



Review

Multicenter comparison of different total body irradiation techniques – Results from the DGMP Working group large-field irradiation techniques

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Abstract

Total body irradiation (TBI) plays a central role in the treatment of hematologic diseases. Due to the large size and heterogeneous nature of the target volume, various irradiation techniques have been developed to ensure a homogeneous dose distribution and accurate dose delivery. In this paper, 22 treatment centers in Germany and Switzerland were asked to present their respective irradiation approaches. In total, four different main techniques, which can be further divided for performing TBI, were identified. This review outlines these methods and discusses clinically relevant aspects associated with each approach. The aim is to provide an overview of current practices and to serve as a decision-making aid for institutions considering or undergoing a transition in their TBI technique. All presented techniques are feasible and clinically

effective; however, intensity-modulated approaches appear to be gaining increasing importance.

Keywords

TBI; Large field irradiation; Multi-isocentric irradiation; Technical review

1. Introduction

Total body irradiation (TBI) is a specialized radiotherapy technique that has become an integral part of the preparative regimen for hematologic stem cell or bone marrow transplantations, particularly in the treatment of many hematologic malignancies [1]. The aim of this form of radiation therapy is to destroy all malignant cells, which are usually spread throughout the body, while at the same time creating an immunological environment that promotes the acceptance of potentially transplanted donor cells. To achieve these goals, the radiation should ideally reach all parts of the body equally and with optimal dose distribution [2]. However, there are various approaches to deliver TBI resulting in significant heterogeneity in clinical practice.

A recent survey highlighted differences in irradiation techniques, prescribed doses, and organ-at-risk (OAR) sparing strategies across treatment centers, not only for TBI but also for all large-field irradiation techniques in Germany and Switzerland [3,4]. To determine the similarities and differences of the methods currently in use, the German Society for Medical Physics e.V. (DGMP) working group on large field irradiation techniques collected standard procedures of TBI techniques from 22 centers (21 in Germany and one in Switzerland). According to the survey by Heuchel et al. [4] and recent updates, these centers can be categorized into distinct technical approaches using their clinical linear accelerators (linacs): seven use static field techniques in different variants, five employ sweeping beam techniques [5,6], four apply multi-isocenter volumetric-modulated arc therapy (VMAT) [7], and six operate Tomotherapy systems.

Comparable reviews and national surveys have been conducted in several other countries, emphasizing the diversity of TBI implementations worldwide. In North America, the American College of Radiology and the American Society for Radiation Oncology published comprehensive guidelines on TBI performance and quality assurance [8], while a Canada-wide survey by Studinski et al. [9] reported significant variations in prescribed doses, beam arrangements, and OAR sparing concepts. Similar analyses have been performed in Europe and Asia, including studies comparing dose homogeneity and feasibility of linac-based and modulated techniques [10,11]. Recent investigations further explored the accuracy and clinical outcomes of modern VMAT- and Tomotherapy-based

approaches, confirming their reliability and potential for improved organ sparing [[10], [11], [12], [13]].

The purpose of this manuscript is to present and critically compare all of these techniques. The overview is intended as guidance for determining, which TBI method is most suitable for centers introducing TBI treatment or, alternatively, changing their TBI technique e.g., due to new equipment. In each case, the guidance should ensure an easy transition and effective implementation of TBI treatments.

2. Material and methods

The following sections will describe the different approaches, using static fields, sweeping beam, multi-isocenter VMAT, and Tomotherapy.

In clinical routine, fraction doses of 2 Gy applied twice a day with at least six hours interval are most commonly prescribed for TBI, although regimens with 3 Gy given in daily fractions are also in use. For the comparison of techniques in this work, dose normalization refers to the prescribed single-fraction dose, with monitor units distributed evenly if opposing fields are used.

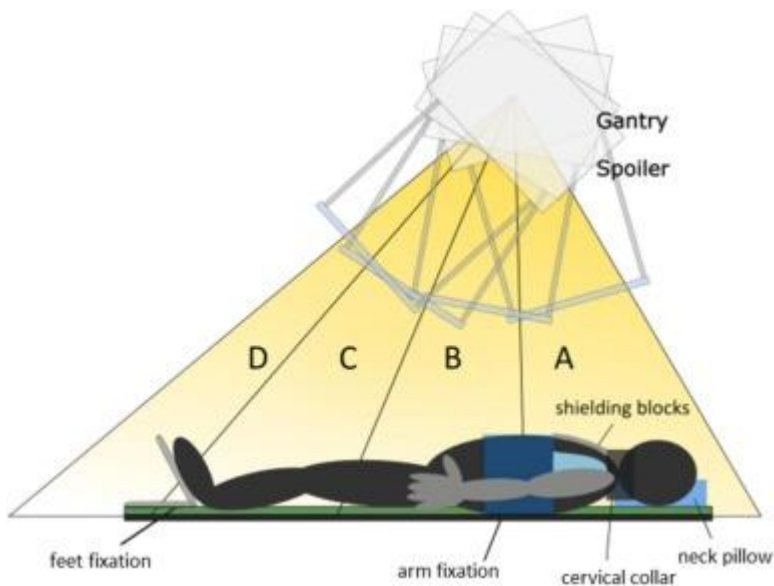
The use of bolus material to increase dose at the patient surface is not technique-specific but rather depends on institutional practice and the desired skin dose level. Some centers aim for full dose coverage of the skin, which is part of the planning target volume (PTV), whereas others accept a reduced surface dose to minimize acute skin reactions. Consequently, the mention of bolus use in the following sections reflects local clinical preferences rather than inherent properties of the techniques.

To verify the delivered dose during irradiation, several methods are available for in vivo dosimetry, including thermoluminescence dosimeters (TLD), Optically Stimulated Luminescence (OSL) dosimeters, metal oxide semiconductor field-effect transistors (MOSFET), Image Guided Radiotherapy (IGRT) and semiconductor diodes [14,15]. Compared to TLD the main advantage of using semiconductor diodes is the immediate readout and reuse. Detector probes are attached to relevant measurement points typically located at the reference point (navel), lung and between the eyes.

2.1. Static fields

2.1.1. Multiple static fields

Multiple static fields TBI can be applied with the patient positioned on the treatment couch with a couch extension in the lowest couch position (see Fig. 1).



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Fig. 1. Scheme of multiple static fields TBI with the patient placed in HFS on the treatment couch lowest position. Neck, arms and feet are fixated. To enhance skin dose a PMMA spoiler is mounted to the satellite carrier of the linac. Irradiation fraction is applied with 3 to 4 adjacent static 6 MV photon beams (A-D) in HFS position and similarly repeated in HFP position. If 12 Gy dose is applied, shielding blocks are placed on the thoracic wall.

Dose calculation is based on two total body CT scans, one in head first supine (HFS) and the other in head first prone (HFP) patient position using the standard treatment planning system (TPS). The verification of the TPS calculated monitor units (MU) is based on previous measured values acquired at the implementation phase of the technique.

To enhance dose build-up on the patient's skin, a spoiler of polymethylmethacrylate (PMMA) mounted on satellite carrier of the linac and therewith placed over the patient is used. For dose calculation, the dose absorbed to the spoiler is accounted for through correction factors to the TPS calculated MU.

Treatment is performed in the lowest couch position at a source-to-surface distance (SSD) of approximately 130 cm and isocentric couch rotation angle of 270° . An extra-long couch extension is necessary for irradiation of the patient successively in HFS and HFP position with 3-4 adjacent static 6 MV photon beams with maximum multileaf collimator (MLC) opening. For every fraction, the field borders are shifted caudally about 1 cm to avoid under- and overdoses at the field boundaries.

If a dose of 12 Gy is scheduled, two patient-customized lung-shielding blocks made of lead are placed on the patient's thoracic wall to reduce the lung dose. The position of the

shielding blocks is verified using the on-board electronic portal imaging device (EPID). The blocks lead to an underdose in the adjacent chest wall, which is compensated by two sets of opposing lateral fields in HFS and HFP calculated in the TPS. [Table 1](#) provides an overview of the described techniques.

Table 1. Overview of the main setup, dosimetric, and practical parameters for all techniques summarized in this manuscript.

	Multiple static fields	Translation technique	Bilateral technique	Seated technique	Sweeping beam
Participating Institutions	4	1	1	1	5
Patient setup	HFS + HFP on couch, extralong couch extension near floor	HFS + HFP on motorized couch near floor	HFS + FFS, wall mounted or extra treatment couch	Patient sits in a special swivel chair (“Berliner Stuhl”)	HFS + HFP on couch, extralong couch extension near floor
Source–Patient Distance	130 –500 cm	200 cm	500 cm	340 cm	200 –300 cm
Planning time	2-4 h	1 h 30 min	1 h 30 min	4h	2 –8 h
Dose normalization	Each field to center of body cross section	Center of abdomen midplane at navel	Midplane	100% at reference points (head, mediastinum, umbilicus)	Average body dose
Preparation time	10 min	10 min	5 h 30 min	40 min	10 min
Irradiation time	45 –60 min	45 –60 min	20 min	20 min	45 min
Required material	Extended couch, 2 cm PMMA spoiler, patient-specific	Lead sheets of various thickness for lung blocks	RT bunker with extended SAD (≥ 3.5 m), wall-mounted or auxiliary couch, PMMA	“Berliner Stuhl”, lung shielding block, water bag and blocks	Floor couch, PMMA slabs, bolus material

	Multiple static fields	Translation technique	Bilateral technique	Seated technique	Sweeping beam
	cervical collar and lung shielding blocks		spoiler, reusable tin- paraffin mixture, milling machine		
Dose calculation	Standard TPS; MU correction including spoiler factor	Beam-zone method; dose calculated at selected reference points	Projection algorithm; dose calculated using TPR data and compensator attenuation	In-house developed software	Based on table geometry and/or commercial TPS
Robustness	Large open fields; lung shield position verified by portal imaging; field border shifts possible between fractions	Stable large open field geometry	High setup reproducibility; low dose gradients	Robust open-field geometry (field size exceeds patient outline)	Stable setup; tolerant to positioning uncertainties and intra/interfraction motion
Advantages	Robust geometry; field weighting adaptable to body diameter	Simple, robust setup with open fields, no field connections	Patient comfort, robust and reproducible setup, missing field connections	Robust setup; possible lung dose reduction without mediastinal underdosage using saturation fields; simple workflow	3D dose optimization; robust against setup errors; no specific linac requirements

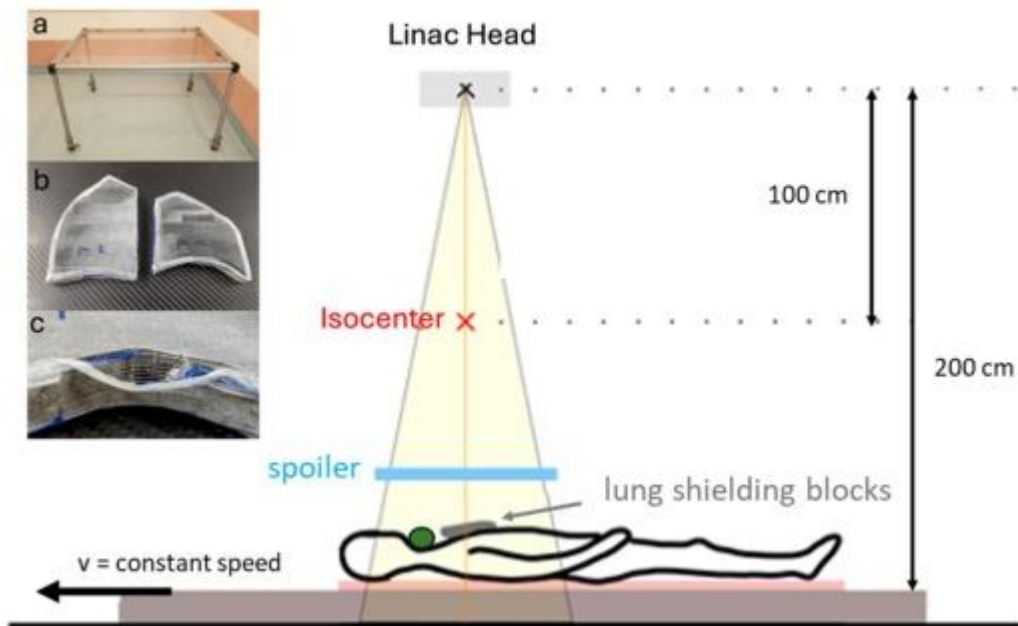
	Multiple static fields	Translation technique	Bilateral technique	Seated technique	Sweeping beam
Disadvantages	Time-consuming for lateral fields; limited dose homogeneity for extreme diameter variations	No full 3D dose information	Lung dose reduction limited due to potential mediastinal and extremities underdosage	Dose inhomogeneity due to lateral fields; additional weight on patient due to water bags	Increased dose inhomogeneity in the extremities
Organ protection	Lung shielding blocks for 12 Gy	Lung shielding blocks for 12 Gy TBI dose, neck bolus, lens protection	Integrated in the compensator design	Patient-specific lung blocks (lung dose < 8 Gy)	Lung shielding blocks
Dose rate	0.15 –0.20 Gy/min	0.75 Gy/min	0.15 –0.20 Gy/min	0.05 –0.1 Gy/min	0.5 –1.5 Gy/min
In-house Materials	Lung shielding blocks, cervical collar, spoiler	Couch/table construction, lung shielding blocks, spoiler, neck bolus	In-house designed 3D compensator, spoiler	“Berliner Stuhl”, lung shielding block	Floor couch, lung shielding blocks, spoiler
Method Variations	Patient positioned on board on the floor, manually shifted; up	Motorized or manual couch translation linked to linac dose-	Use TPS and MLC fields instead of compensators; adjust patient position based	Use of mediastinal saturation fields for improved homogeneity	Different irradiation techniques

Multiple static fields	Translation technique	Bilateral technique	Seated technique	Sweeping beam
to three static fields per position.	rate compensation	on available eSAD; EPID can replace CR imaging		
Variation: AP/PA TBI using very large SSD (~500 cm)				

In addition to this standard setup, some centers have implemented an anterior-posterior/posterior-anterior (AP/PA) TBI technique using an extremely large SSD of approximately 500 cm. In this approach, the patient is positioned on an elevated platform so that the entire body can be covered within a single field. This configuration offers a high degree of dose homogeneity and avoids field junctions, but requires specific room adaptations and is therefore rarely used.

2.1.2. Translation technique

One additional option for TBI with static fields is the translation technique (scheme in [Fig. 2](#)). In this approach, a motorized couch is used to move the patient horizontally through a vertical 6 MV photon field at an extended SSD of approximately 200 cm, in both HFS and HFP positions [16]).



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Fig. 2. Scheme of translation technique with the patient positioned near the floor on a motorized couch passing the patient through a 6 MV photon beam of the linac with constant speed. A spoiler in a table-like construction (see also a)) is used to increase skin dose. Tissue-like bolus material in the neck region compensates smaller patient diameter. Lung shielding blocks made of stacked lead sheets (see also b) and c)) reduce lung dose if 12 Gy TBI dose is applied.

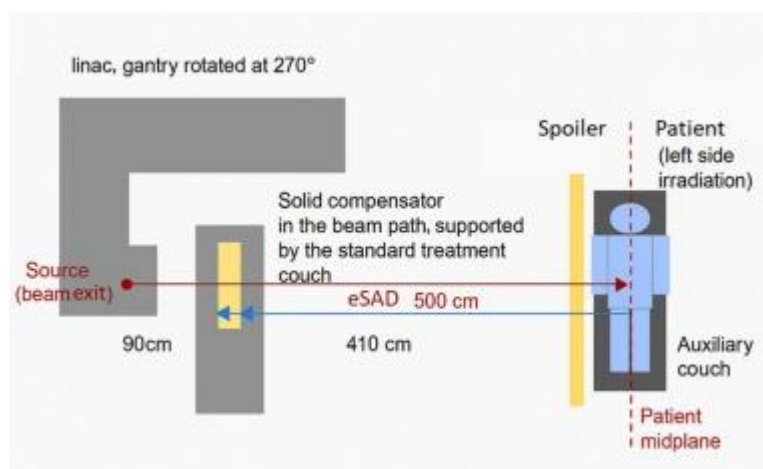
For treatment planning, total body CT scans in HFS and HFP position are needed. As a standard TPS cannot calculate a 3D dose distribution for this technique, the beam zone method [17] is used to conventionally calculate the dose distribution at a few points of interest. The radiation field is divided into sectors that contribute the same dose to the center of the field. The number of sectors represents the treated body surface of the patient and the total dose to the center of the irradiation field. Correction factors consider the individual transversal patient diameter, width and distance from the radiation source. Finally, the translation speed of the motorized couch is adjusted to achieve the prescribed dose at a specific reference point, i.e., in the center of the abdomen midplane at the navel [18]. The total dose delivered to a patient using this technique is approximately linearly proportional to the field size. As the field length increases, the irradiation time for a specific point on the patient also increases. Thus, the bed speed varies depending on the field length, the dose rate, and the desired dose to the patient [19]. As dose is normalized to the navel only, dose inhomogeneities of $\pm 10\%$ are accepted.

Lung sparing is achieved with custom-made shielding blocks to reduce the average lung dose to 8–10 Gy for a TBI dose of 12 Gy [20,21]. The size of the blocks is calculated from the individual thicknesses of lung and chest wall as well as the lung density. Lead sheets are cut to the patient-individual lung shape taken from AP anterior-posterior radiographs of the thorax. Bolus may be applied locally if bony structures are directly beneath the skin [3]. A spoiler made of 1 cm thick PMMA is positioned with a table-like construction over the patient to increase skin dose.

Patients are treated using large open 6 MV photon fields. The field length can be varied, but the field width should always be sufficiently larger than the patient. The patient is located in HFS and later HFP position near the floor on the motorized couch with approximately 200 cm SSD and is moved through the 6 MV photon irradiation field with constant speed in both positions per fraction [22]. Couch speed is controlled by an analog signal derived from the linac, which is proportional to the delivered dose rate [23] and therefore allows compensation of dose rate fluctuations during treatment. Before patient treatment, couch speed is calibrated relative to a given reference speed to apply 1 Gy dose in a defined reference geometry and phantom setup. Robustness is achieved through a 10 cm larger field size than patient's extent. Table 1 summarizes the techniques described above.

2.1.3. Bilateral field technique with solid compensator

The bilateral field TBI technique with solid compensator (see Fig. 3) employs open, horizontal 15 MV photon beams generated by a linac at an extended source-to-axis distance (eSAD) of approximately 500 cm, combined with a solid 3D compensator positioned within the beam path to correct for variations in radiological thickness across the patient's body [[24], [25], [26]].



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Fig. 3. Bilateral field TBI technique with 3D solid compensator, top view, patient in HFS position; right side irradiation shown.

Compensators for the patient's right and left sides are calculated based on a total body CT dataset acquired in HFS position, with the patient immobilized with cushions at the head, knees, and feet. A vector-based model is applied in an inhouse software to achieve dose homogeneity at the patient's midplane and to create a datafile for compensator milling. This model is based on tissue-phantom ratio (TPR) measurements obtained at extended SSD and incorporates the linear attenuation properties of the compensator material.

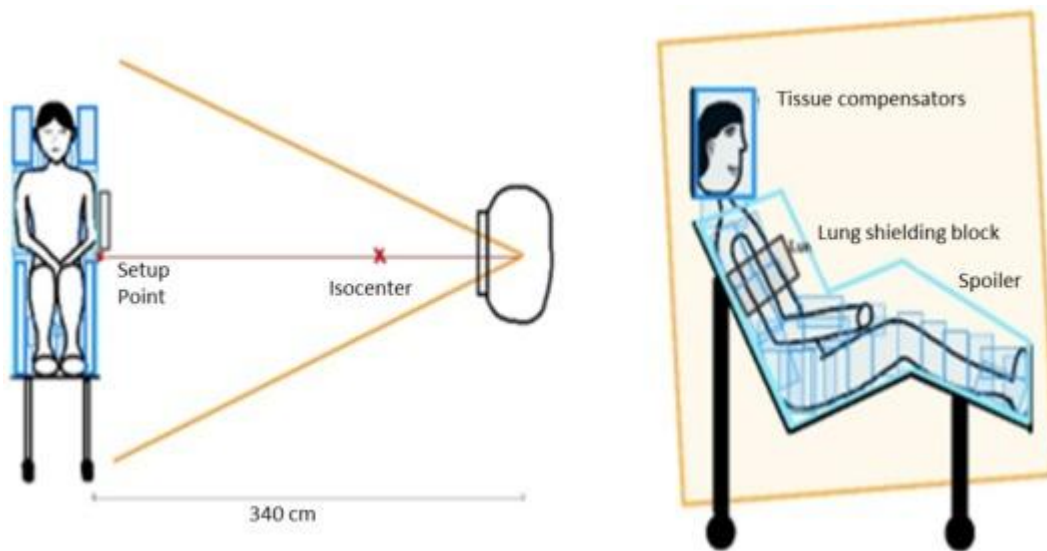
During treatment, the patient is placed on a wall-mounted auxiliary couch at eSAD with similar immobilization with cushions as during CT acquisition. Irradiation is first delivered from one lateral side, after which the patient is repositioned in feet first supine (FFS) to expose the contralateral side, without altering the gantry angle (fixed at either 270° or 90°). The patient position is set using the field light projection through a central hole in the compensator, which is placed at the linac couch. When clinically indicated, lung dose sparing of mean 10 Gy for a prescribed 12 Gy TBI dose of can be integrated into the compensator design.

Compensator molds are milled into polystyrene blocks with a milling machine (MCP HEK Medizintechnik, Lübeck, Germany) using the previously computed datafile and subsequently filled with a high-density material, typically a tin-paraffin mixture. To increase superficial dose deposition from secondary electrons, a 2 cm thick PMMA spoiler is positioned anterior to the patient.

To ensure optimal dose uniformity, photon energies of 15 MV or higher are preferred, with field apertures set to the maximum MLC opening. Patient setup relative to the 3D compensator is verified prior to the first treatment fraction using computed radiography (CR) positioned behind the patient. [Table 1](#) gives an overview of the techniques presented in this work.

2.1.4. Bilateral technique with seated patient

The bilateral TBI technique uses open, horizontal 15 MV photon beams delivered to a seated patient from both lateral directions. During treatment, the patient is positioned in a swivel chair ("Berliner Stuhl", Charité – Universitätsmedizin Berlin, Berlin, Germany), which can be adjusted to accommodate the patient's body width (see [Fig. 4](#)) [27].



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Fig. 4. Scheme of treatment setup of bilateral TBI technique with seated patient (left: front view, right: side view). The gantry is positioned at 90° while the patient is seated in a “Berliner Stuhl”. Spoiler (cyan), tissue compensators (blue) for homogenous dose distribution and lung shielding blocks (grey) to limit maximum lung dose are used. Irradiation with open fields is applied to both left and right side of the patient.

For dose calculation, a total body CT scan acquired in HFS position is required. Patient-specific parameters including lung thickness and length, as well as the width of the arms, head and body are derived from the planning CT. These measurements are used to determine the appropriate chair width, the thickness of the head plates and the size of a potential lung block. The number of MU needed and the dose distribution is calculated by an in-house software, which uses the Pencil Beam algorithm with attenuation correction, assuming a homogeneous water-equivalent block corresponding to the maximum patient width and chair size.

During treatment setup, the distance between armrest and build-up plate to the linac source is fixed at an SSD of approximately 340 cm with the gantry positioned at 90° . To achieve a homogenous dose distribution within the target volume, tissue compensators such as water bags and blocks are used to fill gaps between the PMMA plates of the “Berliner Stuhl” and the patient, thereby creating a uniform effective body width. Patient positioning is guided by room lasers using dedicated markers at the midpoint of the armrest. Irradiation is delivered to both sides of the patient by rotating the swivel chair 180° . Most of the dose build-up occurs within the 2 cm thick PMMA plates.

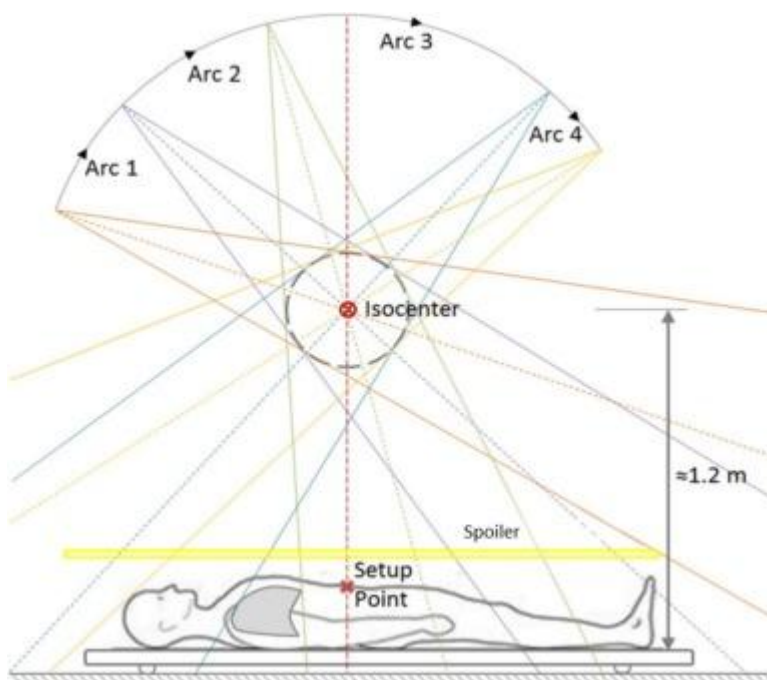
If the prescribed dose equals or exceeds 8 Gy, an individualized lung shielding block is attached to the build-up plate to limit the maximum lung dose to 8 Gy. The block consists of a lead plate and PMMA plates. The doctor verifies the position of the block by

using the light field to check whether the upper edge of the block is at level of the jugulum. In case where the prescribed dose exceeds 10 Gy, underdosing of the target volume is compensated by opposing mediastinal AP/PA saturation fields with an SAD of 135 cm. To achieve this, the patient is repositioned on the treatment couch once a day.

Field apertures are set to the maximum MLC opening, the collimator is rotated to ensure coverage of that patient using the light-field for positioning. Due to the use of open fields, the technique is highly robust against patient positioning uncertainties. The risk of hotspots, especially in regions such as head, neck, or hands, is mitigated through the use of tissue compensators. [Table 1](#) provides a summary of the methods discussed.

2.2. Sweeping beam

The sweeping beam technique delivers dynamic TBI using open 6 MV photon fields (occasionally higher energies) with the patient positioned in supine and prone position on a floor couch underneath the linac isocenter at a distance of about 120 cm. The gantry rotates over an angular range of approximately $\pm 60^\circ$, moving the irradiation field across the patient with resulting SSD ranging from 200–300 cm depending on the gantry angle (see [Fig. 5](#)).



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Fig. 5. Scheme of the sweeping beam TBI technique. The gantry is rotating around the isocenter placed 1.2 m vertically above the patient's navel (setup point). The irradiation fields are split into several short arcs, directly transitioning towards each other to smooth out dose gaps in junctions. A treatment fraction is delivered subsequently in supine and prone position.

For dose calculation, a total body CT is needed. Treatment planning may use a single CT dataset (usually HFS) or, in some cases, two datasets in HFS and HFP positions for dose calculation [28]. The PTV is the entire patient body visualized in the CT dataset.

In CT-based treatment planning, there are various techniques for dose application. These range from simple plans, in which only the diameter and lung contour of the patient are taken from the CT data-set, to classical 3D-conformal radiation therapy (3D-CRT) techniques, in which individual segments are weighted individually for dose homogenization, to 3D-CRT/VMAT hybrid techniques for optimizing dose distribution. However, the TPS needs to be commissioned for the use of an extended SSD larger than 150 cm, which is typically outside common TPS specification. CT-based treatment planning typically takes less than 30 minutes, while dose calculation respectively the computation of MU takes between 2 and 8 hours. A treatment fraction at the linac is associated with treatment times of 45–60 minutes [29].

During the fraction, it is necessary to change the patient's position between prone and supine. Furthermore, bolus material and PMMA slabs are routinely used to improve superficial dose. For TBI doses of more than 8 Gy average, lung sparing is achieved by placing lead or MCP 96 (alloy of bismuth, lead and tin) as lung shielding blocks near the patient or directly on the patient surface. Block localisation is checked by radiographic films or imaging plates positioned below the patient. However, the effect of the blocks on the dose distribution usually cannot be calculated by TPS. In the 3D-CRT/VMAT hybrid technique, lung sparing is integrated into the VMAT arcs resulting from the plan optimization [4]. Irradiation is usually carried out with 6 MV photons, although higher-energy photons are sometimes used to homogenize the dose distribution, especially for 3D-CRT.

Quality assurance (QA) measures are not different from those used for other common QA procedures in TBI, such as in-vivo dosimetry. Furthermore, standard patient-specific plan QA has to be performed if VMAT arcs are applied. Deviations in QA procedures are usually due to internal clinical guidelines that are not caused by the irradiation technique [3].

Sweeping beam TBI is robust against patient positioning uncertainties because there are smooth junctions of different fields leading to nearly no risk of over- or underdosage [30]. [Table 1](#) outlines the key characteristics of the described techniques.

2.3. Multi-isocenter VMAT

Several radiotherapy departments have implemented a multi-isocenter VMAT technique for TBI, as this approach allows the complete treatment workflow—including CT acquisition, treatment planning, QA, as well as image-guided repositioning and

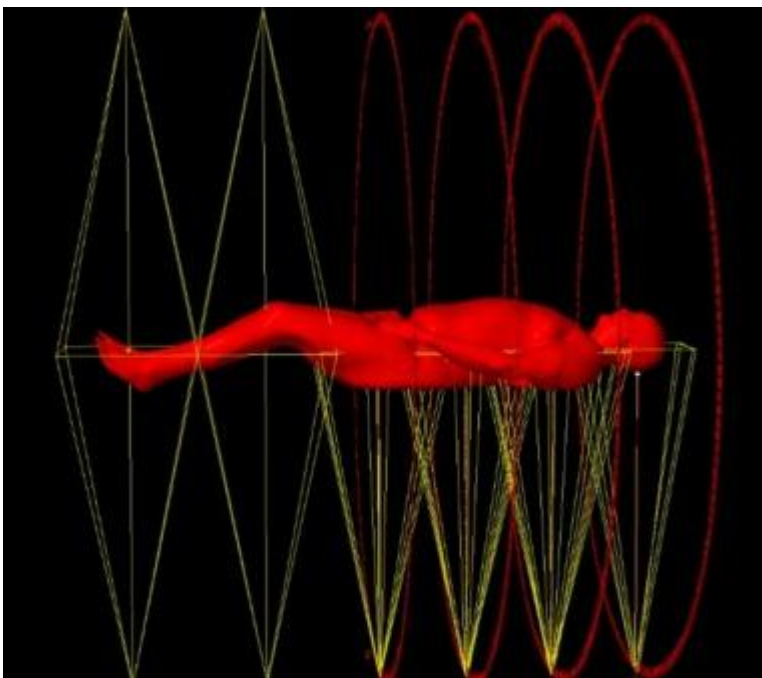
irradiation—to closely resemble that of conventional cancer treatments using a standard linac. The technique uses 6 MV photon beams in VMAT delivery mode at standard SSD (75–90 cm) with multiple isocenters distributed along the patient's longitudinal axis. Furthermore, VMAT enables homogeneous dose distributions with integrated underdosage to spare OAR without additional shielding material, and even overdosage to boost radioresistant tumor regions. Drawbacks include the long preparation time of one day to a week for individual planning and CT-based 3D dose calculation, as well as treatment times of 30–90 minutes per fraction.

The patient is positioned supine on the rotatable tabletop (e.g., TBI STEP, IT-V Medizintechnik GmbH, Innsbruck, Austria), with the arms placed straight at the patient's sides. Standard positioning devices such as head immobilization with a thermoplastic mask as well as knee and feet support indexed at the tabletop enable a reproducible, well centered repositioning of the patient with good comfort and high stability for precise dose application. Bolus may be applied locally if bony structures are directly beneath the skin. If a thermoplastic mask is not possible for or not tolerated by the patient, positioning without such mask is an option but then treatment planning has to be very robust and additional effort for monitoring the head position should be undertaken (e.g., by online surface guidance).

Treatment planning necessitates a CT scan of the individual patient from head to pelvis in HFS and from pelvis to feet in FFS treatment position. These scans are co-registered in the TPS based on a preferably broad overlap region in the pelvis surrounding the tabletop rotation center. If opposing static fields in the legs and feet region are used and CT scanner is feasible, only one total body CT scan may be suitable. Contouring for TBI is simple and therefore performed using templates or scripts to delineate the patient body, couch and patient positioning devices as well as few possibly relevant OAR (e.g., lungs, kidneys, lenses). PTV is defined as body contour with 3 to 5 mm inner margin to take into account dose inhomogeneities due to impaired secondary electrons equilibrium at patient surface.

Due to the required patient rotation, a fixed Cartesian coordinate system relative to the tabletop with point of origin in the patient pelvis close to the tabletop rotation center is typically defined. A number of six to nine isocenters depending on body height and maximum MLC field length is required to cover a complete adult patient for TBI. These isocenters have the same vertical and lateral position but different longitudinal positions with 20–37 cm distance assuring an overlapping MLC field length. Isocenters in head, thorax, abdomen and pelvis are treated in HFS position, isocenters in legs and feet are treated in FFS position turning the patient onto the rotatable couchtop, see [Fig. 6](#). For each isocenter, photon VMAT arcs with varying collimator rotations different from 0° and optimized MLC sequence are applied in alternating clockwise and counterclockwise

direction to keep treatment times short. Reported arc numbers per isocenter range from one for Elekta linacs (Elekta AB, Stockholm, Sweden) to two to four for Varian linacs (Varian Inc., Palo Alto, CA, USA), reflecting differences in the respective TPS optimization algorithms. Arc length is mostly a 360° full gantry rotation but also a reduced arc length may result in sufficient dose coverage and homogeneity with shorter treatment time. Alternatively, opposing static photon fields in AP/PA direction can be applied for isocenters in legs and feet region [31,32]. Treatment planning starts for isocenters treated in FFS position by an inverse optimization of respective VMAT arcs or, alternatively, by manual 3D-conformal planning of the opposing static fields. Subsequently, resulting dose distribution serves as background dose for the inverse optimization of the VMAT arcs at isocenters treated in HFS position. Plan optimization should aim for good dose coverage and homogeneity of the complete body with high robustness and low modulation to consider patient setup variations. Therefore, smooth and broad dose gradients in the overlapping regions of the fields are automatically created by the TPS or by means of additional help contours. Moreover, organs at risk sparing and further planning options depending on TPS such as limitation of beam delivery time or monitor units as well as virtual bolus or flash margin may be applied.



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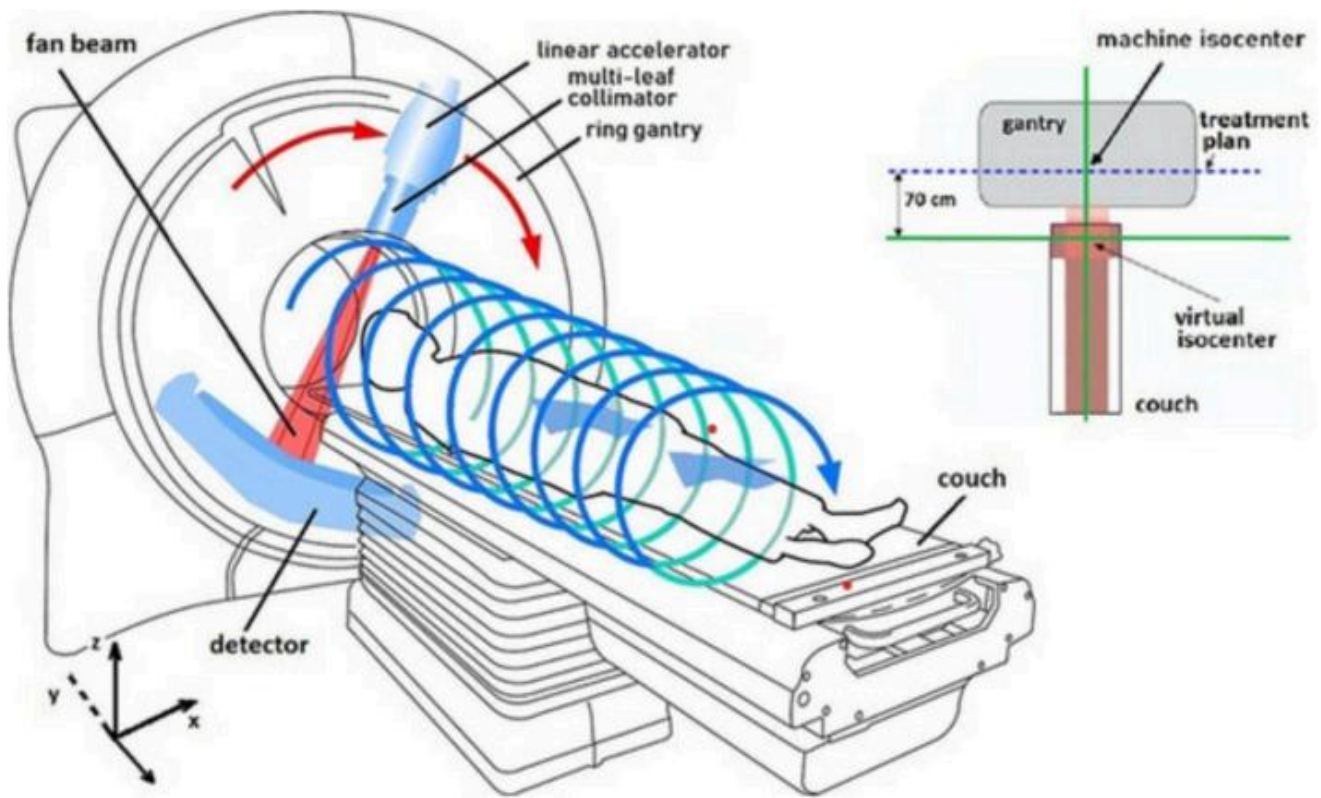
Fig. 6. Schematic drawing of a patient treated with a multi-isocenter VMAT technique for TBI using opposing static fields in FFS patient position (leg region with two isocenters) and VMAT arcs in HFS patient position (pelvis, abdomen, thorax and head regions with four isocenters).

For treatment delivery, precise patient repositioning at the rotatable tabletop is essential. Room lasers combined with skin markings (e.g., at each isocenter) and surface guidance support patient alignment along its entire length. On-board imaging systems to acquire cone-beam CT scans and orthogonal kV or MV images allow patient position verification for at least one isocenter in each HFS and FFS treatment position. Afterwards, irradiation starts at head or foot end by applying the planned VMAT arcs or static fields alternating with necessary couch shifts between the isocenters and tabletop rotation.

QA is similar to that of standard intensity-modulated radiation therapy (IMRT) by means of secondary dose calculation (e.g., by independent TPS) and pre-treatment dose measurement (e.g., by a dedicated 3D phantom with integrated detectors, gantry-mounted transmission ionization chamber or portal dosimetry). In addition, some departments perform in-vivo dosimetry mostly during first treatment fraction. Nevertheless, lots of more QA is typically carried out during the implementation of this TBI technique, for example to investigate dose homogeneity and coverage using an anthropomorphic phantom or to evaluate dose gradients in the overlapping field regions and therewith plan robustness. [Table 1](#) presents an overview of the applied treatment techniques.

2.4. Tomotherapy

Tomotherapy represents an advanced form of IMRT, which enables efficient dose delivery. The Tomotherapy system (Accuray Inc., Sunnyvale, USA) utilizes a table that can move longitudinally during irradiation, coupled with a ring gantry (see [Fig. 7](#)). This setup enables both helical IMRT and, with preselected beam directions, IMRT with single field directions and constant table speed (TomoDirect®), offering two planning options to ensure homogenous target coverage[33]. The maximum couch travel length is limited to 125 cm, which means that for patients over 120 cm in height, two planning CT scans are typically required. One CT scan is performed in HFS and the other in FFS patient position to cover the entire body. The HFS CT typically covers head to mid-femur, while the FFS CT covers feet to femoral heads. The transition from body to leg irradiation is achieved through a 180° rotation.



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Fig. 7. Functional principle of tomotherapy in TBI, image according to Giardina, M et al. [34].

Several treatment planning options are available for the field junction between the two treatment plans, offering good robustness against positional uncertainties. These options tend to favor a slight overdosage rather than underdosage to ensure adequate coverage of the PTV [35]. The field junction is typically located in the femoral area, requiring accurate marking (e.g., with a radiation dens wire) on the patient or positioning aids. PTV definition should be divided into three to four body regions (e.g., ???), outlined 2–3 mm away from the skin to minimize exposure to healthy tissue, and with potentially sparing the lenses, kidneys and lungs for optimal treatment. An additional artificial region of interest in the junction area can further aid in shaping the transition dose gradient.

The goal is to ensure effective coverage of the PTV while assuring a safe field junction and if necessary, sparing the OAR [33,[35], [36], [37]]. To achieve this, planning parameters such as field width, pitch, and modulation factor can be adjusted. A field width of 5 mm and a pitch between 0.27 and 0.43 are particularly useful for ensuring smooth dose distribution and a secure transition between the two plans. The VoloUltra® optimizer in the system own TPS Precision® (Accuray Inc.) performs optimization and calculation efficiently, allowing individualized parameter adjustments during planning. Optimizing the treatment plan requires balancing effective irradiation time with homogenous dose distribution. Before the initial setup, it is advisable to check the

radiation plan without the patient to identify any potential unadjustable travel lengths. Delivery of the HFS plan typically takes about 20 minutes, while the FFS plan about 15 minutes.

Stable patient positioning is essential, especially during table rotation and field alignment. Positioning aids such as total body vacuum mattresses, rotating TBI boards (e.g., TBI STEP, IT-V) and thermoplastic masks for the head and shoulder areas are applied to ensure reproducibility. Additionally, the arms should be positioned in a reproducible manner, e.g., using lateral grip supports to hold the hands in place.

The Tomotherapy system is capable to deliver a 6 MV flattening filter free photon beam with MLC leaf width of 6.25 mm at the isocenter. The verification of the irradiation process is carried out using either low-dose MV-CT with an energy of 3.8 MeV or kV-CT imaging for Radixact® system (Accuray Inc). Imaging over the entire scan area is typically performed to verify patient positioning. Special attention should be given to longitudinal positioning and gap junction, especially to account for possible table shifts [33]. Moreover, the applied dose should be verified during the first fraction using local in-vivo measurement methods, especially in the transition area. For this purpose, detectors with small measurement volumes, depending on the available equipment, can be used [38]. For robust treatment planning of the helical IMRT, a 1 cm virtual air bolus is applied around the entire body to account for potential underdosage and setup uncertainties. To consider respiratory motion, an inner margin of 5–10 mm is subtracted from the inner lung. [Table 1](#) compiles the main features of the respective techniques.

3. Discussion and Conclusion

TBI remains an essential treatment modality, particularly in the management of hematological malignancies. Over time, various irradiation techniques have been developed to optimize dose distribution, minimize side effects, and improve patient comfort. As no direct biological verification method exists, treatment success relies entirely on accurate physical dose delivery.

Previous reference reports, including DGMP report 18 [3], The American Association of Physicists in Medicine report 17 [39], and the European overview by Quast [40], provided comprehensive summaries of available TBI techniques nearly two decades ago. Since then, TBI has undergone substantial technological evolution, leading to a growing diversity of clinical implementations.

Historically, particular attention was paid to limiting the dose rate in the lung region to approximately 0.02–0.05 Gy/min to prevent radiation-induced pneumonitis[41]. The strong correlation between lung dose, dose rate, and pneumonitis risk has been confirmed by several clinical analyses [8,42]. Therefore, early TBI protocols often relied

on prolonged treatment times and partial lung shielding to maintain low effective dose rates. In current implementations, higher instantaneous dose rates are applied, enabled by increased linac output and shorter treatment times. Nevertheless, improved dose modulation, compensation, and shielding strategies maintain clinically acceptable toxicity profiles [12,13,43]. Recent studies have shown that modern intensity-modulated and image-guided techniques, such as VMAT and Tomotherapy, can achieve uniform whole-body dose distributions while keeping the mean lung dose well below 8–10 Gy, with a markedly reduced incidence of radiation-induced pneumonitis compared to historical approaches [10,43]. To further mitigate lung exposure, the dose rate in fields directly passing through the lungs can optionally be reduced to around 100 MU/min [23]. VMAT TBI offers refined modulation of both dose and dose rate, facilitating improved lung protection and potentially reducing the risk of radiation-induced pneumonitis [42,43].

In particular, VMAT-TBI enables precise modulation of both dose and dose rate, allowing for enhanced lung protection and a potential reduction in the risk of radiation-induced pneumonitis. This technological flexibility enables individualized dose shaping for enhanced sparing of critical organs while maintaining effective total-body coverage and treatment efficiency. Consequently, the focus in modern TBI has shifted from strict physical dose-rate limitation toward optimized three-dimensional dose uniformity and biologically guided OAR protection [11].

This publication summarizes all TBI techniques reported by the centers participating in this DGMP working group study, covering data from all 22 active centers and reflecting the full spectrum of technical approaches in clinical use. To provide a concise overview and facilitate comparison, all techniques are summarized side-by-side in Table 1, highlighting their dosimetric, technical, and clinical characteristics. The increasing adoption of IMRT-based concepts such as VMAT and Tomotherapy illustrates the ongoing transition toward image-guided and intensity-modulated TBI across German-speaking centers. Conventional linac-based methods remain widespread due to their simplicity and cost efficiency.

By presenting and comparing these techniques side by side, this work provides the first comprehensive overview of current TBI implementations in the German-speaking region. It is intended to serve as a reference for centers establishing or modifying their own TBI procedures.

Future work will focus on detailed, treatment-plan-based dosimetric analyses and quantitative comparisons of dose homogeneity, OAR sparing, and overall treatment efficiency. These analyses will enable evidence-based evaluation and optimization of each approach.

In summary, this collaborative effort defines the current state of TBI practice in Germany and Switzerland and provides a foundation for future harmonization, standardization, and evidence-based optimization across centers.

CRedit authorship contribution statement




Maya Shariff: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Falk Tillner:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Oliver Schramm:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation. **Heiko Karle:** Writing – review & editing, Writing – original draft, Supervision, Investigation. **Marc Delaperriere:** Writing – review & editing, Writing – original draft, Methodology. **Sascha Großmann:** Writing – review & editing. **Sebastian Neppi:** Writing – review & editing, Methodology. **Christos Moustakis:** Writing – review & editing, Methodology. **Friedericke Lips:** Writing – review & editing, Methodology. **Hendrik Auerbach:** Writing – review & editing, Writing – original draft, Methodology. **Sven Knobe:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Stephan Garbe:** Writing – review & editing, Writing – original draft. **Marie Janning:** Writing – review & editing, Writing – original draft, Methodology. **Janett Köhn:** Writing – review & editing, Writing – original draft, Methodology. **Sophie Kuchler:** Writing – review & editing, Writing – original draft, Methodology. **Marie Gemes:** Writing – review & editing, Writing – original draft, Methodology. **Svea Kühl:** Writing – review & editing, Methodology. **Lisa Mündlein:** Writing – original draft, Methodology. **Frank Ubrich:** Writing – review & editing, Writing – original draft, Methodology. **Enrico Dittrich:** Writing – review & editing, Methodology. **Jerome Krayenbuehl:** Writing – review & editing, Writing – original draft. **Mathias Walke:** Methodology. **Daniel Medenwald:** Methodology. **Manfred Schmidt:** Writing – review & editing, Writing – original draft, Methodology. **Nora Maurer:** Writing – review & editing, Writing – original draft. **Anna Hustedt:** Writing – review & editing, Writing – original draft. **Benjamin Frey:** Supervision. **Christoph Bert:** Writing – review & editing, Supervision, Methodology. **Pauline Riethmüller:** Writing – review & editing, Writing – original draft, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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