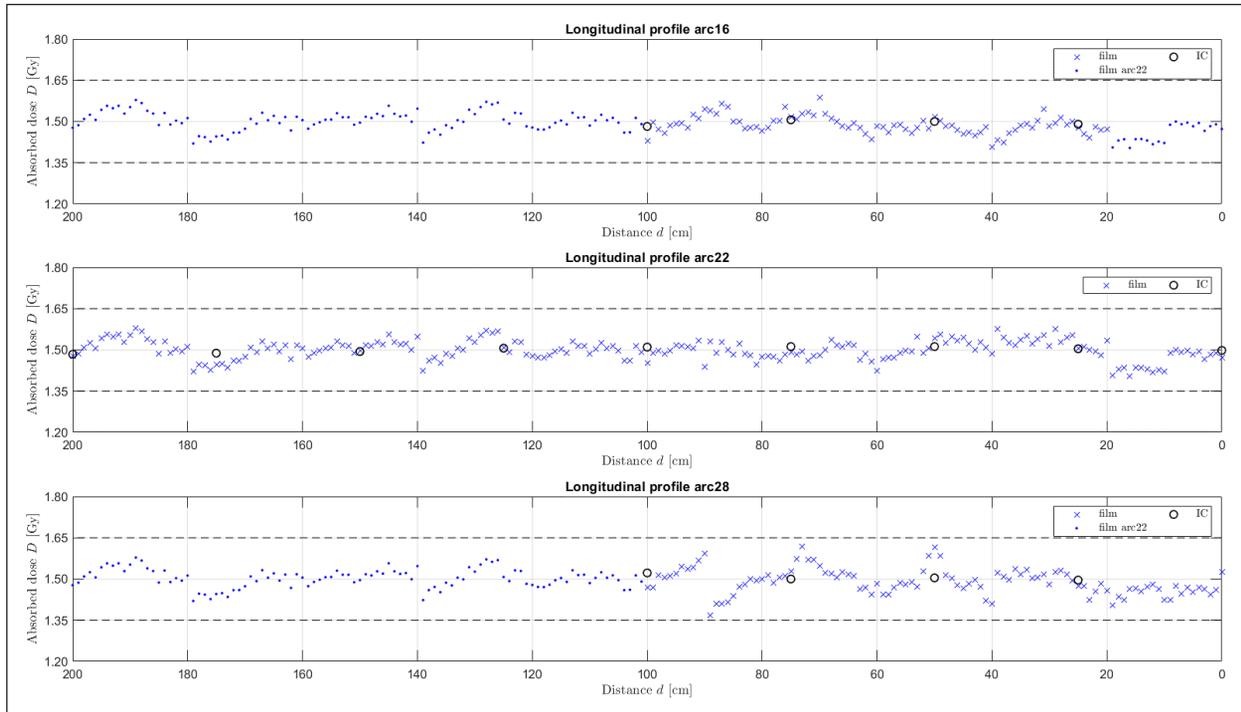
Figure 4. The longitudinal dose profiles measured with ionization chamber and gafchromic film for three patient models — slim (top), medium (middle) and large (bottom) patient. The prescribed dose was 1.5 Gy. The dashed lines indicate the maximal acceptable deviation from the prescribed value. The values marked by dots were copied from arc22 measurements, as the thickness of the phantom and the monitor units (MU) distribution were identical in the affected areas

The longitudinal profiles are presented in Figure 4. The largest set of data was obtained for the medium patient as a typical group representative. Nevertheless, major parts of the patient models coincide; thus, the results in these parts are of the same nature. Larger fluctuations of absorbed dose were observed in the large patient, especially at the transition from the torso and to the thighs ($d = 87$ cm) where the change in phantom thickness is significant. However, dose homogeneity stays within ±10% of prescribed dose (1.5 Gy).

Figure 5 depicts the transverse profile measured in the lung area in the medium patient. The dose values are close to the upper tolerance limit in a large part of the profile. The value of 1.65 Gy was exceeded at two points of measurement. Unlike the dose distribution in the longitudinal direction, the shape of transversal profile cannot be simply affected by the change in MUs in the arc segments. In fact, it reflects the transverse profile of the beam itself.

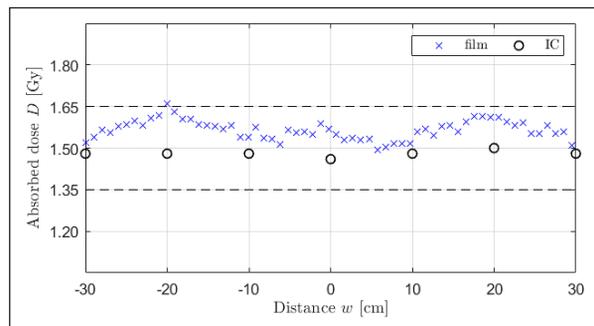Sensitivity to the change of phantom thickness is presented in Figure 6.

Figure 5. The transversal dose profile measured with ionization chamber and gafchromic film for the medium patient (sequence arc22). The prescribed dose was 1.5 Gy. The dashed lines indicate the maximal acceptable deviation from the prescribed value

Discussion

The technique using a low flat couch has proven to be an undemanding and a sufficiently high-quality TBI solution. We have adopted a sweeping beam technique presented by Jahnke et al. [7]. The technique has originally been designed for two different patient thicknesses, 16 cm and 20 cm, and its robustness has been validated for a limited thick-
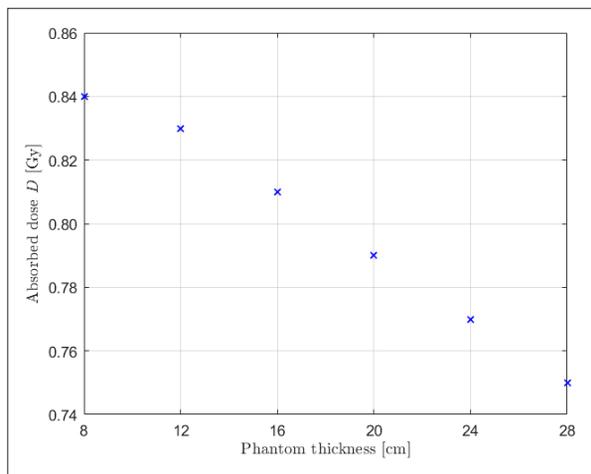
Figure 6. Absorbed dose for different phantom thicknesses in the phantom center measured with an ionization chamber using the arc28 sequence

ness range of 4 cm difference in maximum. At this range, the change in dose was always less than 1% per 1 cm change in phantom thickness.

Jahnke et al. suggested future improvements including variation of patient thickness. Based on our extensive experience, we have modified the technique for a broader range of patient sizes and respected basic anatomic proportions. All the proposed sequences, arc16, arc22 and arc28, were validated in terms of dose profile homogeneity in a homogeneous phantom. All the longitudinal profiles fulfil the ±10% dose homogeneity criterion specified in the AAPM Report 17 [4]. The largest shift in the dose profile can be seen at the boundary of 28 cm thick torso and 16 cm thick thighs, but this is still between ±10% of the prescribed dose. Concerning robustness, the increase in dose in the phantom center is 0.7% per 1 cm reduction in phantom thickness. This can result in higher doses to upper limbs whose thickness is commonly less than 10 cm. Compared with the largest expected chest thickness of 28 cm, the estimated increase could exceed 12% of the prescribed dose. To overcome this drawback, sufficient layer of the bolus could be used. A similar approach can be applied in the neck region. Nonetheless, at our department, uniform bolus thickness of 1 cm is used.

The technique presented is suitable for standard treatment rooms with a standard linear accelerator. The main advantages of the proposed technique include a significant increase in patient comfort, robustness and minimal investment in additional equipment. Irradiation of one arc takes less than 10 minutes using dose rate of 600 MU/min in standard 1.5–2 Gy fractionation; at our department the whole fraction usually takes about 30 minutes including patient positioning. However, it has been proved that dose rate has a significant effect on pulmonary toxicity [8, 9]. Therefore, the risk of side effects associated with the selected dose rate, dose regimen and other factors should be always thoroughly discussed with physicians.

In vivo dosimetry is conducted during every fraction using a gafchromic film. We decided to attach small pieces of the film to the ventral side of the patient and evaluate the arithmetic mean of entrance and exit dose. Thanks to the simplicity of the irradiation method, it is also very easy to make changes in the irradiation sequence when in vivo dosimetry shows unsatisfactory results. Moreover, these changes in MUs can be applied to specific parts of the body where needed.

The technique was designed for adult patients since no children are treated at our facility. However, a similar technique could be adopted for pediatric patients in other oncology centers.

A major drawback is the fact that the treatment planning systems do not usually have data for dose calculations in an extended SSD [10, 11]. As a result, control over the dose delivery within the patient is limited. Techniques performed in a standard SSD, for instance, a VMAT based technique operating with a whole body CT, do not face these problems, but may often lack the robustness and simplicity of implementation and the planning procedure might be very time consuming [12].

Extended SSD VMAT treatment for TBI with the treatment planning system data measured at an extended SSD of 175 cm was presented by Pierce et al. [5] This technique was developed by modifying Jahnke et al.'s standard arcs to accommodate for SSD variation by using patient CT data in the range of the top of the head to approximately middle thigh. The ability to easily shield organs at risk is provided by MLCs, which might be a promising alternative to the use of shielding blocks.

Conclusion

We designed a TBI technique with a flat irradiation couch which includes three irradiation sequences for three model patients of different sizes,

with respect to the shape of the human body. This method is applicable in majority of standard treatment rooms and requires minimal investments into equipment; thus, it can be simply adopted into routine clinical practice. Systematic in-vivo dosimetry should be performed during implementation.

Conflict of interest

None declared.

Funding

None declared.

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