Zeitschrift für Medizinische Physik xxx (xxxx) xxx

Contents lists available at ScienceDirect

Zeitschrift für Medizinische Physik

journal homepage: www.elsevier.com/locate/zemedi

Multicenter evaluation of total body irradiation planning strategies: A DGMP working group study on large-field irradiation techniques

Maya Shariff [a,b,*], Heiko Karle [c], Oliver Schramm [d,e], Johann Brand [a,b], Andre Karius [a,b], Sven Knobe [f], Hendrik Auerbach [f], Jerome Krayenbuehl [g], Sebastian Neppl [h], Julia Kirschke [i], Friedericke Lips [j], Frank Ubrich [k], Marius Treutwein [l], Nora Maurer [m], Tenzin Sonam Stelljes [n], Christos Moustakis [o], Marie Gemes [p], Sophie Küchler [p], Svea Kühl [q], Marc Delaperriere [r], Janett Köhn [s,t], Oliver Neumann [u], Christoph Losert [v], Elisabetta Gargioni [w], Felix Voigt [x], Manfred Schmidt [a,b], Stefanie Corradini [a,b], Christoph Bert [a,b], Pauline Riethmüller [y], Falk Tillner [z,aa,ab]

[a] *Department of Radiation Oncology, Universitätsklinikum Erlangen, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, Germany*
[b] *Comprehensive Cancer Center Erlangen-EMN (CCC ER-EMN), Erlangen, Germany*
[c] *Department of Radiation Oncology, University Medical Center Mainz, Mainz, Germany*
[d] *Department of Radiation Oncology, Heidelberg University Hospital, Heidelberg, Germany*
[e] *Heidelberg Institute of Radiation Oncology (HIRO), Heidelberg, Germany*
[f] *Department of Radiotherapy and Radiation Oncology, Saarland University Medical Center, Homburg/Saar, Germany*
[g] *Department of Radiotherapy and Radiation Oncology, University Hospital Zurich, Zurich, Switzerland*
[h] *Department of Radiation Oncology, Cyberknife and Radiotherapy, Medical Faculty, University Hospital Cologne, Cologne, Germany*
[i] *Department of Radiation Oncology, Helios Klinikum Berlin Buch, Berlin, Germany*
[j] *Hermann-Holthusen-Institute for Radiotherapy, Asklepios Klinik St. Georg, Hamburg, Germany*
[k] *Department of Radiotherapy and Radiation Oncology, University Hospital Marburg, Marburg, Germany*
[l] *Department of Radiotherapy, University Medical Center Regensburg, Regensburg, Germany*
[m] *Department of Radiation Oncology, Marienhospital Stuttgart, Stuttgart, Germany*
[n] *University Clinic for Medical Radiation Physics, Medical Campus Pius Hospital, Carl von Ossietzky University, Oldenburg, Germany*
[o] *Medical Physics Group, Department of Radiation Oncology, University of Leipzig, Leipzig, Germany*
[p] *Department of Medical Physics, Department of Radiation Oncology, University of Freiburg, Freiburg, Germany*
[q] *Department of Radiation Oncology, Städtisches Klinikum Braunschweig, Braunschweig, Germany*
[r] *Clinic of Radiotherapy, Universitätsklinikum Schleswig-Holstein (UKSH), Campus Kiel, Kiel, Germany*
[s] *Department of Radiation Oncology, University Hospital, Goethe University, Frankfurt, Germany*
[t] *Saphir Radiosurgery Center, Frankfurt, Germany*
[u] *Charité – Universitätsmedizin Berlin, Department of Radiation Oncology and Radiotherapy, Berlin, Germany*
[v] *Department of Radiation Oncology, LMU University Hospital, LMU Munich, Munich, Germany*
[w] *Department of Radiotherapy and Radio-Oncology, University Medical Center Hamburg-Eppendorf, Hamburg, Germany*
[x] *Klinik für Radioonkologie, Klinikum Chemnitz gGmbH, Chemnitz, Germany*
[y] *Department of Radiation Oncology, Universitätsklinikum Magdeburg, Otto-von-Guericke Universität Magdeburg, Magdeburg, Germany*
[z] *Department of Radiation Therapy and Radiation Oncology, Faculty of Medicine and University Hospital Carl Gustav Carus, Technische Universität Dresden, Dresden, Germany*
[aa] *OncoRay – National Center for Radiation Research in Oncology, Dresden, Germany*
[ab] *Helmholtz-Zentrum Dresden-Rossendorf, Institute of Radiooncology – OncoRay, Dresden, Germany*

ARTICLE INFO

Keywords:
Total body irradiation
Treatment planning
Multicenter study
Dosimetric evaluation

ABSTRACT

Purpose: Total body irradiation (TBI) is an integral component of conditioning regimens for hematopoietic stem cell transplantation. Despite similar biological objectives, planning and delivery of TBI vary substantially across institutions. The aim of this study was to quantitatively assess inter-institutional and technique-dependent

* Corresponding author: Department of Radiation Oncology, Universitätsklinikum Erlangen, Friedrich-Alexander-Universität Erlangen-Nürnberg, Universitätsstraße 27, 91054 Erlangen, Germany.
E-mail address: maya.shariff@uk-erlangen.de (M. Shariff).

https://doi.org/10.1016/j.zemedi.2026.11.002
Received 24 October 2026; Accepted 5 November 2026

0939-3889/© 2026 Published by Elsevier GmbH on behalf of DGMP, ÖGMP and SSRMP. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

variability in contemporary TBI planning by comparing dose distributions generated under standardized conditions across multiple centers in Germany and Switzerland.

Methods: Twenty-four radiotherapy centers received anonymized total-body computed tomography (CT) datasets of a standardized dummy patient in head-first supine and prone orientations, including predefined points of interest (POI) and organs at risk (OARs). Each center was asked to generate TBI plans for two prescription levels (8 Gy in 4 fractions and 12 Gy in 6 fractions) using its local planning standards, with the entire body defined as the planning target volume (PTV). Submissions included treatment-planning-system (TPS)–based 3D dose distributions and in-house table-based calculations. TPS plans were centrally imported into a TPS for extraction of target coverage and OAR dose metrics, while table-based submissions were evaluated using aggregated POI doses.

Results: In total, 45 TBI treatment plans from 24 centers were analyzed, including 24 plans for 8 Gy and 21 plans for 12 Gy. Both TPS-based and table-based planning approaches were represented across a broad range of clinical techniques, including volumetic modulated arc therapy (VMAT), Tomotherapy, sweeping beam, static field, bilateral, and translation couch setups. Marked inter-institutional variability was observed, particularly for lung, lens, and kidney doses. At the 12 Gy prescription level, mean lung doses differed by more than 3 Gy between centers, corresponding to relative variations of up to approximately 30%. Conformal intensity-modulated techniques (VMAT and Tomotherapy) showed the highest consistency across institutions, whereas non-conformal approaches exhibited substantially larger dose variability. Increased lung sparing at 12 Gy was consistently associated with reduced target coverage compared to 8 Gy.

Conclusion: This study provides the first standardized multicenter planning-based comparison of contemporary TBI approaches in Germany and Switzerland. By quantifying inter-institutional variability in dose distributions under uniform conditions, the results outline the current heterogeneity of clinical practice and the range of achievable dosimetric outcomes. Rather than defining a reference standard, these findings establish a structured benchmark of existing planning strategies and highlight the need for harmonization, thereby providing a foundation for future consensus development and end-to-end validation efforts.

1. Introduction

Total body irradiation (TBI) is a well-established component of conditioning regimens before hematopoietic stem cell transplantation. Its therapeutic role is twofold: (i) eradication of malignant hematopoietic cells distributed throughout the body and (ii) immunosuppression to facilitate engraftment of donor stem cells [1,2]. By combining systemic tumor control with immune modulation, TBI plays a central role in the treatment of hematologic malignancies such as leukemia and lymphoma [3].

Despite these shared biological objectives, the clinical implementation of TBI varies markedly between radiotherapy centers. Some institutions use state-of-the-art treatment planning systems (TPS) to generate individualized dose distributions, while others rely on long-established table-based dose calculation [4–9]. These differences reflect historical traditions, local clinical philosophies, available resources, and differing technological infrastructures.

To characterize this landscape, the German Society for Medical Physics (DGMP) working group on large-field irradiation techniques first conducted a survey capturing current clinical practice for TBI and related extended-field irradiation methods [10]. The survey revealed substantial heterogeneity regarding planning techniques, dose prescriptions, organ-sparing strategies, and technical execution [11]. Although participating centers provided qualitative descriptions of their clinical TBI workflows, optimization strategies, normalization concepts, and planning objectives were intentionally not standardized across institutions. The aim of the present study was to evaluate the resulting dose distributions generated according to each center's local clinical practice and thereby capture the current heterogeneity of TBI planning approaches without influencing existing institutional standards.

This study constitutes the next step in this coordinated effort. It provides a standardized multicenter comparison of total body irradiation planning based on anonymized TBI plans generated by 24 radiotherapy centers under uniform conditions. By evaluating both TPS-based and table-based planning approaches applied to identical computed tomography (CT) datasets, this work aims to identify specific variations in dose distributions, assess the influence of different TBI techniques on organ-at-risk (OAR) exposure, and highlight opportunities for harmonization of TBI planning practices across centers as well as participating countries.

2. Material and Methods

2.1. Study design

An anonymized total-body CT dataset of a clinical female TBI patient (age 70 years, height 160 cm, weight 45 kg) was distributed to the participating institutions of the DGMP working group on large-field irradiation techniques and served as a standardized reference case for all planning tasks. CT datasets were acquired in head-first supine (HFS) and head-first prone (HFP) positions using a low-dose protocol (100 kV, 80 mAs, 10 mm slice thickness) with extended in-plane field-of-view reconstruction to cover the full patient cross-section. The in-plane pixel size was 1.5×1.5 mm^2, and datasets encompassed the entire body length in craniocaudal direction. Since TBI is generally implemented with various clinical setups across centers, the provided CT datasets did not necessarily correspond to the standard imaging procedures and treatment positions used in the respective clinical workflows. To accommodate different clinical delivery techniques, each center received the datasets in two orientations — HFS and HFP —including predefined points of interest (POIs) (see Fig. 2) and a comprehensive organ-at-risk (OAR) set in Digital Imaging and Communications in Medicine (DICOM) format (see Fig. 1).

The OARs were delineated from head to toe and included brain, brainstem, eye globes, lenses, optic nerves, optic chiasm, parotid glands, oral cavity, lips, larynx, esophagus, spinal cord, heart, lungs, liver, stomach, spleen, kidneys, bowel, rectum, bladder, proximal femora, and aorta. OAR delineation was performed in both CT datasets using the autosegmentation tool of syngo.via (version VB80, Siemens Healthineers, Forchheim, Germany) and subsequently reviewed and, if necessary, manually corrected by a radiation oncologist.

A corresponding set of anatomically fixed POIs was defined and provided in both CT datasets, including locations in the brain, lungs, kidneys, liver, and pelvis. POIs were selected at anatomically reproducible reference locations to enable consistent point-dose evaluation across different planning modalities. In addition, POI-based dose summation was used to combine dose contributions from HFS and HFP, as robust image fusion between these orientations is not routinely available for total-body CT datasets.

Two prescription levels of 8 Gy in 4 fractions and 12 Gy in 6 fractions (2 Gy per fraction) were defined as planning goals. No instructions

regarding plan normalization, dose constraints, or the handling of auxiliary structures were given, allowing each institution to apply its local clinical standards and thereby represent the existing diversity of TBI planning practice. This approach was chosen deliberately to avoid influencing institutional planning strategies and to allow characterization of the currently applied clinical standards across participating centers.

A total of 24 institutions participated in the study and were asked to generate treatment plans for both prescription levels. Treatment plans for the 8 Gy prescription level were submitted by all participating centers, whereas 21 institutions additionally submitted treatment plans for the 12 Gy prescription level.

The distributed DICOM datasets consisted of two CT image series representing the HFS and HFP patient orientations together with RTSTRUCT objects containing the predefined OAR contours and POIs. Participating centers generated treatment plans on these datasets according to their local clinical standards and returned the corresponding RTPLAN and RTDOSE objects for centralized analysis. TPS-based submissions were accompanied by two completed protocol sheets corresponding to the HFS and HFP CT datasets. Table-based submissions consisted of protocol sheets for both prescription levels, reporting POI doses and general planning information. An example of the protocol sheet used for data collection and dose reporting is provided in Supplementary Material. Submissions lacking the 12 Gy component were classified as incomplete. Reported reasons included personnel changes at participating centers, limited time resources, and the additional effort required for recalculation. In several cases, no further follow-up was possible due to staffing constraints. These submissions formed the basis for the subsequent technique-specific dosimetric analysis.

2.2. TBI planning techniques

In addition to the dosimetric plan submissions, each participating center provided a structured description of its routinely used clinical TBI technique. These descriptions covered key aspects of the clinical setup, including patient positioning (supine, prone, upright, or seated), number and orientation of treatment fields, nominal beam energy, treatment distance, immobilization strategies, and the use of compensators or shielding. Technique-specific challenges, such as surface dose considerations, shoulder geometry, and reproducibility of extended source-to-surface distance (SSD) setups, were also documented to support

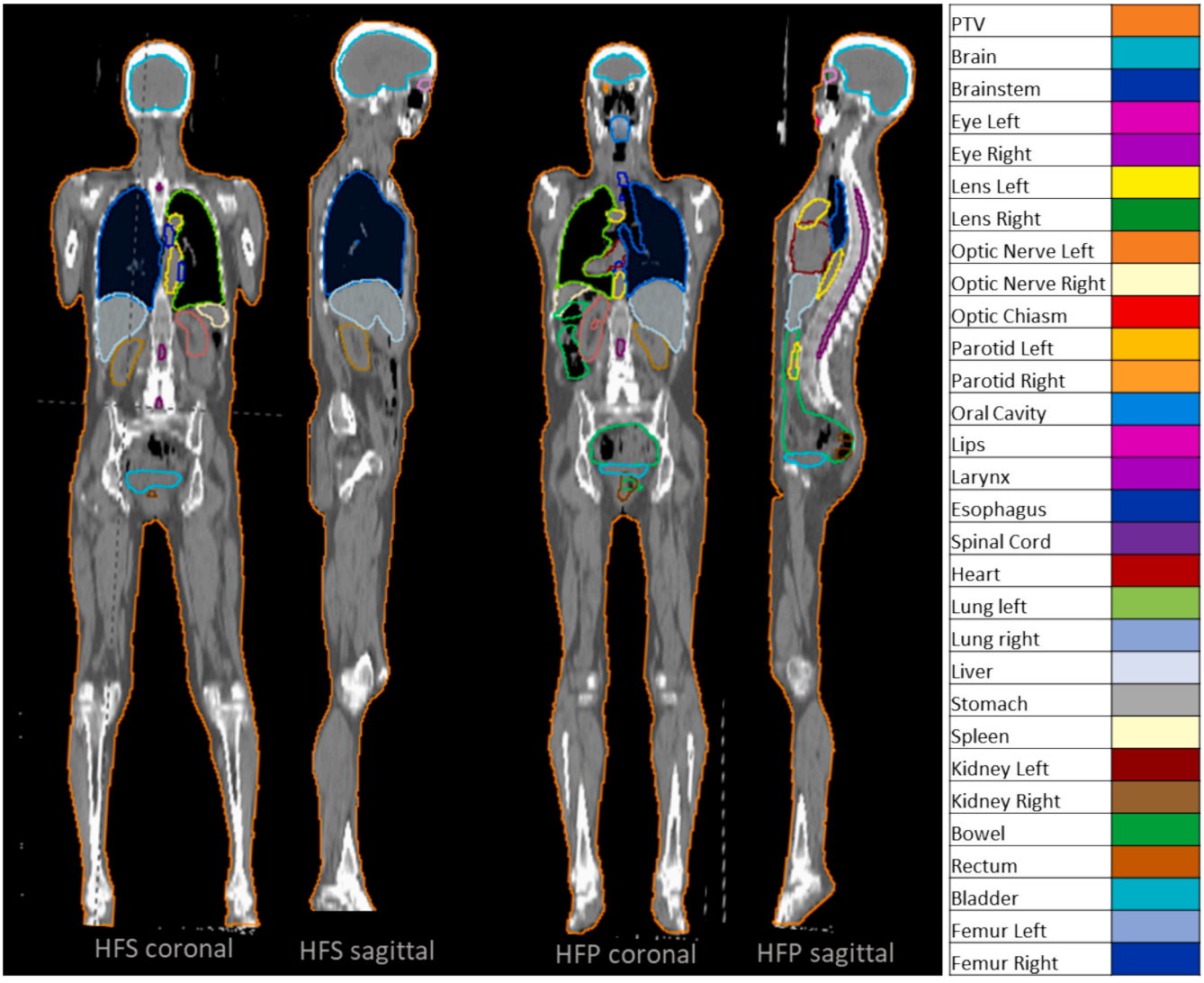


Fig. 1. TBI patient in head-first supine (HFS) and head-first prone (HFP) patient position in both coronal and sagittal views. The entire body (orange outline) was defined as the Patient body planning target volume (PTV). Several organs-at-risk (OARs) were autosegmented, including brain, brainstem, eye globes, lenses, optic nerves, optic chiasm, parotid glands, oral cavity, lips, larynx, esophagus, spinal cord, heart, lungs, liver, stomach, spleen, kidneys, bowel, rectum, bladder, proximal femora, and aorta.

contextual interpretation of the dosimetric results. Centers also reported typical planning and treatment times requirements as well as practical considerations regarding patient preparation and material handling. Participating centers were instructed to reproduce their routine clinical TBI workflows according to local standards. Consequently, the use of bolus, spoiler, or build-up material varied between techniques and institutions and was not standardized within the study. Conventional extended-SSD techniques, particularly floor-based and Berlin-chair approaches, frequently incorporated spoiler or build-up devices to increase surface dose, whereas VMAT- and Tomotherapy-based techniques were generally planned without additional build-up material. A detailed description of technique-specific workflow characteristics has been reported previously by the DGMP working group. Fig. 3 provides a schematic overview of TBI techniques presented in this study and serves as a visual reference for the technique categories described below. The following subsections describe the implementation of each technique category when using the standardized CT data.

2.2.1. Static fields

Static field techniques were reproduced using the provided CT datasets as surrogates for the clinical irradiation geometry. In routine clinical practice, these approaches are typically delivered either with the patient standing upright or in a supine position at extended SSD. Static field techniques were reproduced using the provided CT datasets as surrogates for the clinical irradiation geometry. In routine clinical practice, these approaches are typically delivered with the patient in both head-first supine (HFS) and head-first prone (HFP) positions at extended SSD. To reflect this workflow, both CT datasets were provided and could be incorporated according to the respective institutional implementation. The geometric configuration was reconstructed by

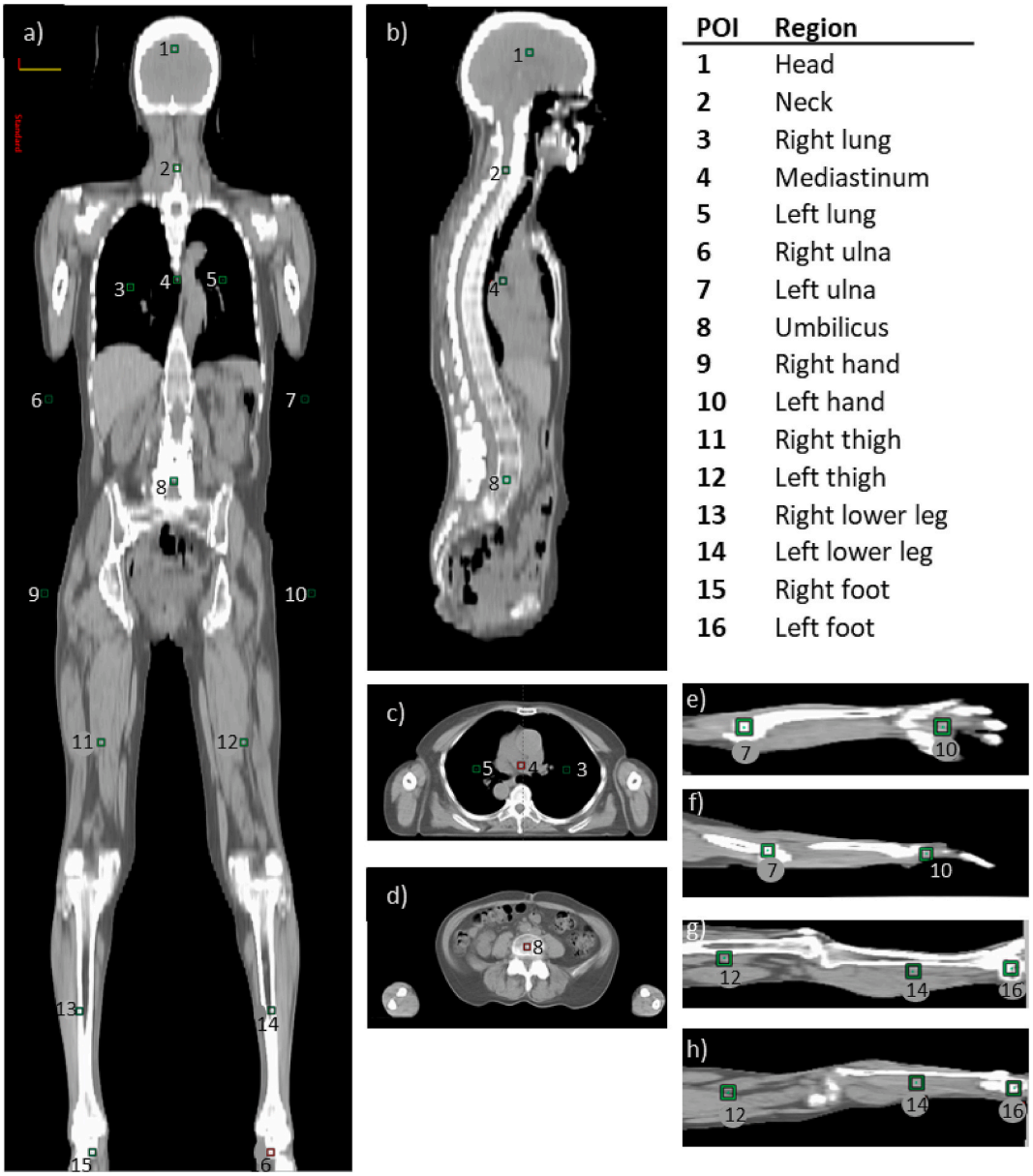


Fig. 2. Visualization of the predefined points of interest (POIs) used for point-dose evaluation. (a) Coronal overview showing the full-body distribution of all POIs, with the corresponding POI numbering indicated in the inset legend within the figure. Due to slice orientation, POIs located in the upper extremities do not exhibit direct anatomical correspondence in this view. (b) Sagittal visualization of POIs 1, 2, and 4 in the upper torso region. (c) Axial view of POIs 3, 4, and 5 in the thoracic region. (d) Axial view of POI 8 located in the umbilical region. (e,f) Sagittal and coronal views of POIs 7 and 10 in the upper left extremity. (g,h) Sagittal and coronal views of POIs 12, 14, and 16 in the lower left extremity. Corresponding right-sided POIs (upper extremity: POIs 6 and 9; lower extremity: POIs 11, 13, and 15) were defined analogously as mirror-symmetric locations.

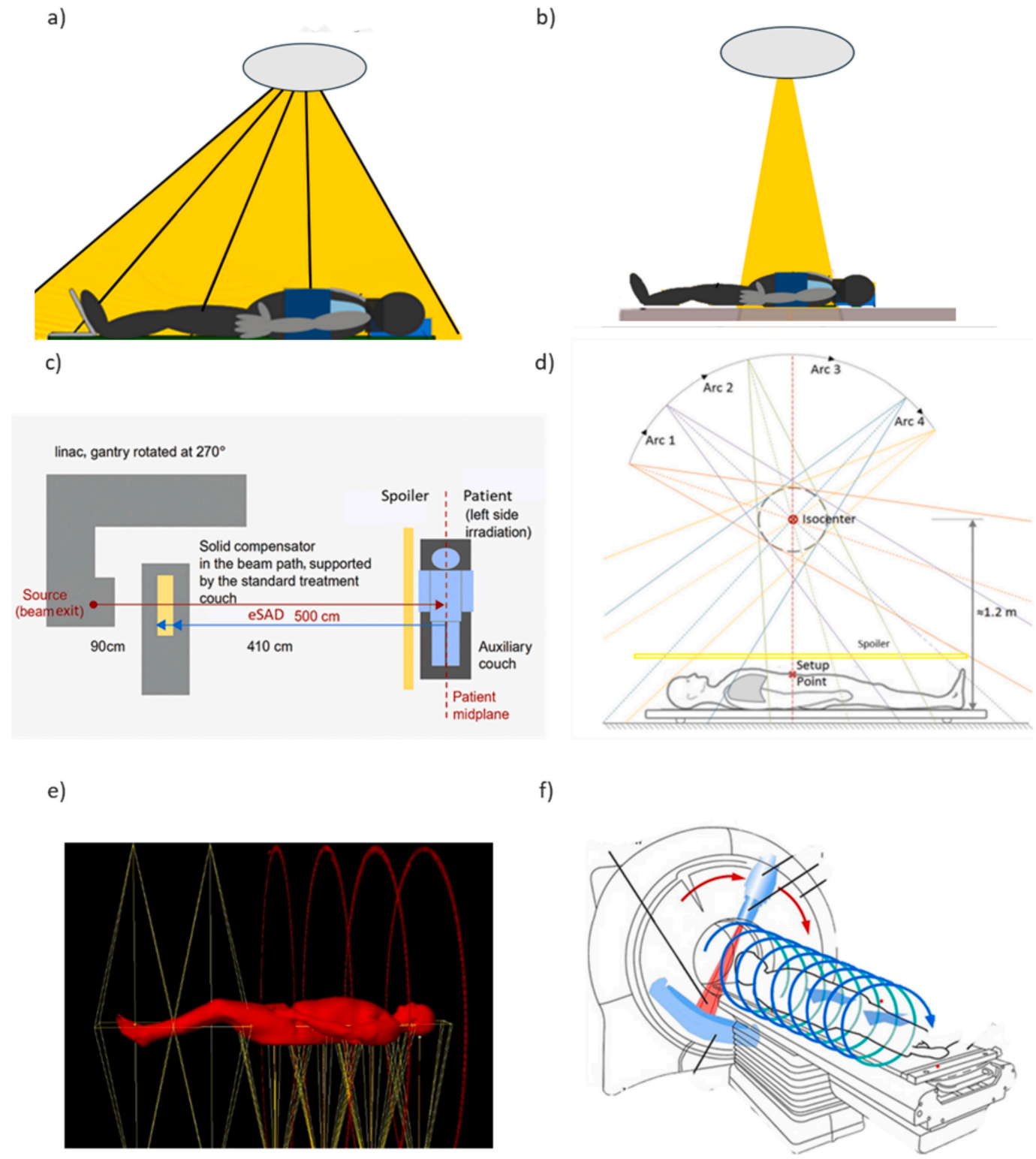


Fig. 3. Overview of TBI techniques presented in this multicenter study. (a) Multiple static fields technique, (b) translation couch technique, (c) bilateral technique with solid compensator, (d) sweeping beam technique, (e) multi-isocenter volumetric modulated arc therapy (VMAT), and (f) helical Tomotherapy. Panels (a)–(e) are reproduced from [11] and are included here for illustration and reference. Panel (f) is adapted from [12].

applying laterally opposed photon fields to the HFS and HFP CT datasets, with cumulative dose contributions being combined where clinically applicable.

For multiple fields techniques, additional static fields were introduced at angular offsets of approximately 10°–30°, resulting in configurations comprising between two and sixteen fields, as illustrated in Fig. 3a. Photon energies ranged from 6 MV to 15 MV, reflecting institutional practice.

CT-derived geometric parameters, including lateral separation, midline depth, and organ-specific distances, were used to approximate extended SSD dose delivery within the respective TPS. Dose calculation was performed using locally commissioned planning algorithms, with

extended SSD handling implemented according to institutional standards. For static field techniques, OAR sparing was inherently constrained by the fixed beam geometry. Lung sparing strategies, where applied in clinical routine, varied between centers and included beam weighting, field arrangement modifications, and physical shielding concepts. These approaches were approximated within the CT-based planning simulation according to local implementation practices.

Centers employing translation couch techniques reproduced their clinical workflow using the provided CT datasets as geometric surrogates. In routine clinical practice, patients are irradiated while being transported at constant speed on a motorized floor-mounted couch through a stationary photon beam of the linear accelerator.

As continuous mechanical translation cannot be directly simulated on static CT data, the HFS CT dataset served as the primary anatomical reference for dose approximation. The geometric setup was represented by static opposed photon fields, reflecting the effective beam arrangement experienced during couch translation, as schematically shown in Fig. 3b.

Dose estimation was performed using point-dose–based calculations. POI doses derived from the static field approximation were converted to delivered dose values by scaling with the effective irradiation time, determined from the clinically applied couch translation speed, field length, and machine output. Additional measurement-based correction factors routinely used at the respective institutions were applied where available. For workflows involving irradiation in both supine and prone orientations, dose contributions from the second orientation were obtained either from calculations on the HFP CT dataset or—when symmetric irradiation was assumed—by doubling the HFS-based dose contribution.

OAR sparing in translation couch techniques is primarily governed by the time-averaged exposure resulting from patient motion through the radiation field rather than by active fluence modulation. Lung sparing, where applied, is therefore typically achieved through geometric field definition and transmission shielding concepts incorporated into the underlying point-dose model.

Bilateral TBI techniques, including both supine and seated implementations, were reproduced using the HFS CT dataset as the primary anatomical reference. In clinical practice, irradiation is delivered using opposed lateral photon fields, with patient-specific compensation to account for variations in body contour and tissue thickness, as schematically shown in Fig. 3c.

Relevant anatomical dimensions, including lateral patient separation and organ depths, were extracted from the HFS CT dataset to approximate the clinical irradiation geometry. For compensator-based techniques, compensator thicknesses and shielding block dimensions were derived from CT-based transverse diameters, thereby reproducing the attenuation relationships applied in routine clinical workflows.

Seated bilateral setups (commonly referred to as the “Berliner Stuhl”) could not be directly represented by the provided CT datasets, as no seated imaging was available. These configurations were therefore approximated by assuming rotationally symmetric body contours and applying tabulated mid-plane dose calculations based on CT-derived patient dimensions.

Dose calculation relied on measurement-based or tabulated correction factors routinely used for bilateral TBI rather than on full 3D dose computation. Lung sparing was incorporated according to local clinical practice, typically through compensator shaping or partial shielding, which was represented within the calculation framework using the same correction-based approach.

2.2.2. Sweeping beam

Sweeping beam techniques were reproduced using large arc trajectories, typically spanning 300°–60°, with 6 MV photon beams to represent the characteristic extended SSD geometry of this approach, as shown in Fig. 3d. The HFS CT dataset served as the primary anatomical reference for reconstructing patient geometry and beam arrangement.

Depending on institutional practice, some centers additionally used the HFP CT dataset to improve dose estimation in posterior anatomical regions, without performing a separate full treatment plan. In most cases, however, cumulative point doses were derived by assuming rotational symmetry of dose contributions, reflecting the clinical delivery concept of sweeping beam irradiation.

Dose calculation was performed within the respective TPS, which were required to be commissioned for extended SSD conditions [4,13]. Where part of the clinical workflow, fluence modulation was approximated using field-in-field techniques or arc-based modulation strategies to reproduce local practice.

Lung sparing was implemented according to institutional standards, typically by modelling transmission blocks placed directly on the patient surface. Modern TPS implementations employing Monte Carlo–based dose calculation algorithms enabled the approximation of lung shielding using high-density materials such as lead or MCP 96 alloy (bismuth–lead–tin) within the CT-based planning simulation.

2.2.3. VMAT

VMAT-based TBI was reproduced on the provided CT datasets using a multi-isocenter approach along the cranio-caudal axis, typically employing 5 to 7 isocenters with 1 to 4 arcs per isocenter with photon energies of 6 MV or 15 MV. Each isocenter was planned individually, and centers applied either automatic or manual junction strategies to replicate their clinical planning workflow, as schematically shown in Fig. 3e.

The provided CT dataset (HFS) was used to approximate the longitudinal treatment geometry required for full-body coverage. If the treatment was clinically performed using a single orientation, only the corresponding CT dataset was used.

Dose calculation was performed fully 3D within the respective TPS. Deviations between the provided CT geometry and local clinical setups—such as the use of extended SSD—were addressed by adapting SSD and field geometry within the TPS to best represent institutional practice [5,6,14–17].

OAR sparing in VMAT-based TBI was primarily achieved through inverse planning and intensity modulation. Lung sparing, where prioritized clinically, was implemented via explicit dose objectives within the optimization process, allowing modulation of fluence while maintaining longitudinal target coverage.

2.2.4. Tomotherapy

Helical Tomotherapy–based TBI was performed exclusively on the HFS CT dataset, without separation into supine and prone delivery components. Continuous helical beam delivery with 6 MV flattening-filter-free photons inherently allowed full-body coverage within a single treatment plan, as schematically depicted in Fig. 3f.

To reflect institutional clinical practice, centers replicated their routinely used jaw width, pitch, and modulation factor settings as closely as possible. When the longitudinal target extent exceeded the available couch travel range, treatment was divided into two sequential subplans on the HFS CT dataset, typically covering head-to-torso and feet-to-torso with a defined junction region. The resulting dose distributions were summed to approximate the total delivered dose. If treatment was clinically performed without longitudinal splitting, only the corresponding CT dataset was used.

Dose calculation was performed fully 3D within the Tomotherapy TPS. Deviations between the standardized CT geometry and actual clinical setup conditions, including patient immobilization, extended bore positioning, and prolonged beam-on times, were reported qualitatively by participating centers but were not incorporated into the dose calculation or planning model [7–9].

OARs sparing in Tomotherapy-based TBI was primarily achieved through inverse planning and continuous intensity modulation along the longitudinal axis. Lung sparing, where applied clinically, was implemented via optimization objectives rather than geometric shielding concepts.

2.3. Study Evaluation

Plan evaluation for all submitted datasets was based on predefined POI doses. For table-based submissions, the analysis was necessarily limited to POI-based dose values, as no volumetric dose information was available. POIs were defined at corresponding anatomical locations in the HFS and HFP CT datasets, allowing summation of supine and prone dose contributions to obtain cumulative delivered doses. For table-based submissions, participating centers reported the POI doses according to their established clinical workflows. Depending on the applied technique, the reported values were derived from CT-based geometric information and institution-specific calculation procedures. An example of the corresponding data collection and reporting form is provided as Supplementary Material.

Because POI-based dose estimates fundamentally differ from volumetric OAR metrics derived from dose–volume histograms (DVH), POI-based and volume-based results were analyzed and interpreted separately. This distinction is particularly relevant for the lungs, where tissue heterogeneity and pronounced dose gradients can cause localized point doses—especially center-of-organ POIs—to systematically deviate from mean or volume-based dose descriptors.

For TPS-based submissions, full 3D dose information was available. All TPS-based DICOM plans were imported into RayStation TPS research environment (version 12A; RaySearch Laboratories, Stockholm, Sweden) using a dedicated study patient. The submitted RTDOSE distributions were imported and evaluated without recalculation. RayStation was used exclusively for extraction and comparison of dosimetric parameters, thereby preserving the original dose calculation algorithms and commissioning data of the respective participating institutions. Dose parameters were extracted using the built-in RayStation plan comparison tool combined with standardized in-house Python scripts. For each plan, DVH metrics were calculated for the PTV and selected OARs. The OAR evaluation focused on organs relevant to the organ-sparing strategies used by participating centers. Other organs within the TBI target volume, including the cochleae, were expected to receive approximately the prescribed total dose of 8 or 12 Gy in 2 Gy fractions unless specifically spared. PTV coverage was defined as $V_{95\%}$, representing the percentage of the planning target volume receiving at least 95% of the prescribed dose. OAR doses were evaluated in terms of mean dose and maximum dose or $D^{3}_{0.5cm}$, depending on the organ and in accordance with the metrics reported in Fig. 5, where $D^{3}_{0.5cm}$ denotes the dose received by the most highly exposed 0.5 cm^3 of the respective organ.

In addition to the plan-specific TPS-based DVH analysis, an aggregated evaluation of total lung DVHs was conducted for all TPS-based 12 Gy TBI plans (n = 11) using the RayIntelligence platform (RaySearch Laboratories, Stockholm, Sweden). This cloud-based analysis was used to extract and combine lung DVH data across institutions, enabling percentile-based summary statistics, including the median, interquartile range (25th–75th percentile), and full range of observed lung dose distributions. The RayIntelligence evaluation served exclusively for cross-institutional DVH aggregation and visualization and did not replace the primary TPS-based dosimetric analysis.

To ensure comparability across techniques, all plans were categorized according to (i) prescription level (8 Gy vs. 12 Gy) and (ii) planning method (TPS-based vs. table-based). For TPS-based plans, an additional grouping by technique category (VMAT/Tomotherapy, sweeping beam, static fields, and bilateral/translation techniques) was applied to allow direct correspondence with the figures presented in the Results section. For all metrics, results were summarized using boxplots to illustrate inter-institutional variability and technique-dependent clustering.

Table 1
Overview of participating radiotherapy centers, applied total body irradiation techniques, and corresponding grouping used for analysis. The table summarizes the number of submitted plans for the 8 Gy and 12 Gy prescription levels, distinguishing between TPS-based and table-based approaches.

	Total		TPS-based		Table-based		Analysis group (Fig. 4 and Fig. 5)
	8 Gy	12 Gy	8 Gy	12 Gy	8 Gy	12 Gy	
VMAT	8	6	8	6	0	0	VMAT + Tomo
Tomotherapy	2	2	2	2	0	0	VMAT + Tomo
Sweeping beam	6	5	4	2	2	3	Sweeping beam
Static fields	8	8	3	1	5	7	Static fields
Total	24	21	17	11	7	10	

3. Results

3.1. Study design

In total, treatment planning datasets from 24 radiotherapy institutions were available for analysis. All centers submitted treatment plans for the 8 Gy prescription level, while 21 centers additionally provided plans for the 12 Gy prescription level, resulting in a total of 45 evaluated TBI plans. Of these, 17 TPS-based and 7 table-based plans were submitted for 8 Gy, whereas 11 TPS-based and 10 table-based plans were available for 12 Gy. An overview of the submitted datasets and applied techniques is provided in Table 1.

Depending on the technique, centers either used one or both CT orientations directly within their TPS or derived geometric parameters (e.g., body width, lung thickness, midline distances) from the CTs to perform table-based dose calculations.

3.2. Plan Evaluation

3.2.1. POI-based plan evaluation

POI dose evaluations were performed for all submitted datasets using the predefined POIs provided in the HFS and HFP CT datasets. For table-based submissions, these POIs represented the only source of dose information, whereas TPS-based plans allowed a direct extraction of POI values from the corresponding DICOM dose distributions. The use of anatomically consistent POIs ensured comparability across planning techniques, despite the differing geometric assumptions of the techniques and the fact that the clinical irradiation geometries—particularly for sweeping beam, bilateral, and translation setups—do not directly correspond to the CT positions supplied in this study.

Fig. 4 summarizes the POI doses for both prescription levels, with 24 evaluated datasets for 8 Gy and 21 evaluated datasets for 12 Gy. For the 8 Gy prescription level, most POI doses across all techniques spanned a range of approximately 6.5–9.5 Gy, corresponding to deviations of up to ±20% from the prescribed dose at individual anatomical locations. VMAT and Tomotherapy exhibited the smallest interquartile ranges, typically within ±5–8% of the prescription dose across most POIs, with median values closely aligned to the prescribed dose, indicating high reproducibility of geometric and dosimetric modelling across institutions using conformal, intensity-modulated techniques. In contrast, sweeping beam plans demonstrated the broadest POI dose distributions, with interquartile ranges frequently exceeding ±15% and total spreads of up to 30% relative to the prescription. Static field approaches showed intermediate variability, with POI dose ranges typically within

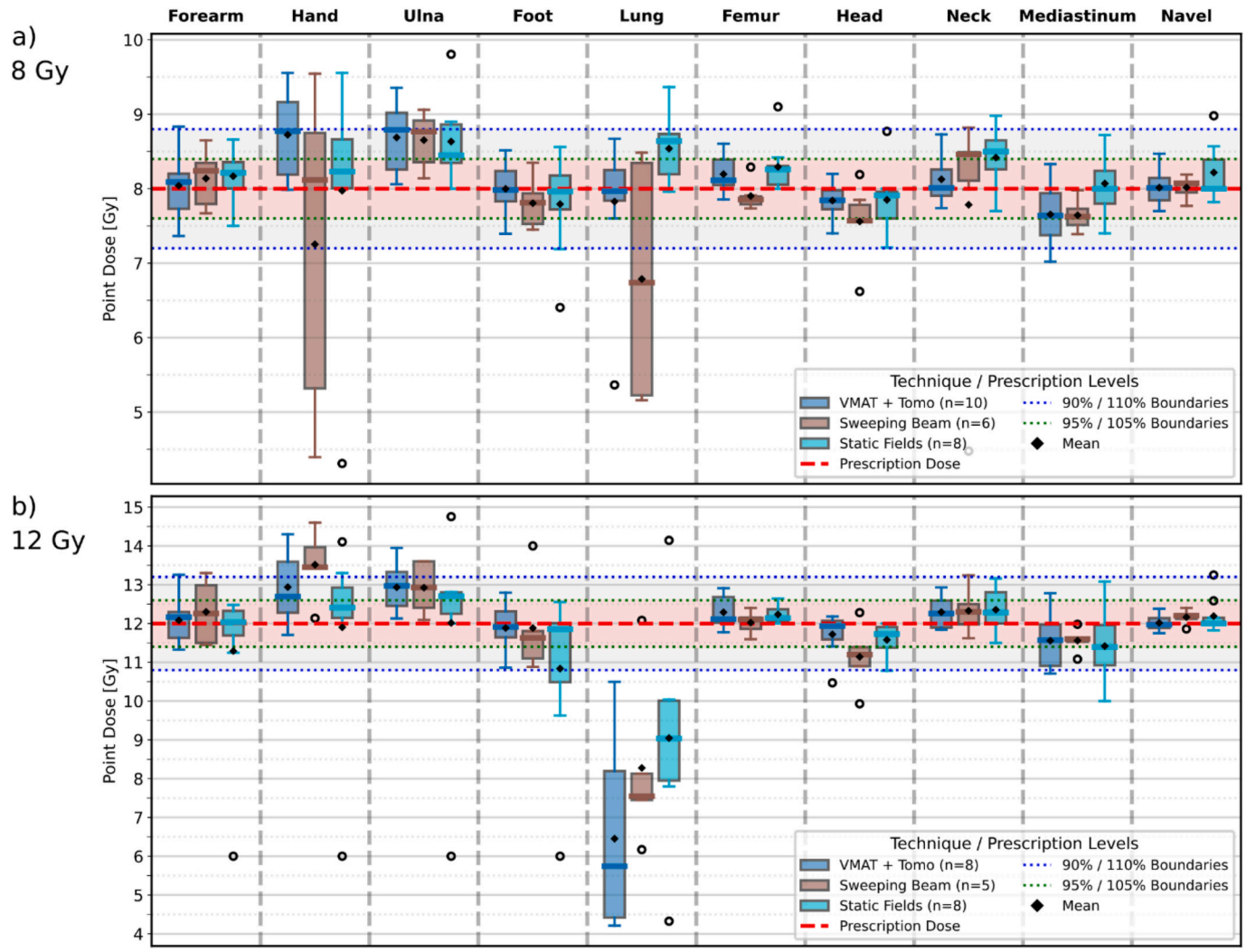


Fig. 4. POI dose distributions at selected anatomical sites for all 24 centers at the 8 Gy (a) and all 21 centers at the 12 Gy (b) prescription levels. Boxplots are grouped by technique according to Table 1. The thick horizontal line within each box denotes the median, the box limits represent the interquartile range (25th–75th percentile), and the whiskers indicate the data range excluding outliers. Black diamonds mark the mean values, while open circles denote statistical outliers. The red dashed line indicates the prescribed dose; dotted and dashed lines indicate ±5% and ±10% deviation bands, respectively. For bilaterally defined anatomical regions (e.g., hands, feet, femora), left and right POI measurements were pooled and analyzed jointly to generate a single boxplot per anatomical region. The exact anatomical POI locations are illustrated in Fig. 2.

±10–15% of the prescription dose, reflecting heterogeneity in beam arrangements, extended source-to-surface distance setups, and center-specific approximations used to map clinical workflows onto the supplied CT datasets. Median lung POI doses were reduced by approximately 1–2 Gy in several submissions, consistent with institution-specific lung sparing strategies.

At the 12 Gy prescription level, the overall distribution patterns remained comparable. VMAT and Tomotherapy again demonstrated the narrowest dose distributions across most anatomical sites, whereas sweeping beam approaches exhibited the largest spread of POI values. Static field techniques showed intermediate variability. Lung sparing effects were more pronounced than at 8 Gy, with median lung POI doses reduced by up to 2.5–3 Gy in several submissions. Similar reductions were observed at selected distal extremity POIs, reflecting technique-specific dose modulation and institutional planning objectives.

To assess whether these differences reflected systematic technique-related effects, group differences in POI doses between conformal techniques (VMAT and Tomotherapy) and non-conformal approaches (sweeping beam and static fields) were evaluated using two-sided Mann–Whitney U tests. For the 8 Gy prescription level, no significant group-level differences were observed for lung POIs (7.83 ± 0.93 Gy for VMAT and Tomotherapy vs. 7.69 ± 1.44 Gy for sweeping beam and static fields; $p = 0.683$) or for distal extremity doses at the hand POIs (8.72 ± 0.58 Gy vs. 6.79 ± 3.22 Gy; $p = 0.288$).

Similarly, for the 12 Gy prescription level, no consistent group-level differences were observed for lung POIs (6.79 ± 3.11 Gy for VMAT and Tomotherapy vs. 7.56 ± 4.01 Gy for sweeping beam and static fields; $p = 0.921$) or for hand POIs (12.94 ± 0.96 Gy vs. 13.92 ± 0.48 Gy; $p = 0.133$).

Overall, the observed differences were driven primarily by inter-institutional variability and dispersion of results rather than by a consistent systematic offset between technique groups.

3.2.2. *DVH-based plan evaluation*

DVH-based analysis was performed exclusively for TPS-based submissions, as only these provided full volumetric dose information. Evaluated parameters included PTV coverage (V95%), mean organ doses, and $D0.5cm^3$ for selected serial organs, following the definitions shown in Fig. 5. Because several TPS-based techniques were planned using separate HFS and HFP datasets, a consistent volumetric dose summation across both patient orientations was not feasible for all

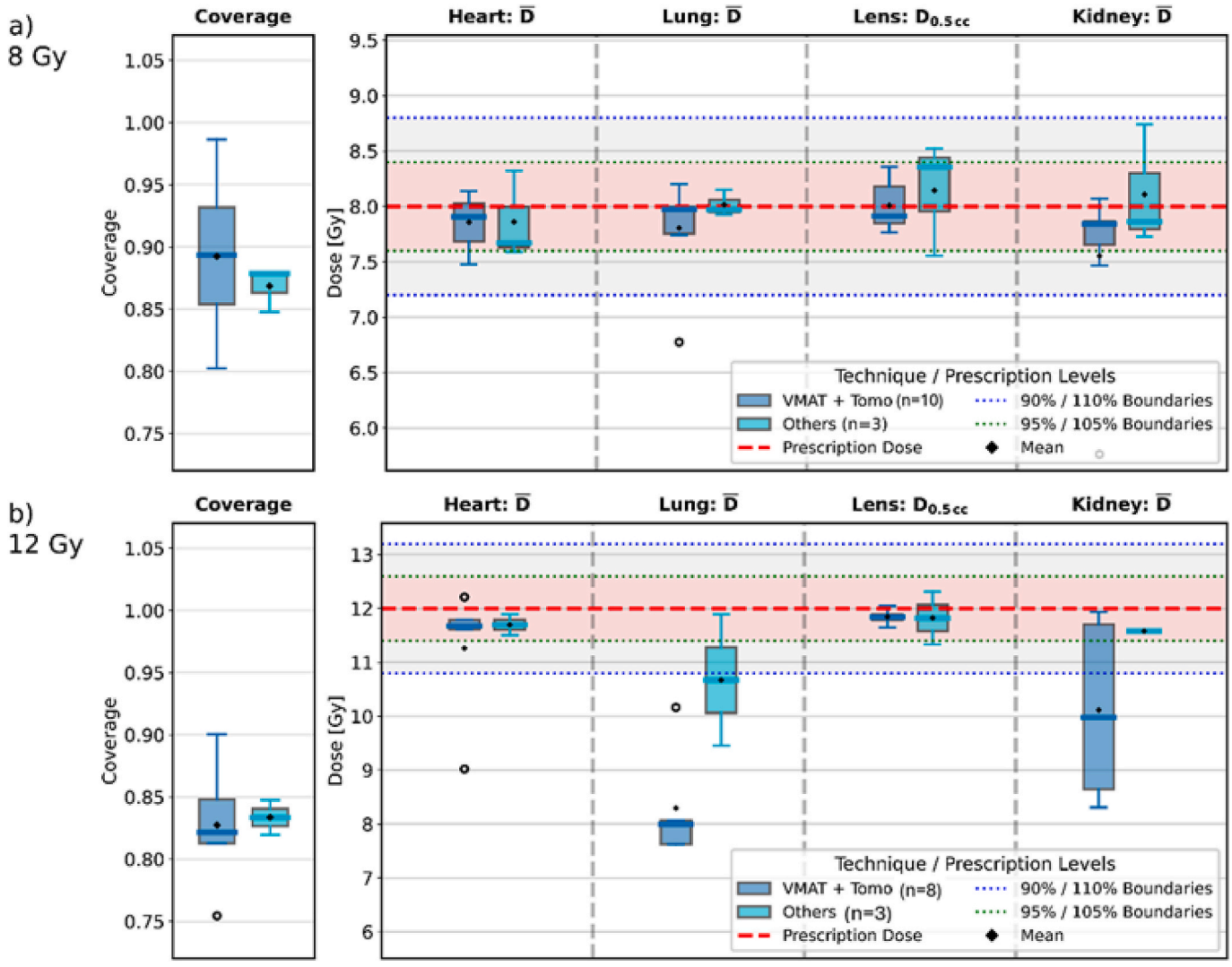


Fig. 5. DVH–derived dose metrics for VMAT, Tomotherapy, and non-conformal techniques at the 8 Gy (a) and 12 Gy (b) prescription levels. Shown are planning target volume (PTV) coverage ($V_{95\%}$), mean lung dose, mean hart dose, lens dose ($D^{3}_{0.5cm}$), and mean kidney dose. Boxplots depict the median (thick horizontal line), interquartile range (box limits, 25th–75th percentile), and data range excluding outliers (whiskers). Black diamonds indicate mean values, and open circles represent statistical outliers. VMAT and Tomotherapy are jointly displayed as the conformal technique group, while sweeping-beam and static-field submissions represent non-conformal techniques. The red dashed line indicates the prescribed dose; dotted and dashed lines indicate ±5% and ±10% deviation bands, respectively.

submitted plans. Therefore, DVH-based analyses were restricted to TPS-based plans available as complete dose distributions on a single CT dataset, whereas plans requiring HFS/HFP dose summation were evaluated using the predefined POIs only. At the 8 Gy prescription level, VMAT and Tomotherapy demonstrated tightly clustered coverage values with V95% = 0.898 ± 0.061 (VMAT and Tomotherapy, n = 10), compared with 0.869 ± 0.018 for non-conformal techniques (sweeping beam + static field, n = 7; Mann–Whitney U test: p = 0.517), indicating limited inter-institutional variability within the evaluated TPS-based datasets. For the lungs, mean dose values were 7.28 ± 1.41 Gy for VMAT and Tomotherapy and 8.02 ± 1.12 Gy for sweeping beam and static field (p = 0.781). For the lenses, D0.5cm^3 was 8.02 ± 0.23 Gy (VMAT + Tomo) versus 8.15 ± 0.52 Gy (sweeping beam + static field; p = 0.517), i.e., broadly centered close to the prescription dose. Kidney mean doses were 7.04 ± 1.43 Gy (VMAT + Tomo) and 8.11 ± 1.55 Gy (sweeping beam + static field; p = 0.517).

At the 12 Gy prescription level, target coverage decreased overall, with V95% values of 0.842 ± 0.031 for VMAT and Tomotherapy (n = 8) and 0.834 ± 0.020 for sweeping beam and static field techniques (n = 3), noting that the PTV comprised the entire body including the lungs, such that lung sparing objectives inherently reduced V95%. The absolute difference in mean target coverage between groups was small (ΔV95% ≈ 0.008) and was smaller than the within-group variability observed for the VMAT and Tomotherapy plans. Statistical testing did not indicate a significant group-level difference (p = 0.857); however, this result should be interpreted with caution given the very small subgroup size of the non-conformal techniques. Mean lung doses increased to 7.86 ± 2.61 Gy for VMAT and Tomotherapy and 10.67 ± 1.72 Gy for sweeping beam + static field (p = 0.429). Lens D0.5cm^3 was 11.77 ± 0.44 Gy (VMAT + Tomo) versus 10.67 ± 1.72 Gy (sweeping beam + static field; p = 0.857). Kidney mean doses were 9.28 ± 2.26 Gy (VMAT + Tomo) compared with 11.58 ± 0.02 Gy (sweeping beam + static field; p = 0.643). Given the limited number of TPS-based submissions in some technique subgroups, particularly at the 12 Gy prescription level, statistical comparisons were interpreted as exploratory, with greater emphasis placed on effect sizes and the dispersion of results rather than on p-values alone.

Fig. 6 shows the aggregated total lung DVH distribution for all TPS-based 12 Gy TBI plans. The semi-transparent light blue area represents the full range of lung DVHs observed across all institutions. The median lung DVH is depicted as a pink curve, while the orange curves correspond to the 25th and 75th percentiles, analogous to an interquartile

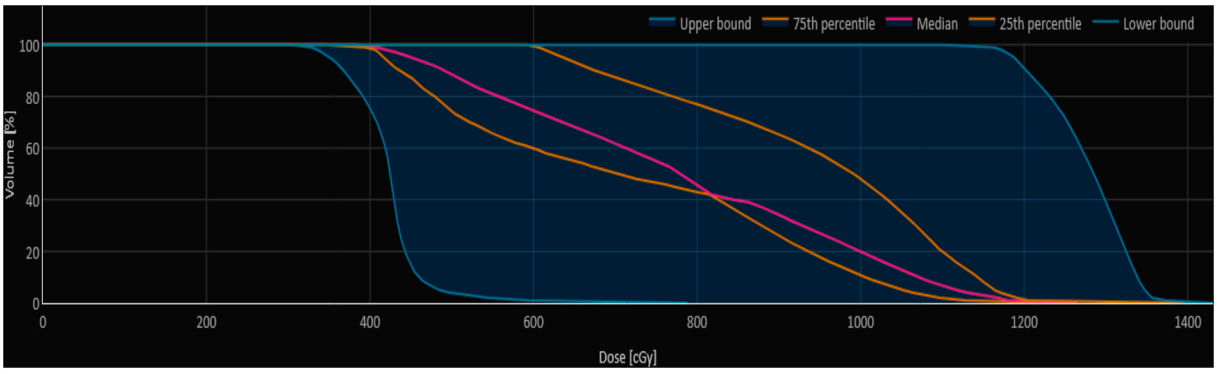


Fig. 6. Percentile-based aggregated total lung DVH for all TPS-based 12 Gy TBI plans (n = 11). The shaded area shows the full range of lung DVHs, the pink line represents the median, and the orange lines denote the 25th and 75th percentiles.

range representation in a boxplot but displayed in DVH form. The close proximity of the median to the center of the interquartile envelope indicates a consistent clustering of lung dose distributions among most institutions, despite the absence of harmonized lung dose constraints. Overall, the aggregated DVH analysis corroborates the DVH-based findings obtained from individual treatment plans and highlights the variability in lung dose sparing across centers.

4. Discussion

This multicenter planning study provides the most comprehensive overview to date of current TBI planning practice in Germany and Switzerland. By evaluating multiple plans under standardized conditions, the study revealed substantial inter-institutional variability in both PTV coverage and OAR sparing. For example, DVH-based target coverage ($V_{95\%}$) at the 8 Gy prescription level ranged from approximately 0.85 to 0.95 across institutions, while mean lung doses at 12 Gy varied by more than 2–3 Gy, depending on technique and local planning objectives. These findings reflect heterogeneous planning philosophies, clinical priorities, and technical resources across centers. The results complement earlier DGMP survey findings, yet extend them through a direct, quantitative comparison of dose distributions rather than self-reported descriptions of clinical practice [10,11].

Importantly, this study goes beyond previous descriptive surveys by establishing a common, well-defined patient dataset and standardized planning framework, thereby enabling direct, clinic-independent dosimetric comparisons for the first time. While earlier studies primarily contrasted different TBI techniques in a qualitative manner, the present work provides a quantitative assessment of dose distributions generated by multiple institutions under identical anatomical conditions.

Comparable heterogeneity in TBI practice has recently been reported in a nationwide Japanese survey including 73 institutions [18]. This study demonstrated marked variation in irradiation techniques, patient positioning, beam energy, organ shielding strategies, and the use of in vivo dosimetry, with long SSD techniques dominating clinical practice and IMRT-based approaches such as Tomotherapy and VMAT being used in a minority of centers. Although based on self-reported workflows rather than dosimetric plan comparison, the Japanese data reinforce the conclusion that substantial variability in TBI implementation exists internationally and underline the need for harmonized approaches to planning, delivery, and quality assurance.

A key observation of the present study is the technique-dependent variability in dose homogeneity. Modern conformal, intensity-modulated methods such as VMAT and Tomotherapy demonstrated narrow institution-to-institution variability and a consistent reproduction of planned dose metrics. This consistency was not solely attributable to the delivery technique itself but was strongly influenced by the application of similar institutional lung dose objectives, typically aiming for a mean lung dose in the range of approximately 7–8 Gy for a 12 Gy prescription, combined with comparable target coverage priorities and internal planning guidelines. Consequently, the tighter clustering of VMAT and Tomotherapy plans should not be interpreted as an inherent dosimetric superiority of the modality alone, but rather as the result of an interplay between technical capabilities and harmonized clinical constraints. In contrast, non-conformal approaches—including sweeping beam, static field, bilateral, and translation techniques—showed wider dispersion in both POI-based and DVH-derived parameters, reflecting not only their limited modulation capabilities but also long-standing local traditions with diverse constraint philosophies.

Despite the clinical importance of lung sparing in TBI, widely used lung toxicity constraints from thoracic radiotherapy (e.g., $V_{20Gy}<30\%$) are not directly applicable in this low-dose setting, given the lack of robust dose–response evidence for clinically relevant pneumonitis at such low fractional doses. Instead, lung objectives in TBI are largely protocol- and center-specific, and no universally adopted international guideline defines strict, harmonized lung dose limits for TBI [19]. Historical work on TBI dosimetry has focused on physical parameters and mean lung dose as a comparative metric rather than on defined constraint thresholds [2,20]. In particular, the lower lung doses observed for VMAT plans primarily resulted from institution-specific dose objectives (e.g., mean lung dose $\leq$ 7–8 Gy at a 12 Gy prescription) rather than from an intrinsic dosimetric advantage of the technique itself. In contrast, kidney, heart, and lens sparing were applied far less uniformly. Only a minority of centers used explicit dose constraints for these organs, consistent with previous findings from the national DGMP survey [10]. Accordingly, the observed inter-institutional variability for these OARs was driven more strongly by clinical preference than by technical limitations. The particularly wide interquartile ranges observed for lung and hand POI doses in the sweeping beam group at 8 Gy (Fig. 4a) can be attributed to technique-specific geometric factors, including differences in lung shielding concepts, sweep length and field margins, as well as variable handling of distal extremities that are not fully encompassed by the homogeneous dose region.

An additional clinical consideration concerns the interpretation of mean lung dose levels. While excessive lung doses are well known to increase the risk of radiation pneumonitis, there is no evidence that extremely low lung doses (e.g., $<$ 6 Gy at a 12 Gy TBI prescription) are clinically advantageous. A minimal dose contribution to the lung is therefore considered relevant for immunosuppression and antileukemic efficacy, whereas excessive doses increase pulmonary toxicity [1,2,8]. Consequently, variations in lung sparing must be interpreted in the context of institutional clinical intent rather than as a universal indicator of plan quality.

At the higher prescription level of 12 Gy, the trade-off between target coverage and OAR protection became more pronounced. Coverage values declined systematically across all techniques, particularly in institutions prioritizing aggressive lung sparing. This finding highlights a central clinical dilemma of TBI: increasing prescription doses intensifies

the need for lung dose reduction while simultaneously challenging the ability of non-modulated techniques to maintain uniform whole-body dose coverage. These observations are consistent with earlier reports describing the balance between simplicity, robustness, and dosimetric precision in large-field irradiation techniques [4,8,13].

Regarding our planning-based comparison study, several inherent limitations have to be acknowledged. Such analyses cannot fully capture clinically relevant aspects related to patient motion, setup robustness, surface dose, and patient tolerability. Particularly for highly conformal techniques such as VMAT and Tomotherapy, intrafractional motion, prolonged treatment times, and discomfort during immobilization may result in dose deviations that are not reflected in planned dose distributions. Attempts to mitigate surface underdosage using virtual bolus structures during planning have been reported, but clinical evidence demonstrating their effectiveness remains limited. In contrast, translation couch TBI techniques is less sensitive to intrafractional motion and prolonged immobilization, which may offer practical advantages with respect to robustness, patient comfort, and treatment continuity. These aspects illustrate that dosimetric plan quality alone does not fully represent the overall clinical performance of a given TBI technique.

Further methodological limitations of the present study include the use of virtual planning scenarios rather than delivered dose, precluding direct assessment of real-world uncertainties such as patient setup, extended SSD scatter conditions, surface dose modelling, and anatomical deformation. In addition, differences in dose calculation algorithms could not be isolated from technique-related effects and contributed to inter-institutional variability, particularly for lung and kidney doses. Finally, some clinical techniques—such as seated bilateral setups or translation couch approaches—require geometric approximations when transferred to the supine and prone CT datasets provided in this study.

To address these limitations, follow-up activities within the DGMP working group are planned as part of a broader stepwise initiative to evaluate and harmonize large-field irradiation techniques. Following previous survey-based and technique-oriented analyses and the present multicenter planning comparison, future work will focus on end-to-end dosimetric verification using dedicated phantom measurements to assess the accuracy and robustness of the investigated techniques under clinically realistic conditions. These efforts aim to complement the virtual planning analysis with experimental data and to provide a stronger basis for the future development of harmonized recommendations and risk-management concepts for TBI planning and delivery in collaboration with clinical experts. Therefore, the present study should be interpreted as a benchmark of current practice rather than as a basis for recommending a specific planning technique.

5. Conclusion

This multicenter planning comparison demonstrates the considerable heterogeneity of TBI planning across German and Swiss radiotherapy centers. Modern conformal approaches such as VMAT and Tomotherapy yielded reproducible dose distributions, while non-conformal techniques showed greater variability driven by both technical limitations and divergent institutional planning philosophies. Lung sparing emerged as the only uniformly applied OAR objective, whereas constraints for other organs varied substantially. These findings provide the essential groundwork for harmonizing TBI planning practice.

CRediT authorship contribution statement

Maya Shariff: Writing – original draft, Conceptualization, Investigation, Data curation, Methodology, Project administration. **Heiko Karle:** Methodology, Conceptualization, Writing – original draft. **Oliver Schramm:** Conceptualization, Writing – original draft, Methodology, Validation. **Johann Brand:** Formal analysis, Data curation, Software. **Andre Karius:** Writing – review & editing, Methodology. **Sven Knobe:** Writing – original draft, Validation, Methodology. **Hendrik Auerbach:** Writing – original draft. **Jerome Krayenbuehl:** Writing – original draft. **Sebastian Neppl:** Writing – original draft. **Julia Kirschke:** Writing – original draft. **Friedericke Lips:** Writing – original draft. **Frank Ubrich:** Writing – original draft. **Marius Treutwein:** Writing – original draft. **Nora Maurer:** Writing – original draft. **Tenzin Sonam Stelljes:** Writing – original draft. **Christos Moustakis:** Writing – original draft. **Marie Gemes:** Writing – original draft. **Sophie Küchler:** Writing – original draft. **Svea Kühl:** Writing – original draft. **Marc Delaperriere:** Writing – original draft. **Janett Köhn:** Writing – original draft. **Oliver Neumann:** Writing – original draft, Methodology. **Christoph Losert:** Writing – original draft, Methodology. **Elisabetta Gargioni:** Writing – original draft. **Felix Voigt:** Writing – original draft. **Manfred Schmidt:** Writing – original draft. **Stefanie Corradini:** Writing – review & editing. **Christoph Bert:** Writing – original draft, Methodology. **Pauline Riethmüller:** Writing – original draft. **Falk Tillner:** Writing – original draft, Conceptualization, Investigation, 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.

Acknowledgments

We gratefully acknowledge RaySearch Laboratories for providing complimentary research access to the RayIntelligence platform, which enabled centralized evaluation and visualization of TPS-based dose metrics in this study. We also thank all participating radiotherapy centers for their contributions and for completing the detailed technique and planning documentation that formed the basis of this multicenter analysis.

Declaration of generative AI use

During manuscript preparation, ChatGPT (OpenAI) was used to improve language. All AI-assisted content was critically reviewed and thoroughly revised by all authors to ensure accuracy and consistency with their scientific analysis and interpretation. All authors approved the final manuscript and take full responsibility for its content.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.zemedi.2026.11.002.

References

[1] Peters M, Taylor B, Turner E. An Evidence-Based Review of Total Body Irradiation. J Med Imaging Radiat Sci 2015;46(4):442–9.
[2] Quast U. Whole body radiotherapy: A TBI-guideline. J Med Phys 2006;31(1):5–12.
[3] U. Quast, H.S., M. Engelhard, H.Pape, K. Bratengeier, R. Müller, K. Rittmann, V. Runde, U. W. Schaefer, Whole Body Radiotherapy - Guidelines in Radio- Oncology. 2003.
[4] Pla M, Chenery SG, Podgorsak EB. Total body irradiation with a sweeping beam. Int J Radiat Oncol Biol Phys 1983;9(1):83–9.
[5] Simiele E, et al. A Step Toward Making VMAT TBI More Prevalent: Automating the Treatment Planning Process. Pract Radiat Oncol 2021;11(5):415–23.
[6] Kovalchuk N, et al. The Stanford Volumetric Modulated Arc Therapy Total Body Irradiation Technique. Pract Radiat Oncol 2022;12(3):245–58.
[7] Cleuziou JP, et al. Total body irradiation using helical tomotherapy: Set-up experience and in-vivo dosimetric evaluation. Cancer Radiother 2021;25(3):213–21.
[8] 8. J. Van Dyk, J.M.G., G. P. Glasgow, E. B. Podgorsak, Report No. 017 - The Physical Aspects of Total and Half Body Photon Irradiation (1986). 1986.
[9] Quast U. Total body irradiation–review of treatment techniques in Europe. Radiother Oncol 1987;9(2):91–106.
[10] Heuchel L, et al. Large-field irradiation techniques in Germany: A DGMP Working Group survey on the current clinical implementation of total body irradiation, total skin irradiation and craniospinal irradiation. Zeitschrift für Medizinische Physik 2024.

[11] Shariff, M., et al., Multicenter Comparison of Different Total Body Irradiation Techniques – Results from the DGMP Working Group Large-Field Irradiation Techniques. 2025.
[12] Giardina M, et al. SAPERO: a new tool for safety analyses in advanced radiotherapy. The European Physical Journal Plus 2023;138(9):865.
[13] Härtl PM, et al. Total body irradiation-an attachment free sweeping beam technique. Radiat Oncol 2016;11:81.
[14] Hui C, et al. Volumetric modulated arc therapy total body irradiation improves toxicity outcomes compared to 2D total body irradiation. Front Oncol 2024;14:1459287.
[15] Ngo N, et al. Improved organ sparing using auto-planned Stanford volumetric modulated arc therapy for total body irradiation technique. Pediatric Blood & Cancer 2023;70(10):e30589.
[16] Springer A, et al. Total body irradiation with volumetric modulated arc therapy: Dosimetric data and first clinical experience. Radiat Oncol 2016;11:46.
[17] Tas B, et al. Total-body irradiation using linac-based volumetric modulated arc therapy: Its clinical accuracy, feasibility and reliability. Radiother Oncol 2018;129(3):527–33.
[18] Kitagawa M, et al. A multi-institutional survey on technical variations in total body irradiation in Japan. Radiol Phys Technol 2025;18(2):347–57.
[19] Hoeben BAW, et al. ESTRO ACROP and SIOPE recommendations for myeloablative Total Body Irradiation in children. Radiotherapy and Oncology 2022;173:119–33.
[20] Quast U, Dutreix A, Broerse JJ. Late effects of total body irradiation in correlation with physical parameters. Radiother Oncol 1990;18(Suppl 1):158–62.