



Modification of a modulated arc total body irradiation technique: Implementation and first clinical experience for paediatric patients

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Abstract

Introduction: To implement the modulated arc total body irradiation (MATBI) technique within the existing infrastructure of a radiation oncology department. The technique needed to treat paediatric patients of all ages, some of whom would require general anaesthesia (GA). **Methods:** The MATBI technique required minor modifications to be incorporated within existing departmental infrastructure. Ancillary equipment essential to the technique were identified and in some cases custom designed to meet health and safety criteria. GA equipment was also considered. To evaluate the effectiveness of the implemented technique, an audit of the cases clinically treated was conducted. **Results:** A motorised treatment couch was designed to allow the patient to be positioned in stabilisation equipment at a height, then lowered to the floor to accommodate source-to-skin-distances from 180 cm to 198 cm to treat the fixed 40 cm × 40 cm field size. Treatment couch design also facilitated positioning of the bespoke two-part spoiler. While organ at risk dose is limited using a beam weight optimisation technique, the dose is further reduced using compensators placed close to the patient's skin on a 3D printed custom-made support bridge. A digital radiography system is used to verify compensator position. Fifteen patients have been treated to date for various diseases using a variety of dose fractionations ranging from 2 Gy in a single fraction to 12 Gy in 6 fractions. Five patients have required GA due to age or behavioural issues. **Conclusion:** The modified MATBI technique and the equipment required for treatment delivery has been found to be well tolerated by all patients.

Introduction

In late 2014, with the opening of the Lady Cilento Children's Hospital Brisbane, Radiation Oncology Princess Alexandra Hospital - Raymond Terrace (ROPART) became the primary provider of paediatric radiation therapy services in Queensland. As a result, a Total Body Irradiation (TBI) protocol needed to be developed and implemented as TBI had not previously been offered by the department. Primarily patients diagnosed with acute forms of leukaemia, aplastic

anaemia and non-Hodgkin's lymphoma will undergo chemotherapy in conjunction with TBI in preparation for a hematopoietic stem-cell transplant or bone marrow transplant.¹ Paediatric patients referred to ROPART range in age from 1 to 18 years.

Initially the project team conducted an extensive evidence-based review of different TBI techniques.² The decision was made based on specific criteria, including requirements for 3D planning, the use of lung and kidney compensation and a preference for minimal use of additional bolus. The department was equipped with the

Pinnacle³ treatment planning system (TPS) versions 9.8 and 14.0 (Philips Healthcare, Fitchburg, WI), two Somatom Open computed tomography (CT) scanners (Siemens Medical Solutions, Forchheim, Germany) for planning purposes and four Clinac iX (Varian Medical Systems, Palo Alto, CA) linear accelerators (linacs). Each linac is equipped with onboard imaging (OBI) capabilities. TBI technique selection was also dependant on its suitability for implementation within existing infrastructure. Ultimately two options were presented to the multi-disciplinary team for consideration, a lateral field-in-field (FIF) technique³ and the anterior posterior modulated arc total body irradiation (MATBI) technique.⁴ The existing bunkers within the department are 7.1 m × 7.2 m in size and their layout precluded the use of a lateral FIF technique. After preliminary dosimetric testing and review by the multi-disciplinary oncology team, MATBI was chosen as the preferred technique.

MATBI is an anterior posterior technique requiring the patient to lie both supine and prone. Multiple static fields with a 3–5° gantry angle variation are positioned in an arc formation to treat the full length of the patient. Figure 1 shows a schematic of the beam arrangement used in MATBI. As described by Kirby *et al.*,⁴ MATBI is optimally treated at an extended source-to-skin distance (SSD) of approximately 200 cm. This is best achieved by the patient lying on a bed close to the floor. A Perspex spoiler positioned over the patient ensures full build-up conditions on the patient's skin. Compensators are used to lower the dose delivered to organs at risk and are best placed as close to the skin surface as possible. A fixed field size of 40 cm × 40 cm and collimator rotation of 0° is used. At the time of implementation, this technique had not been previously used in Australia.

Favourable features for implementing the MATBI technique included the facilitation of lung and kidney compensation and improved dose homogeneity over the length of the patient without the extensive use of bolus to equalise variations in separation. An inverse planning approach using the Pinnacle³ TPS beam weight optimisation option is able to be used to determine the monitor units required for each static field, optimising dose homogeneity throughout the body. This technique allowed for greater ease and accuracy of beam modelling data to be collected using a standard 3D water phantom. The MATBI technique required no physical modifications to the existing infrastructure in terms of room layout. However additional ancillary treatment and imaging equipment would be required as the OBI cannot be utilised for verification imaging of the compensators due to an extended SSD of around 200 cm. Consequently, an alternative imaging system needed to be sourced for use.

This paper provides a framework for implementation of MATBI and focuses on the identification and design of ancillary equipment. The adaptations and modifications made to the MATBI technique, in order to implement TBI treatments at ROPART, will be discussed.

Method

Ancillary equipment

The selection of the MATBI technique required an assessment of the constraints inherent with the bunker design at ROPART. Part of the implementation process required equipment to be either purchased or constructed including the following:

- TBI couch
- Spoiler
- Compensator bridge
- Treatment verification imaging
- Patient positioning and stabilisation equipment
- General anaesthetic (GA) facilitation

TBI couch development

MATBI requires an extended SSD of approximately 200 cm. The treatment couch on the Clinac iX linac only allows for an SSD to the couch top of approximately 160 cm. At a setup SSD of 140 cm the maximum field size achievable is 56 cm × 56 cm and insufficient to cover the lateral separation of the majority of patients. Therefore, a treatment couch that would allow the patient to be lowered closer to the floor was needed.

Consideration for TBI couch design had to take into account the existing room infrastructure. The distance from the isocentre axis to the linac couch stand is 47.5 cm. Therefore, the total width of the TBI couch plus the spoiler needed to be less than 95 cm. Preferably the TBI couch would accommodate imaging equipment and be compatible with the safe and efficient placement of a compensator bridge.

The modified massage couch as described by Held *et al.*,⁵ whilst readily available, presented a number of occupational health and safety risks. Without wheels or castors, the massage couch would have to be physically lifted into position from its storage area increasing the risk of injury to staff. Also, the massage bed height cannot be altered to compensate for changes in patient separation.

Having an adjustable couch height was considered an important feature for staff occupational safety and efficiency. This feature allows the patient to be positioned on the TBI couch at a more ergonomically safe height.

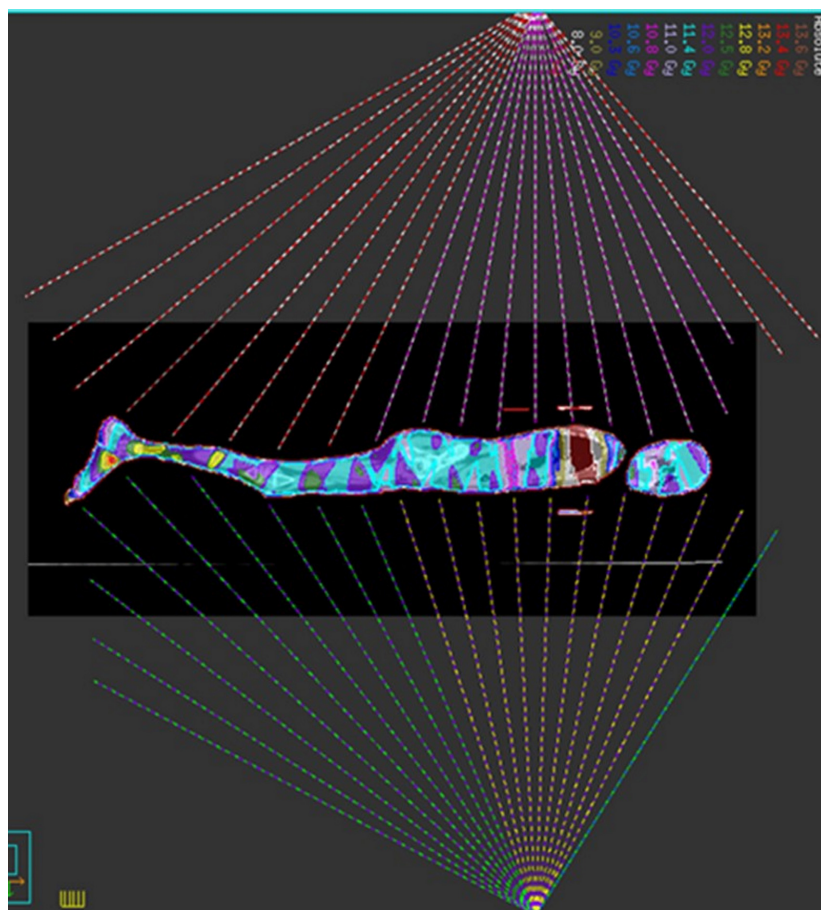


Figure 1. Schematic of beam arrangement for MATBI plan. Note anterior beams are delivered with the patient in the supine position.

Once the patient is positioned, the TBI couch could be lowered to the calculated treatment SSD. This feature is also vital for the safe induction of a patient undergoing a GA and the safe movement of the patient between prone and supine positions.

Many commercially available hospital and nursing home beds either do not lower to the floor enough to enable a greater SSD than the linac couch or had large bed ends that could not be removed. Collaboration was sought with a manufacturing company for a bespoke couch with the following design features:

- Height adjustable – motorised (battery or mains powered)
- Minimum couch top height of 15 cm
- Total width of 69 cm
- Couch top length of 180 cm
- Non-metal top to reduce scatter
- Must have a maximum weight restriction of 120 kg or greater

- Hospital grade Perspex surface for cleaning and stability
- Imaging panel space (3 cm) below the top surface
- Lockable castors/wheels for manoeuvrability
- Compensator bridge guide

Spoiler

Skin sparing is usually a desirable feature of megavoltage radiation therapy. However, for patients undergoing TBI, as leukaemic cells may circulate through or infiltrate the skin, it is advantageous to have the skin receive as close to the prescribed dose as possible. The use of a 1 cm thick Perspex screen, placed 10–15 cm from the patient's skin surface creates scatter electrons thereby increasing the dose to the patient's skin.⁶

The manufacture of the spoiler was dependant on the final TBI couch length and width. The height of the spoiler needed to be adjustable to accommodate a variety

of patient separations and the inclusion of the compensator bridge. Spoiler design needed to allow for the safe and efficient placement and removal should the patient require assistance during treatment. Finally, spoiler length was based on a 75th percentile height of approximately 180 cm for an 18 year old male.⁷

Compensators and compensator bridge

Compensators are used during the treatment of TBI patients to reduce the toxicity to organs at risk. Mean lung doses of 10–12 Gy have been associated with increased risk of interstitial pneumonitis, so lead compensators are utilised to reduce the mean lung dose to 10 Gy.⁸ Kidney compensation may also be requested by the radiation oncologist (RO) and applied in the prone position. Compensators are manufactured from layers of lead shaped as per the outline marked on the planning CT scan by the RO. Compensator details are displayed in Table 1.

For maximum benefit, compensators should be placed directly on the patient's surface. This limits the amount of primary beam incident on the patient under the blocks when being irradiated at oblique angles. Skin placement was not an option due to the weight of compensators for paediatric patients and the anatomical shape of the thorax made it difficult to keep the compensators level and in place. Alternatively, the compensators are placed on a flat surface as close to the patient's skin surface as possible. The compensator bridge was designed to accommodate a range of patient separations, to be stable and able to support up to 4kg and be radio-translucent.

Treatment image verification

For compensator placement verification, the standard linear accelerator kV imaging equipment could not be used. Various computed radiography (CR) and digital radiography (DR) imaging systems were compared for image quality, efficiency or image assessment, accuracy of spatial information and user friendliness.

Table 1. Compensator attenuation and thickness.

	Number of lead sheets				
	1	2	3	4	6
Approximate attenuation (%)	10	20	30	40	50
Thickness (cm)	0.28 ¹	0.56	0.84	1.12	1.68

¹Physical density of each lead sheet is 11.2 g/cm³.

Patient positioning

Existing equipment was evaluated to create a comfortable and reproducible patient position. As only the prone CT data set is used for treatment planning, it was imperative that there was accurate replication of the patient position between prone and supine positions, including the head position. Ideally when lying prone, the posterior surface of the shoulders, buttocks, heels and posterior surface of the head need to be level and parallel to the treatment couch as if they would be lying supine.

Initial testing was performed using anthropomorphic phantoms of different sizes. This provided preliminary information on positioning issues. Secondary testing involved staff and children volunteers across a variety of ages, heights and weights. It was identified that equipment requirements for accurate positioning varied between patients due to the different patient sizes expected in a paediatric cohort.

General anaesthetic facilitation

Although every measure is taken to eliminate the use of daily anaesthesia, at times it is required. From the literature, GA is advised for patients less than three years of age.⁹

With any GA there are inherent risks involved, including nausea and vomiting, sore throat and reactions to medications.¹⁰ Extra care is needed when positioned prone, as the risks are potentially greater and include a decrease in cardiac output, inferior vena cava obstruction and pressure sores.¹¹ If an emergency situation arises, it is critical that the anaesthetic team are provided fast and easy access to the patient.

Clinical review of MATBI at ROPART

An exemption from institutional ethics approval was granted (reference number HREC/16/QPAH/718) to perform an audit of the clinical cases treated since commencement of the department's paediatric service. Data collected included age, height, weight, disease type, delivered dose, number of treatment fields and use of general anaesthetic.

Results

Ancillary equipment

Treatment couch

The TBI couch has a maximum working height of 78 cm and lowers to a minimum floor to couch top distance of 14 cm (Fig. 2A and B). This provides a maximum SSD to

the couch top of 216 cm. The TBI couch top is 69 cm wide, 188 cm long with two levels. The top surface of the couch supports the patient, stabilisation equipment and compensator support bridge while the second level accommodates the digital imaging panel. The distance between the two levels is 3 cm allowing for easy positioning and removal of the imaging panel. The TBI couch is made using hospital grade Perspex for infection control reasons. The non-porous material makes it easy to clean and does not interfere with the image quality. The bespoke couch enabled the patients to be treated within the confines of existing bunker infrastructure and room layout.

Spoiler

The open-ended design of the spoiler optimises access for additional devices should a patient arrive with intravenous infusion equipment. Due to limitations in bunker size, the spoiler was manufactured in two halves that are locked together when positioned over the patient. The spoiler is 1 cm thick with a height ranging from 35 to 60 cm off the floor. The height of the spoiler is determined during the planning process to be positioned approximately 10 cm from the patient's skin surface (Fig. 3). The total width is 83 cm and the combined length of the two sections is 241 cm. The sides of the spoiler provide strength and allows the patient to easily

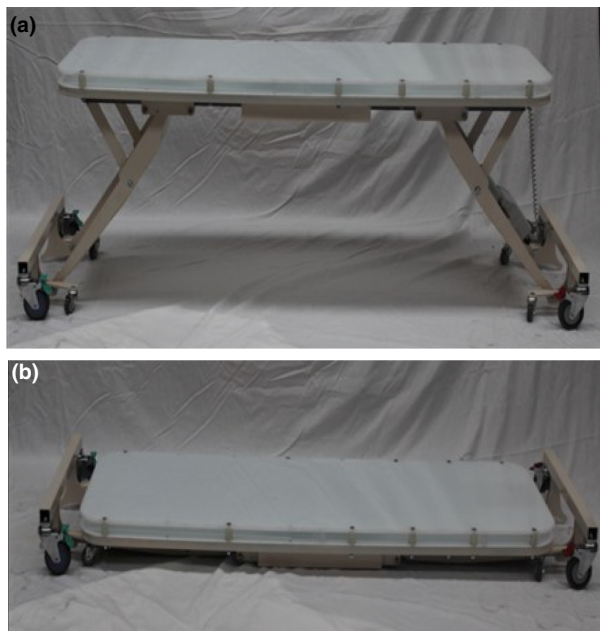


Figure 2. The treatment couch (supplied by Maxi-Care Promotions Pty Ltd). (A) Full working height. (B) Lowered treatment position.

view distraction devices. The spoiler was also constructed with lockable casters/wheels to aid in ergonomic and safe positioning over the patient.

Compensator and compensator bridge

TBI compensator blocks are suspended above the patient on a bridge constructed using 3D printed polylactic acid (PLA) plastic to minimise the effect on beam attenuation to $<0.5\%$ (Fig. 4). Two different sized compensator bridges were created to accommodate compensators of differing length or for cases where extra length is required to support kidney compensators. Each bridge is designed to accommodate a weight of up to 4 kg. The underside of the compensator bridge is set approximately 2 cm from the patient's skin surface. This allows for the patient's chest to rise and fall with breathing without touching the bridge. The compensator bridge was designed in-house and, in part, constructed using a Makerbot2 3D printer (MakerBot Industries, Brooklyn, NY).

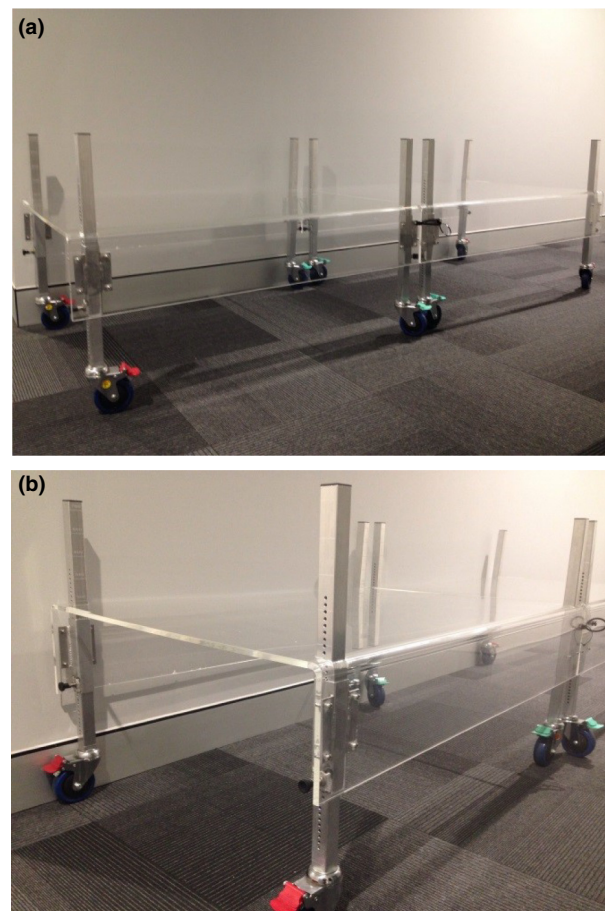


Figure 3. The spoiler. (A) Two-part Spoiler connected. (B) Spoiler (end view).

Channels made of the same hospital grade Perspex as the treatment couch were added along each edge of the TBI couch to prevent lateral movement of the compensator bridge during treatment. These channels therefore only allow the bridge to be moved superior or inferior to reposition compensators post imaging. This feature reduces the risk of potential injury to the patient from dislodged compensators (Fig. 4D).

Imaging

A Canon CXDI-701C was purchased. This DR imaging system enables multiple pre-treatment verification images

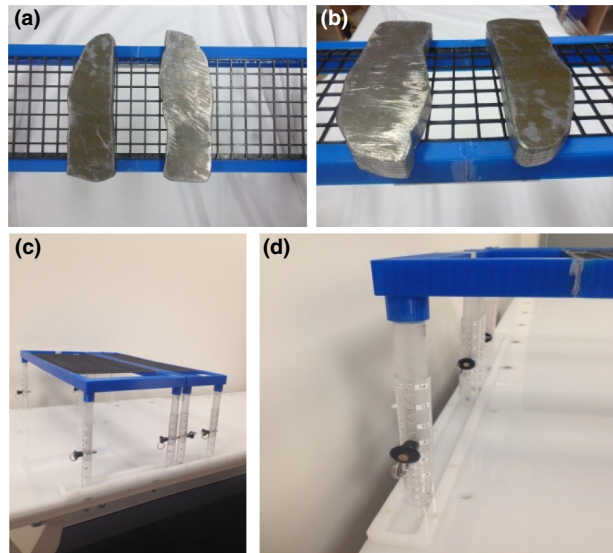


Figure 4. Compensators & Bridge. (A and B) Lung compensation blocks on bridge (C) Compensator bridges (large and small) (D) Compensator bridge in bad channels.

to be acquired while leaving the cassette in place. Images are transferred via Wi-Fi to the DR laptop. Treatment images are then easily transferred and saved to the MOSAIQ Oncology Management System (Elekta, Stockholm, Sweden), (Versions 2.4.1 & 2.6.0), for visual comparison against planning DRRs and for future reference. Image quality while not as high as early phantom testing indicated (Fig. 5A–C) has provided sufficient visualisation to confirm the accurate placement of the compensators.

Patient positioning

Vacbags are utilised for all patients for both supine and prone positioning, generally encompassing the shoulders to the knees. Large foam boards and wedges placed under the prone vacbag raise the torso and legs of the patient to achieve the required flat posterior surface that is parallel

Table 2. CT measurements.

Area	Measurement (cm)	
	Prone	Supine
Separation from table top (mid-thorax)		
Top of head – Top of shoulders		
ITN – Top of shoulders		
Tip of chin – Top of shoulders		
RT shoulder – LT shoulder		
RT inner elbow – CW		
Lt inner elbow – CW		
Iliac crest – malleolus		
RT med malleolus – LT med malleolus		

ITN, Inferior Tragal Notch; RT, Right; LT, Left; CW, Chest Wall; Med, Medial.

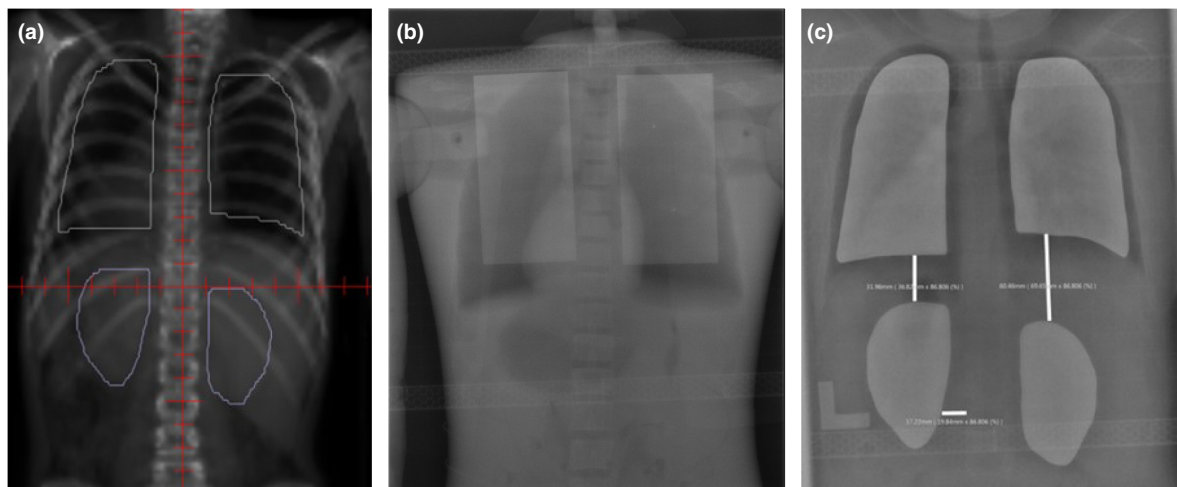


Figure 5. Compensator position on planning DRR versus treatment DR. (A) Digitally reconstructed radiograph (DRR) image. (B) Test Image. (C) Digital radiography (DR) image.

to the treatment couch. The patient is set up in the prone position first as testing revealed that there are greater options to replicate the prone position when the patient is supine. Measurements are taken using various landmarks to aid reproducibility of the patient's position when supine. If a patient did not find lying with their head straight comfortable while in the prone position then a head turn to the left would be required. Head position must be consistent when repositioning between prone and supine. Table 2 shows the measurements taken to ensure consistent positioning between supine and prone set-ups.

Anaesthetic considerations

To assist with access to the patient's airway throughout the planning and treatment process, patients who require general anaesthesia are treated with their head turned to their left side. This also allows the anaesthetist to visualise the patient's face from the closed-circuit television (CCTV) screen outside of the treatment room when prone. For the supine fields, the patient also has their head turned towards their left shoulder to ensure even dose through the head. While the face cannot be viewed in this position as it is facing away from the CCTV, the rise and fall of the chest is easily viewed and acceptable to the anaesthetic team.

Clinical review of MATBI at ROPART

Since the technique's inception early in 2015, 15 patients have been treated with the MATBI technique. Table 3 provides summary of patient-specific information and treatment details. Patient ages ranged from 2 to 15 years while fractionation ranged from 1 to 6 fractions. Eleven patients received 12 Gy in 6 bi-daily fractions while the remaining four patients received a single fraction with a prescribed dose ranging from 2.0 to 4.5 Gy. Total beam on time for these patients ranged from 30 to 80 min. The longer beam on time for Patients 2 and 10 was due to the higher fraction dose which required the dose to be delivered at a reduced dose rate of 100 MU/min and 60 MU/min for fields treating lung tissue.

Five patients were treated while under GA (all single fractions). Due to developmental behavioural issues, a 7-year-old girl and 10-year-old boy were unable to comply with the position required for treatment despite play therapy. In these cases, the decision to use GA was in the best interest of the patient.

One patient's height of 198 cm exceeded the length of the TBI couch top. In this case the patient's head was positioned on the table top with the lower legs and feet supported above and over the end of the metal frame of

Table 3. A summary of patients treated between January 2015 and July 2017 using MATBI.

Patient	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Age (years)	10	10	13	6	15	2	7	13	3	11	15	4	6	13	15
Disease	ALL	AML	ALL	ALL	ALL	ALL→AML	SAA	ALL	ALL	AML	ALL	ALL	ALL	BPDCN	ALL
Height (cm)	137	135	163	119	165	92	135	153	92	167	159	101	124	162	198
Weight (kg)	28	22.5	53	24.3	42.9	15.9	29	60	15.2	65	74	16.5	28.8	71	75
Fractions	6	1	6	6	6	1	1	6	6	1	6	6	6	6	6
Dose per fraction (Gy)	2	4.5	2	2	2	2	3	2	2	3	2	2	2	2	2
Beam number	21(P)	20(P)	23(P)	19(P)	24(P)	16(P)	18(P)	20(P)	16(P)	23(P)	21(P)	18(P)	17(P)	22(P)	24(P)
	19(S)	21(S)	23(S)	20(S)	22(S)	16(S)	19(S)	23(S)	16(S)	23(S)	23(S)	19(S)	19(S)	22(P)	23(S)
Beam on time ¹ (mins)	30	80	36	31	34	28	39	34	28	70	35	30	30	38	37
Anaesthetic required	N	Y	N	N	N	Y	Y	N	Y	N	N	Y	N	N	N

ALL, Acute Lymphoblastic Leukaemia; AML, Acute Myeloid Leukaemia; SAA, Severe Aplastic Anaemia; BPDCN, Blastic Plasmacytoid Dendritic Cell Neoplasm; P, Prone; S, Supine; N, No; Y, Yes.
¹Note the beam on time does not include set-up time.

the couch using a vacbag. The spoiler length easily covered the patient length. In vivo measurements confirmed no additional scatter was received to the ankles and feet.

Discussion

MATBI is the first TBI technique implemented at ROPART. The TBI investigation team were tasked with identifying a TBI technique that would accommodate paediatric patients ranging in age from 1 to 18 years, fit within current bunker infrastructure and be able to be delivered using a Clinac iX linear accelerator. To meet these constraints, custom designed equipment was required.

The height adjustable treatment couch was designed to allow greater ease and accuracy of setup compared with the original static massage table. A static height requires the patient to be setup at simulation on the linac to determine the treatment SSD,⁴ whereas an adjustable height removes this step. Staff and patient preferences have been mixed with regards to the adjustable height. The majority of the patients have found it easier to get onto the couch at a height close to the floor as it is easier to manoeuvre into the vacbag. Some staff prefer to setup the patient close to treatment height, whereas others raise the couch to a working height, including the anaesthetic team. The adjustable height allows individual preferences to be met and enables height adjustment for inter-fraction setup variation.

While Held *et al.*⁵ opted not to use a spoiler, the literature supported the importance of increasing skin dose⁶ and there was an RO preference for its use, especially in the paediatric population. The spoiler was designed as two equal halves to improve manoeuvrability and has the advantage of easy and efficient placement and rapid removal. While there have been no emergency situations, staff report finding the two halves easy and efficient to manoeuvre in the tight spaces required.

The DR system employed for compensator placement verification is the first use of its type in radiation therapy and in particular, TBI treatment. DR imaging allows for real-time assessment of compensator positioning reducing time the patient is required to remain motionless, therefore increasing accurate placement of compensators. While this system improves treatment efficiency compared with other options, it does pose a challenge to staff due to infrequent use and poor image quality. As a result, there continues to be a training session with the treating team prior to each TBI patient. This session aims to refresh staff on setup considerations and equipment use, including the DR system. Feedback from staff suggests this approach allows more efficient treatment flow and improves staff confidence.

Patient comfort is vital to ensure the patient remains still during dose delivery. The only patient comfort issue needing to be addressed and not initially anticipated was the post-planning insertion of a prophylactic nasogastric (NG) tube due to potential mucositis. If the NG tube is placed in the right nostril, positioning the head turned to the left is uncomfortable. This has been mitigated through communication and education of appropriate paediatric hospital staff.

Clinical challenges experienced have been minimal with the greatest challenge being the 198 cm male patient and a couch length of 188 cm. The lower legs required additional support over and above the metal couch end frame. This was successfully achieved with no measurable scatter from the couch to the patient. In summary 15 patients of varying ages and heights have been treated with 5 of the 15 patients requiring GA.

Conclusion

The MATBI technique has been successfully implemented within the existing bunker infrastructure and clinical environment within ROPART. Although only a small number of patients have been treated to date, the design of the equipment developed has easily accommodated a wide range of patient ages and sizes, with and without the use of anaesthetic equipment.

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Conflict of Interest

The authors declare no conflict of interest.

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